Renewable energy implementation and use in German regions

Contributions to regional energy transition strategies considering context, time and practice

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Gutachter Prof. Dr. Henrik von Wehrden

Gutachter Prof. Dr. Michael Stauffacher

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Abstract

The German energy system is under transformation. The so-called *Energiewende* (in English, Energy turn) relies, among other things, on renewable energies for building a more sustainable energy system. Regions (Landkreise) are one relevant level where different administrative bodies make decisions and plans both for the implementation and for the use of renewable energies. However, in order to realize the goals of the Energiewende, developments in the wider society are necessary. This is why, scientific research can and should foster such developments with more research on the social aspects of energy-related topics.

The present work contributes to the understanding of transition processes towards a sustainable use of regional renewable energy by focusing on the role of contextual conditions, practical experiences, and temporal dynamics in the implementation and use of renewable energy in German regions. In this way, this work wants to contribute fostering the development of regional energy transition strategies for the realization of the Energiewende. The conceptual background for this piece of transformation research lies in three bodies of literature dealing respectively with transitions of socio-technical systems, transformations of socioecological systems, and time ecology. From a critical engagement with this literature, three main results have emerged. First, an evidence-based, spatially distinct analysis of contextual conditions for the use of renewable energy in all German regions has resulted in the identification of nine types of regions, so-called energy context types. Second, empirical research on practices in regional settings learned from the know-how of actors from regional administration has shown that political and economic conditions are crucial as well as that process management, exchange, and learning are helpful for renewable energy implementation. Third, conceptual work about a deeper understanding of the temporal dimensions of transformation processes has made it possible to point out a three-step approach to include temporal dynamics into sustainability transformations "management" – the time-in-transformations-approach.

The literature suggests that regions need to be treated individually; but developing an energy transition strategy for each region individually would be extremely resource intensive. Overall, my work outlines a compromise for a more efficient approach towards regional energy transition strategies which still considers the individuality of regions. As a result, I suggest to develop generic regional energy transition strategies that are adapted to each of the nine energy context types of German regions, that include the experiences of practitioners, and that consider temporal dynamics of transformation processes. Transdisciplinary research is a promising approach to meet many of the challenges for the realization of the Energiewende. A transdisciplinary steering board on the national level

could create generic regional energy transition strategies that guide the energy transition and give clear goals and orientation for the realization of policies on the lower levels. On the regional level, these strategies would need to be adapted with regard to each region's situation. Relying on the results of my research, I conclude that this could also be informed through transdisciplinary processes.

Zusammenfassung

Das deutsche Energiesystem ist im Wandel. Im Rahmen der Energiewende soll ein nachhaltiges Energiesystem entstehen, das unter anderem auf der Nutzung erneuerbarer Energien basiert. Regionen (Landkreise) sind dabei besonders relevant, da auf dieser administrativ-politischen Ebene die konkrete Umsetzung von Politik und damit die Implementierung und Nutzung von erneuerbaren Energien stattfindet. Um die Energiewende zu realisieren sind Entwicklungen auf gesamtgesellschaftlicher Ebene notwendig; und damit ist auch sozialwissenschaftlicher Forschung zur Energiewende notwendig und interessant.

Diese Dissertation trägt zu einem besseren Verständnis des Transformationsprozesses hin zur regionalen Nutzung von erneuerbaren Energien bei. Mit einer empirischen, räumlich differenzierten Analyse der naturräumlichen und sozio-ökonomischen Kontextbedingen für die Nutzung erneuerbarer Energie in allen deutschen Landkreisen identifizierte ich 9 Typen von Regionen, die *energy context types*. In einem energy context type befragte ich Akteure aus der regionalen Administration zu ihren praktischen Erfahrungen mit der Implementierung von erneuerbaren Energien. Als erfolgsversprechend haben sich eindeutige politische und wirtschaftliche Rahmenbedingungen herausgestellt, sowie Prozessmanagement, der Austausch mit ExpertInnen und MitarbeiterInnen anderer Regionen sowie eine breit aufgestellte Finanzierung aus mehreren Quellen. Ergänzend zu den empirischen Untersuchungen präsentiere ich in dieser Dissertation konzeptionelle Arbeit zur zeitlichen Dynamik von Transformationsprozessen: der *time-in-transformations-approach* ermöglicht es, zeitliche Dynamiken konkreter in Begleitung und Management von Transformationsprozessen berücksichtigen zu können.

In der Literatur wird häufig die Position vertreten, dass Regionen individuell betrachtet werden müssen. Es wäre allerdings sehr zeit- und geldintensiv, für jede der 412 Regionen eine eigene Energiewendestrategie zu entwickeln. Mit dieser Dissertation stelle ich einen Kompromiss vor, der einerseits eine effiziente Entwicklung von regionalen Energiewendestrategien ermöglicht, anderseits aber auch die Individualität der Regionen berücksichtigt: für jeden der neun *energy context types* könnten generische regionale Energiewendestrategien entwickelt werden, die auch die Erfahrungen aus der Praxis sowie zeitliche Dynamiken von Transformationsprozessen berücksichtigen. Transdisziplinäre Forschung ist ein erfolgversprechender Ansatz, um vielen Herausforderungen der Energiewende zu begegnen. Eine transdisziplinäre Steuerungsgruppe könnte auf der nationalen Ebene die generischen regionalen Energiewendestrategien entwickeln, und damit klare Rahmenbedingungen für die regionale Praxis schaffen. Folgend könnten diese Strategien in den Regionen in transdisziplinären Prozessen angepasst werden.

Table of content

Chapter 1

Empirical and conceptual contributions to regional energy transition strategies and suggestions for their realization

Lotte M. Lutz

1. Introduction

Renewable energies are widely acknowledged as basis for the realization of more sustainable energy systems (Chu and Majumdar, 2012; Dincer and Acar, 2015; IPCC, 2011; WBGU, 2011). Because renewable energies emit considerably less greenhouse gases (GHG) in comparison to fossil fuels, they offer the opportunity to decouple increasing energy use from increasing GHG emissions (Sathaye et al., 2011). The year 2016 showed 8.7 % growth of renewables worldwide (IRENA, 2017) despite declining investments, which is discussed as a sign for the maturity of renewable energy technologies (FS UNEP Centre and BNEF, 2017). Renewable energies also seem to have advantages over fossil and nuclear energy technologies with regard to health concerns, waste disposal and catastrophic potential (Gallego Carrera and Mack, 2010). And yet, one single global solution for a sustainable use of renewable energies is not possible, as many renewable energy solutions strongly depend on local, regional, and cultural contexts (Sathaye et al., 2011). Several frameworks for a sustainable use of renewable energies in local and regional contexts have been developed; they either focus on socio-economic development (del Río and Burguillo, 2008; Neves and Leal, 2010) or take a more traditional engineering perspective (Mainali and Silveira, 2015). However, most of these have not yet been tested empirically.

According to Giddens (2011), all levels of "the state" from international to local will need to play a decisive role in climate change mitigation. The transition of the energy system, which includes the growing use of renewable energies, is governed on multiple scales. A multitude of global and international policies and programs foster the use of renewable energies (e.g. European Commission, 2014, 2011; IRENA, 2016; OECD et al., 2016; UNFCCC, 2015). While national parliaments design binding policies, it is the regional level that holds the power to transform: in the EU, it "is the governance scale where a wide array of policies are actually implemented and realised" (Morgan, 2004, p. 872).

In this dissertation, I use the term "implementation" for the process in which the use of renewable energy is prepared, for example with discussion, decision making, search for funding, technical considerations, and the setting up of installations such as a wind park or a solar panel. In comparison, the term "use" describes the period of time in which renewable energy installations are set up and running.

Implementation and use of renewable energies is being widely discussed and analyzed in research. Place-based case studies concentrate on different aspects of the implementation and use of renewable energy, e.g. technologies (Blaschke et al., 2013; Blumer et al., 2013; Kostevsek et al., 2013; Trutnevyte et al., 2012b), acceptance (Hitzeroth and Megerle, 2013; Musall and Kuik, 2011; Zoellner et al., 2008), process dynamics (Hecher et al., 2016; McCauley and Stephens, 2012; Späth, 2012; Walker, 2008; Walker et al., 2010), energy landscapes and spatial planning (Binder et al., 2016; Kienast et al., 2017) or developing and discussing visions (Schreuer et al., 2010; Späth and Rohracher, 2010; Trutnevyte et al., 2012a, 2011).

One prominent approach to analyze changing systems, e.g. energy systems, is the socio-technical transitions theory (Berkhout et al., 2012; Child and Breyer, 2017; Sovacool, 2016). According to this theory, transition processes derive from technological or socio-technical innovations which contribute to change the system radically (Geels, 2004, 2012; Geels et al., 2016; Grin et al., 2010; Kemp, 1994; Markard et al., 2012; Rotmans et al., 2001). A growing number of publications highlights the space and place of transition processes from a geographical perspective (Coenen et al., 2012; Fuenfschilling and Truffer, 2014; Hansen and Coenen, 2014).

With Germany being both an industrialized and economically strong country as well as one of the forerunners of renewable energy use, there is strong international interest in the German *Energiewende* (Nature, 2013). A large number of (inter-) national authors publish on *Energiewende*-topics from different disciplinary perspectives (e.g. Hake et al., 2015; Jacobsson and Lauber, 2012; Lauber and Mez, 2004; Nordensvärd and Urban, 2015; Schmid et al., 2016, 2013; Schneidewind and Augenstein, 2012). A number of relevant social science research institutions started programs and research alliances after the Fukushima accident in 2011 to better understand and contribute to this transformation. For example, the HelmholtzAlliance ENERGY-TRANS was founded in the year 2012 in order to complement the predominantly technological energy research with a social science perspective and integrate research on technological development, organizational structures and consumer behavior (Grunwald et al., 2016). Social-ecological research on the transformation of the energy system expands this perspective with 33 research projects that work closely together with partners from administration, politics, economy, and the public (ISOE Institut für sozial-ökologische Forschung, 2014). Research related to spatial planning highlighted the positive tensions between claims to steer the *Energiewende* centrally and the general decentral character of renewable energies (Beckmann et al., 2013; Gailing et al., 2013), which is also a topic of great political and economic interest (Agora Energiewende, 2017a).

One relevant approach to realize *Energiewende* can be transdisciplinary research (Schneidewind et al., 2011). Transdisciplinarity is a research mode which plays a crucial role in sustainability science (Jahn, 2008; Lang et al., 2012; Wiek et al., 2012a). According to some authors, transdisciplinary research can support the creation of robust solutions to real-world sustainability problems (Miller et al., 2014; Wiek et al., 2012b) by conducting integrative reflexive research. This does not only include researchers from relevant disciplinary backgrounds, but also practitioners from different societal sectors such as politics, economy, administration and civil society (see e.g. Scholz et al., 2006; Stauffacher et al., 2008). Transdisciplinary research for sustainability transformations contributes to three different kinds of knowledge: system, target and transformation knowledge (Brandt et al., 2013; Grunwald, 2007; Hirsch Hadorn et al., 2006; ProClim– Forum for Climate and Global Change, 1997). System knowledge focuses on the current state of a given system, its context and the factors that cause, determine, drive, or buffer the extent of change (Wiek et al., 2012b); target knowledge provides, among other things, guiding ideas, visions, and scenarios of a desired future state and critical levels or conditions that would need to be considered (Wiek and Iwaniec, 2014); transformation knowledge describes how to shape and implement the change process to a desired future state (Fazey et al., 2018).

The terms "transition" and "transformation" are used nearly interchangeably in the literature to generally define processes of change towards more sustainable energy systems (Child and Breyer, 2017). In this dissertation, I use the term "transformation" according to WBGU (2011) for the fundamental change of society towards sustainability, which is based on a general paradigm shift in politics, economy, and civil society and encompasses all sectors of society. Also, I use the term "transition" to refer to the radical change processes in the energy sector that result from socio-technical innovation (see e.g. Verbong and Geels, 2007).

With this dissertation, I aim to contribute both to transformation and to transition research. First, I contribute to transformation research as a new research field that strives to develop conceptual and empirical insights on the multi-causal connections between technical, social, and natural factors driving and hindering transformation processes (WBGU, 2012). Second, I contribute to the calls for more research on social aspects of energy transitions, especially from fields that are not dominant in the energy research such as public policy and geography (Sathaye et al., 2011; Sovacool, 2014a). More specifically, I respond to the need for evidence-based and context-sensitive research on the use and implementation of renewable energy in regional energy transitions.

Hence, the overall aim of this dissertation is to contribute to the understanding of transition and transformation processes by focusing on the use of regional renewable energy so as to gain a deeper understanding of contextual conditions, practical experiences, and temporal dynamics regarding the implementation and use of renewable energy in German regions (see also Figure 1.1: Overview of the dissertation):

- Contribution 1: what and where
  to provide an evidence-based, spatially distinct, and comprehensive understanding of the contextual conditions regarding the use of renewable energy in German regions
- Contribution 2: how and who
  to create evidence on practical experience from German regions and combine it with scientific knowledge on driving factors for renewable energy implementation in order to learn how the implementation process of renewable energy can be achieved successfully
- Contribution 3: when
  to develop a deeper understanding of the temporal dimension and dynamics of transformation processes in general and of processes related to renewable energy use and implementation in particular
- Contribution 4: Synthesis
  to show how these pieces of research contribute to the discourse presented above and how this contributes to a comprehensive perspective on renewable energy implementation as part of a changing energy system.

The rest of this framework paper is structured as follows. *Energiewende* is shortly discussed as the research context of this dissertation (section 2), before the literatures on sustainability transitions and transformations as well as time ecology are presented as conceptual background of this dissertation (section 3). Section 4 encompasses the cumulative research design and a short discussion of the methodology used. The articles making up this dissertation are summarized in section 5. The synthesizing discussion highlights the contributions to system and transformation knowledge (section 6.1) and thus prepare the discussion of policy implications in section 6.2, which presents generic regional energy transition strategies as potential application of this work. Then follows a discussion of the approach and possible further research (6.3) before section 7 concludes the framework paper.

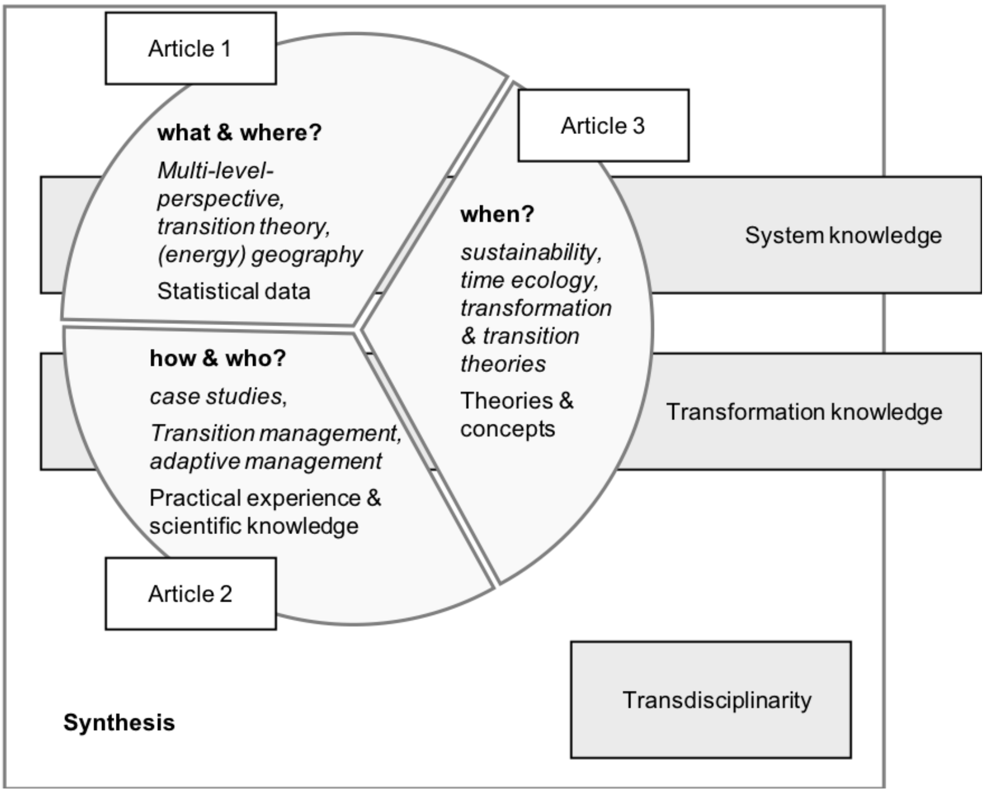
Intro

Modern renewable energies (RE) are widely acknowledged as sustainable solution for a future energy system, but more social research on local and regional solutions is necessary. With this dissertation, I focus on RE implementation and use in German regions.

Aims

Provide evidence-based and context-sensitive research on RE implementation and use in German regions
- provide evidence-based, spatially distinct understanding of contextual conditions of RE use in German regions
- learn for successful RE implementation from combining scientific and practical knowledge and experience
- understand and apply understanding of temporal dynamics of change processes of energy system

Conceptual and empirical work



Synthesis

Synthesis of results	**Implications for regional RE transition strategies**
• 9 *energy context types* of regions can operationalize the differing contextual conditions • Differences are most pronounced between rural and urban regions as well as along economic strength and energy potentials • Regions need stable political and economic boundary conditions to implement RE successfully • Design guidelines for interventions provide insights on temporal dynamics of RE implementation	• Generic, adapted strategies for each *energy context type* enable coherent regional contributions to *Energiewende* • Transdisciplinary science-practice collaborations necessary to handle the complexity of energy transition and produce system, target and transformation knowledge for national and regional levels • Regional strategies need to be tailored to specifically fit conditions and performance of each region, e.g. by a transdisciplinary steering board

Figure 1.1: Overview of the dissertation

2. Research context: *Energiewende* policies and the region's network scenario

The German *Energiewende* is motivated by the pressing need of avoiding catastrophic climate change (Bundesregierung des Deutschen Bundestags, 2010; WBGU, 2011). It targets reducing GHG emissions, increasing the use of renewable energy, reducing primary energy consumption and a complete shut-down of nuclear power plants. By now, the electricity sector has seen the strongest changes: in 2016, an installed electricity capacity of 104 GW generated about one third of Germany's electricity from RE; onshore wind and solar PV had the highest shares by far. The heating and mobility sectors change much slower, which is reflected in increasing GHG emissions for 2016 caused by industry, heating and transport (Agora Energiewende, 2017b).

The nuclear accident in Fukushima in 2011 opened a window of opportunity for the German *Energiewende* (Schmid et al., 2016). It shook the paradigm of safe and cheap nuclear energy and thus led to a change in the values related to energy supply in the German society. The existing energy system was perceived as a potential threat to society, which enabled a change in behaviors and policies. Still, the drastic change towards *Energiewende* was only possible because this policy had been prepared in content, structure and technology in the years and decades before (Reisch and Bietz, 2015). Important steps in this process were, among others, the '1000 roofs' program, the introduction of the Renewable Energy Act, and the first phasing out of nuclear energy (Deutscher Bundestag, 2010; Jacobsson and Lauber, 2012; Lauber and Mez, 2004).

Federalism strongly shapes the German political system. Regions (*Landkreise*) are one relevant level where concrete renewable energy implementation and use takes place, is planned by administrative bodies and decided upon. This is linked to the fact that grid infrastructure and energy supply services are historically grown in local and regional structures (Hall et al., 2016; Tietz, 2007). One possibility to supply Germany by 2050 with 100% renewable electricity is presented in the "region`s network scenario" (Umweltbundesamt, 2010). The document suggests a coordinated network of regions, in which each region makes extensive use of its renewable energy potentials, and feeds into the national system. According to the scenario, a secure supply with renewable electricity can be achieved with today's best technologies, given that electricity use is reduced with strict efficiency measures (Lehmann and Nowakowski, 2014). In this scenario, a region is not clearly defined and can be, for example, a metropolitan area, a rural community, or a *Landkreis*.

3. Conceptual Background

This dissertation draws on the literatures on sustainability transitions and transformations. Although this literature suggests that change processes contribute to more sustainability, one must keep in mind that innovation does not automatically contribute to social-ecological benefit, but can also lead to more damage and lock-in (Westley et al., 2011). Examples related to renewable energy are monocultures of energy crops that can have GHG emissions comparable to fossil fuels (Butterbach-Bahl et al., 2010) or the impacts that renewable energy installations can have on wildlife (Kuvlesky et al., 2007).

Acknowledging different scales is relevant for sustainability transformations (Gibson et al., 2000; Kates et al., 2001), which is also true for transitions in the energy sector. My work focuses mainly on the regional level. The local level is included in the empirical work, and the national level is regarded as the background against which regional strategies need to work, to which regional activities contribute, and which sets the general goals of the *Energiewende*. In this thesis, I develop both system knowledge on the regional use of renewable energy and transformation knowledge on the regional implementation process of renewable energy (see Figure 1.2). Although target knowledge for *Energiewende* is also necessary (see e.g. Lutz and Bergmann, 2018 in the Appendix), it is not part of this dissertation.

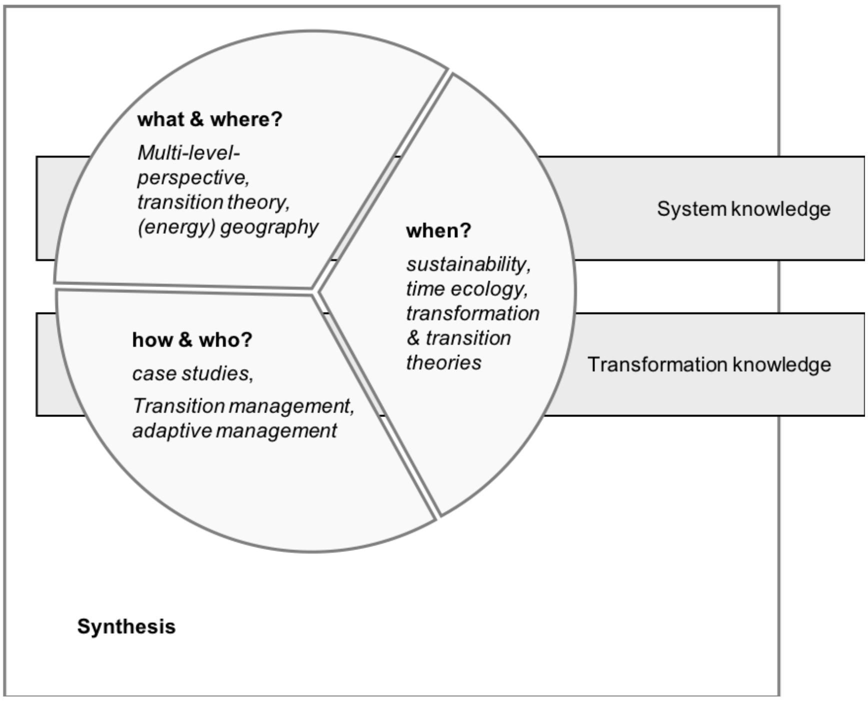


Figure 1.2: Conceptual background of the contributions

3.1 What and where

A transition of socio-technical systems is defined as a long-term (40-50 years) societal change process initiated by technological innovation which leads to a radically different new status quo (Göpel, 2016). The socio-technical transitions approach is often applied to economic or societal sectors such as energy or health. It builds on four central notions (Grin et al., 2010), of which the multilevel perspective (MLP) and the multi-phase concept are relevant for this dissertation. The MLP offers an understanding of spatial and functional interactions. It is not spatially distinct but describes three nested functional levels. These interactions and their correspondence to transition phases are presented in Figure 1.3.

In recent years, publications started to cover spatial dimensions of socio-technical transitions such as the distribution of different transition processes across space (Coenen et al., 2012; Frantzeskaki et al., 2018; Hansen and Coenen, 2014; Noseleit, 2018). Most of the publications from this sub-field cover urban and regional visions and policies. They highlight conflicts in the governance of sustainability transitions and often combine ecological goals with economic competitiveness (Hansen and Coenen, 2014). These publications mostly agree that regions need to be treated individually because they differ with regard to their socio-economic contexts and therefore in their innovative potentials. Policies should thus reflect this differing potential for transitions. Few articles on socio-technical transitions focus on the significance of local resources for renewable energy (Carvalho et al., 2012; Späth and Rohracher, 2010; Trutnevyte et al., 2012a). The geographical perspective on socio-technical transitions is neighbored by the literature on energy geography. According to Calvert (2016), this field expands along four themes, one of them geographical perspectives on socio-technical (energy) transitions. Energy is understood as (geo)political resource: decisions about which resources to prioritize and where to build new infrastructure is a process that may reproduce or overcome uneven economic development at regional scales (Pasqualetti, 2011).

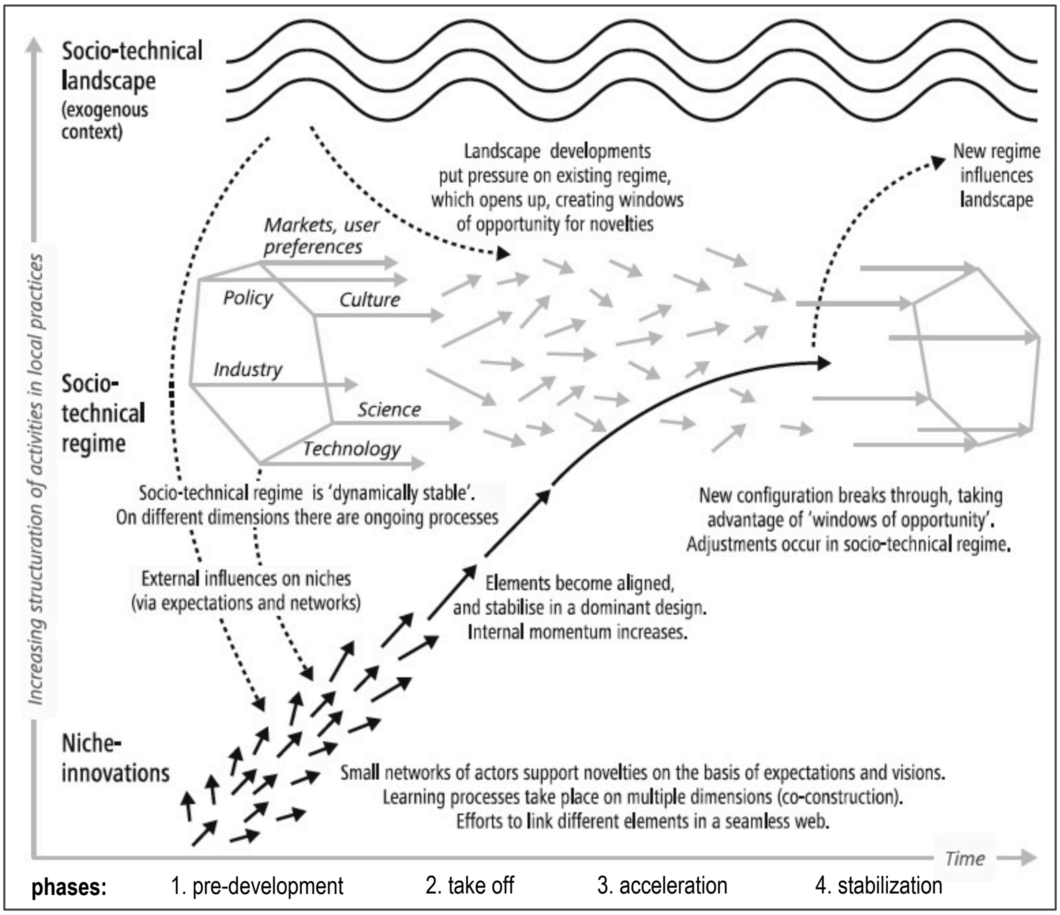


Figure 1.3: Dynamic multi-level interactions according to MLP and multi-phase concept. Niches are a sheltered environment that allow for experimentation and failure where radical innovations emerge. The regime is the incumbent system state; a tightly knotted web of technologies, policies, contracts, actors, investments, lifestyles and values that resists change. The landscape level holds deeply rooted aspects of society that cannot be changed by intentional action in the short- or medium-term such as hegemonic paradigms and values or natural developments such as climate change. According to the multi-phase concept, pre-development processes take off and accelerate before they may stabilize as the new system configuration (Rotmans 2001). The figure is taken from Geels and Schot (2010, p. 25); phase names along the time axis have been added by the author.

3.2 How and who

The implementation and use of renewable energy in regions is a complex challenge that necessitates a process of learning and exchange. In this thesis, I combine the knowledge and experience of practitioners in the field of renewable energy use with a scientific approach. The concepts transition management (Loorbach, 2007) and adaptive co-management (Holling, 1978) served as orientation. Both concepts have similar theoretical roots, but differ in their fields of application: while transition management is one strand of socio-technical systems research, adaptive (co)management is applied in social-ecological systems (van der Brugge and van Raak, 2007). Both approaches agree that societal change and the adjusting systems are too complex for straightforward management, but need a step-by step process of anticipating and adapting to the changing system structures (Folke et al., 2005; Lee, 1999; Rotmans and Loorbach, 2010).

Transition management can be described as long-term planning which is based on learning and experimenting and thus makes sure that the anticipated change proceeds in small steps (Kemp et al., 2007). It distinguishes between the strategic, the tactical, and the operational level which differ in their scopes and functions of governance (Loorbach, 2007). Adaptive co-management is a place-based and problem-specific type of adaptive management that builds on the participation of local resource managers and users as well as the community, but that also includes various organizations and networks at higher levels (Hasselman, 2016). It emphasizes the roles of social capital and focuses on leadership, networking, and trust. In an adaptive co-management process, institutional arrangements and ecological knowledge are tested and revised in dynamic learning-by-doing (Folke et al., 2005).

3.3 When

Time is an inherent dimension of sustainability. Sustainability builds, among other things, on the notion of intergenerational justice (Gibson, 2006; WCED, 1987), which can be described as the need to act in such a way that it does not compromise the quality of life of coming generations. Sustainability challenges per se necessitate a long-term perspective in domestic and international politics (Giddens, 2011). This long-term perspective goes along with a strong sense of urgency. Experts agree that the global community needs to start intense climate change mitigation activities now, so that the effects of climate change stay within dimensions which global society can cope with (Stern, 2006; UNFCCC, 2015). The need to act swiftly may be difficult to convey to decision-makers and the public as long as climate change is not tangible in people's everyday lives (Giddens, 2011). Immediate and concrete action is especially important in the energy sector. Because energy infrastructure needs high investments and has long life spans, today's decisions create path dependencies for many decades (Sovacool, 2016). Most historical energy transition processes from traditional renewable energy to coal and from coal to oil/gas/electricity took several decades. Sovacool (2016) argues that the current transition might happen speedier than the former two because the current energy transition is fueled by new and significant drivers – scarcity of fossil fuels, climate change-related social and political costs, and the knowledge and innovation potential that earlier generations did not have.

The temporal dimension of socio-technical transitions is conceptualized in the multi-phase concept. According to this conceptualization, transitions undergo four phases, which are related to developments on all three levels of the system (see again Figure 1.3). One specific temporal element is the 'window of opportunity': The take-off phase is often linked to specific moments in time, when contextual conditions pressure the incumbent system and thus open a window of opportunity that facilitates change (Geels, 2005). Windows of opportunity may be motivated by very different developments or events on the landscape or regime level (Geels and Schot, 2010, p. 26). The multi-phase concept allows to understand the temporal dimensions of the whole transition process in "coarse resolution". A finer grained understanding of the temporal dynamics of change processes is presented in time ecology.

Time ecology allows to understand and describe temporal dynamics of human-nature systems, especially the impacts social life has on ecosystems. One basic assumption of time ecology is that an explicit and integrative temporal perspective is necessary to understand how ecology, economy and society interlink. Time ecology does not (yet) explicitly link to the sustainability transformations literature, but argues that a deeper and more nuanced understanding of temporal dynamics allows to contribute to the understanding of the concept "sustainable development" (Held, 2001). Opposed to the conventional understanding of time as linear and homogenous clock-time, time ecology conceptualizes time as a dynamic system entity that can have many different characteristics (Held and Geißler, 1995; Kümmerer et al., 2010). One significant temporal feature of each system is its inherent time, which relates to the time span of a system's reproduction. Inherent times show a system specific degree of variability. This is especially relevant because human systems accelerate, but the temporal elasticity of natural systems is limited and when overstretched, a system cannot regenerate fully (Kümmerer and Held, 1997). Other time-related approaches do not have this conceptual richness. In the social sciences, most time-related research goes back to Hägerstrand's time geography (Crang, 2012; Shaw, 2012; Sui, 2012). Its starting point is the life time of individuals, and how this can be conceptualized in regards to space in a socio-economic model (Hägerstrand, 1970).

4. Research design and methodology

This dissertation is compiled in a cumulative way and consists of the following peer-reviewed articles:

1. Lutz, L.M., Lang, D.J., von Wehrden, H., 2017: Facilitating regional energy transition strategies: Toward a typology of regions. Sustainability 9, 1560.
2. Lutz, L.M., Fischer, L.-B., Newig, J., Lang, D.J., 2017. Driving factors for the regional implementation of renewable energy - a multiple case study on the German energy transition. Energy Policy 105, 136–147.
3. Weiser, A., Lutz, L.M., Lang, D.J., Kümmerer, K., 2017: Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems. Journal of Cleaner Production 162, 273-285.

One additional publication in the appendix to this thesis provides a supplementary perspective on *Energiewende*:

> Lutz, L. M. & Bergmann, M. 2018: Transdisziplinarität: Forschungsansatz für die Energiewende. In: Holstenkamp, L. & Radtke, J. (Eds.), *Handbuch Energiewende & Partizipation*. Springer VS, Wiesbaden.

For articles 1 and 2 of the thesis, I conducted empirical research. Article 1 applied multi-variate statistical analysis over all 412 German regions (in R 64 2.15.1 GUI 1.52). For this, satellite data and statistical data from official sources, mostly open source, were used. Article 2 applied Rough Set Analysis on data derived from a survey over 18 regions. In order to learn from practice, this was done with case experts from administration who have been in charge of or were strongly involved in the implementation process of RE. This empirical work is complemented by article 3 which elaborates on the temporal dynamics of transformation processes. It builds on the literatures on time ecology, transformation processes, and sustainable energy and resource futures.

The empirical methods complement each other in several ways. Both multivariate statistics and RSA were used to find patterns: with the former, I identified types of regions on the spatial scale of Germany; with the latter, I identified shared patterns of activities and practices of a specific group of regions. The approaches are designed to work with different data sets. While multivariate statistics need a large number of cases in relation to a small number of variables, RSA allows to analyze data sets that are characterized by a small number of cases and a large number of variables. This then leads to the difference that the former is able to identify causalities, while RSA can only identify co-occurrences in the data set. The results of the multivariate statistics of article 1 fed into the sampling of regions for article 2 and thus enabled to analyze a sample of regions with comparable contextual conditions regarding the use of RE.

In the course of this dissertation, I addressed several methodological challenges. Regional energy transitions are complex, offer many interesting scientific questions and challenges, and research may make the difference for the developments in German regions. Realizing that the whole picture would be much too big, my aim was to still keep a broad picture in mind to do justice to the many interconnected factors that influence regional energy transitions. Therefore, I decided for a broad approach hoping that my results and conclusions may work beyond one specific factor (Sovacool, 2014b). This decision meant that I needed to identify and operationalize the core characteristics of many aspects of regional renewable energy strategies that are usually studied in much greater detail. One example for this is the energy potential from different sources of waste biomass that needed to be operationalized in a feasible and at the same time meaningful way, so that the approach allowed to assess the biomass potential for each of the 412 regions (article 1). For my dissertation as a whole it meant that I studied and combined thoughts from different disciplines and fields and now offer empirical findings as well as conceptual insights.

5. Summary of articles

The following section outline briefly the main contributions of each article to the overall aims of the research.

5.1 Article 1: Contexts of renewable energy use in German regions

The article *Facilitating regional energy transition strategies: toward a typology of regions* feeds into contribution 1 and provides an evidence-based, spatially distinct understanding of contextual conditions regarding the use of renewable energy in all German regions. The empirical work mainly builds on public statistical data which is analyzed via multivariate statistics (see section 4).

In general, all considered energy sources wind, solar energy, and biomass can be used in most regions. Still, for greater efficiency of material and financial resource investments, it seems wise to prioritize which energy potentials to use where and to what extent. The analysis identified 3 spatial patterns that show differing contextual conditions for the use of renewable energy in regions: (i) rural and urban regions differ strongly in terms of socioeconomic and natural contextual conditions; (ii) a gradient from East to West mirrors the differences of economic strength (unemployment and tax income); (iii) a gradient from North to South traces the patterns of wind and radiation intensities. The cluster analysis allowed to identify nine types of regions, which I call *energy context types*. They separate sharply along the variable settlement density and also mirror the East-West and North-South oriented gradients.

This structured picture of regional socio-economic and natural conditions for the use of renewable energy may allow to allocate shares of national renewable energy goals to energy context types. A generic regional energy transition strategy for each of the nine energy context types seems to be an efficient tool to target *Energiewende* policies and activities. Possible strategy elements would need to relate to the differences and include technological and organizational options that fit to the respective socio-economic strengths and weaknesses as well as the energy potentials. For example, shared renewable energy facilities can supply several homes with electricity and heat. In regions where most people live on rent, ownership and management of these may be concentrated with housing companies or the community, while cooperatives or neighborhood institutions can fulfil this role in a region with high property rates. These shared facilities can consist of different technological options such as a district heating system based on combined heat and power plants, or micro wind power on rooftops.

5.2 Article 2: Driving factors of regional renewable energy use

The article *Driving factors for the regional implementation of renewable energy – A multiple case study on the German energy transition* feeds into contribution 2. In order to learn how the implementation process of renewable energy can be achieved successfully it combines scientific knowledge and experience with practical knowledge and experience from 18 German regions that strive for 100 % supply with regional renewable energy. The results represent the perspective from actors in administration, for example regional and local climate managers or energy managers. The empirical data was collected in a survey and analyzed via Rough Set Analysis (see section 4).

According to the analysis, a successful renewable energy implementation is often based on combinations from several fields of activities: planning, exchange and participation, actors and networks, and funding. Regions differ in their motivations and their approaches towards the implementations of RE. Some regions strive at a more holistic approach and see the use of renewable energy as one part of comprehensive climate protection measures. The renewable energy implementation process in these regions usually needs more time, but the regional process is more relevant in the light of supra-regional climate mitigation. Other regions are more focused on renewable energy use, which leads to a faster and less complex implementation process. In these regions, there is less awareness for or less contribution to supra-regional climate change mitigation. Interestingly, nearly all case study regions experienced the use of renewable energy to positively impact the regional economy.

The analysis led to four concrete key findings. First, process management and especially the use of specific goals and milestones seem to be helpful to monitor and assess the complex process of renewable energy implementation. Second, exchange and learning seem to influence the process, which is a new and complex challenge, positively. An intense cooperation in and with formal networks and experts, and a knowledge exchange with practitioners from other regions both seem to push the renewable energy implementation process. Third, diverse funding structures including public sources such as the LEADER EU-program, regional businesses, and private households appear to be helpful. Fourth, the case experts named the following skills of their key actors as helpful and inspiring: expert knowledge, environmental consciousness, and networking skills.

5.3 Article 3: Time in transformation processes

The article *Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems* feeds into contribution 3 and provides a first basis for a deeper understanding of the temporal dimensions of transformation processes in general and of the energy system in particular. Because sustainability challenges are usually not restricted to one specific field or sector of society, the article puts a focus on interconnected systems and uses the example of specific metals (mineral sector) that are necessary in renewable energy technologies (energy sector).

Combining the literatures on time ecology and transformation processes allowed to identify three requirements, from which we developed a three-step approach to include temporal dynamics into sustainability transformations "management" – the *time-in-transformations-approach*. Step 1 identifies relevant temporal features of the analyzed systems and relates them to each other. Step 2 differentiates four types of change patterns based on the temporal extent and the irregularity of a change process. Step 3 presents three guidelines for designing interventions into interconnected systems, which operationalize the findings on temporal dynamics.

The transformation of the energy system is complex and intertwined with other systems as, for example, mineral resources. In comparison to metals, processes related to the use of renewable energy have relatively short inherent times, so-called *Eigenzeiten*. For example, wind turbines work for 20-25 years before they are repowered. After this relatively short period, the metallic parts of the wind turbines can usually work longer; repowering usually takes place because the investments have paid off and more efficient technologies are available in the meantime. Considering time helps to align these different systems into one picture and to operationalize interventions. Thus, coherent strategies across levels and temporal scales, but also across the natural, socio-technical and regulatory spheres become possible. The *time-in-transformations-approach* considers the transformability and adaptability of a system and thus offers one option to design interventions according to the desired effect: stabilize or overcome a system state.

6. SYNTHESIS

Having addressed the key contributions of each article individually, this chapter synthesizes the insights and sets these into the research context on energy transitions. It then presents implications for developing regional energy transition strategies and discusses the potential to apply the presented approach to other countries or other research fields.

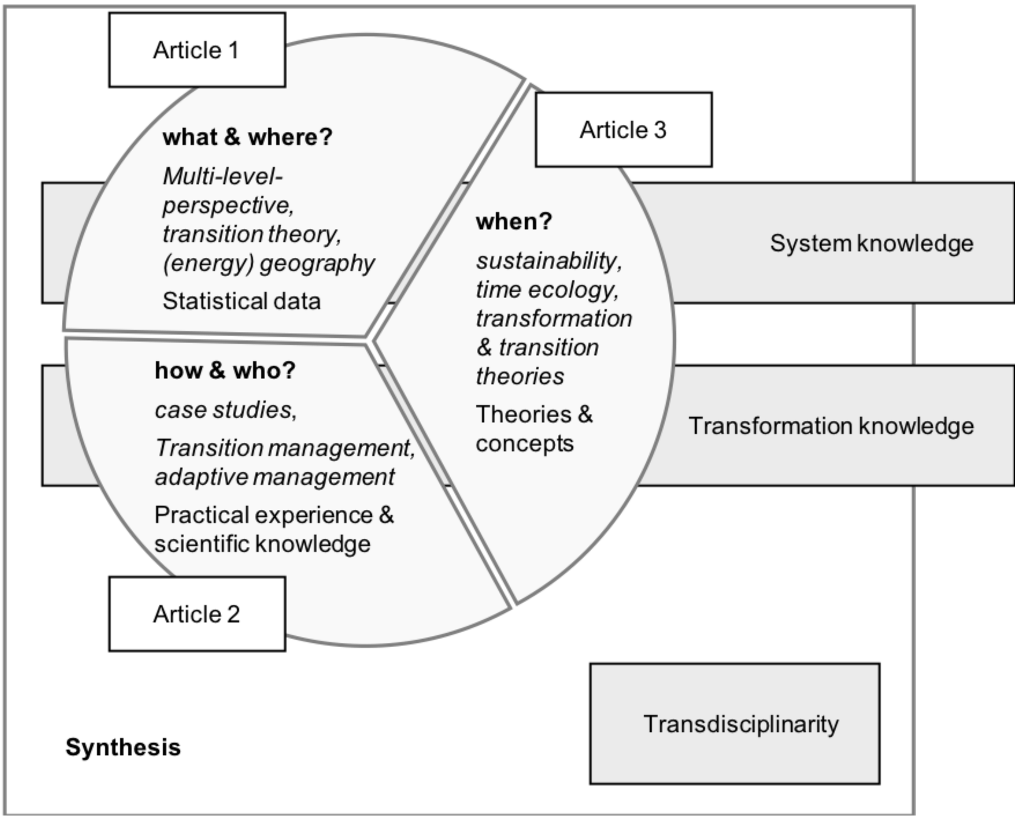


Figure 1.4: Schematic overview on the synthesis.
In addition to system and transformation knowledge generated in this work, transdisciplinarity is discussed to explore the potential policy implications of the dissertation.

6.1 Synthesis of results

Here, I discuss how the findings of the three articles can inform the use and implementation of renewable energy in German regions. The first section is on system knowledge on the use of renewable energies, specifically on contextual conditions for the use of renewable energy and their spatial patterns (Article 1, Lutz et al., 2017b), and the temporal characteristics of the energy system (Article 3, Weiser et al., 2017) (see also fig. 1.4). The second section discusses the contributions to transformation knowledge, especially building on insights concerning the temporal dynamics of change processes (Article 3, Weiser et al., 2017) and on insights based on practitioners' experience on successful local and regional renewable energy implementation processes (Article 2, Lutz et al., 2017a) (see also fig. 1.4).

The literature on sustainability transitions does not yet engage extensively with the spatial perspective. Therefore, for instance, Coenen et al. (2012) request that research elaborates on the spatial contexts of socio-technical transition processes. I address this request with a spatially explicit analysis of the socio-technical and natural contextual conditions of the renewable energy sources biomass, wind and solar radiation for all German regions. The literature on regional innovation systems (see e.g. Mattes et al., 2015; Tödtling and Trippl, 2005) and findings from several empirical case studies (see e.g. Trutnevyte et al., 2012a) agree that regions need to be treated individually because they differ with regard to their socio-technical contexts. Also the IPCC agrees that sustainable renewable energy solutions depend on the context (Sathaye et al., 2011). Developing an energy transition strategy for each region individually would be extremely resource intensive with regard to time, expertise, and money. My work outlines a compromise for a more efficient approach towards regional energy transition strategies which still considers the individuality of regions. I suggest to develop generic regional energy transition strategies that are adapted to each of the 9 energy context types of German regions (Lutz et al., 2017b). These would not only consider the socio-economic context, but also the resource availability in each region. According to Hansen and Coenen (2014), only few studies in the transition literature so far consider the local resource availability in the commune or region for local use (see also Lutz et al., 2017b).

The use of renewable energy both in Germany and globally is sustainable for many reasons, if compared to nuclear and fossil fuels. One reason for this is that *Eigenzeiten* of renewable energy technologies are relatively short (Weiser et al., 2017). This makes renewable energy use less path dependent in comparison to fossil and nuclear power plants and keeps the system more flexible for social and technological innovations that can be expected in the coming years and decades (Sovacool, 2016). The relatively short *Eigenzeiten* may also be helpful for sustainable adaptable strategy-making because they fit to the human abilities to perceive change and plan for the future (Pahl et al., 2014).

One major challenge related to the use of renewable energies is that the fluctuating energy provision does not fit the temporal and spatial patterns of energy demand. Many current attempts of technological solutions basically aim to move these patterns to a better temporal overlap: storage solutions (e.g. power to gas to power, pumped-storage hydroelectricity, batteries…) aim to shift the provision of electricity to those times when it is needed; changing user practices aims to shift demand to those times when electricity supply is high. In addition to these approaches on the temporal scale, the spatial scale can be relevant when we think of Germany as a tightly connected mosaic of regions with different potentials and patterns of demand and supply. Rural regions generally have a potential to supply cities with energy

(Umweltbundesamt, 2010). My analysis showed that this is especially pronounced in north-east Germany, a sparsely populated area with weak economy that is rich in renewable energy sources (Lutz et al., 2017b). If political actors are able to use this energy abundance as political resource (Pasqualetti, 2011), the generic regional energy transition strategies as concept of collaboration between (predominantly) producers and (predominantly) users of energy may also contribute to a positive development in such areas.

Transformation knowledge on the regional implementation of renewable energy

In the following, I apply the guidelines for designing interventions from Article 3, *Time in Transformation processes* (Weiser et al., 2017), on the regional implementation of renewable energy. For this, I combine it with empirical insights from Lutz et al. (2017a) and elaborate on these findings giving concrete examples for the regional use and implementation of renewable energy. The *time-in-transformation-approach* may help in the understanding of when to intervene in a given system in a way that it leads to the desired change and thus contribute to transition and transformation literature.

1. Avoid temporal (and other) misfits:

Misfits of temporal or other nature can strongly hinder transformation processes (Weiser et al., 2017). Factors such as skilled key actors (individuals and institutions), availability of money, and a reliable political context seem to be helpful for a successful implementation of renewable energy (Lutz et al., 2017a). In order to avoid misfits in this situation, ideally all of these factors are satisfied in time when necessary, on all relevant political levels (commune, region, federal state and nation state) and for all of the identified relevant fields of activities (e.g. energy, building & infrastructure, societal development).

Regional use of renewable energy is highly complex and many different processes are related. In the bigger picture of climate change mitigation, comprehensive planning for renewable energy use should also include measures to reduce energy consumption and consider the fields electricity, heating/cooling and mobility in order to avoid serious misfits. Comprehensive concepts do of course need more time to be developed, but regional actors who see renewable energy as one component of comprehensive climate protection seem to be better prepared to deal with national and international policies and developments (Lutz et al., 2017a).

Structured planning processes, including specifically formulated goals and milestones, can help to oversee complex processes and thus contribute to a successful realization of the intended process (Lutz et al., 2017a). Avoiding misfits can in this case mean that important formal networks such as LEADER support regional processes not only with funding but also with expertise. For example, a network can offer trainings for regional actors to help them gain necessary project management skills in the beginning of the implementation process.

2. Minimize (negative) impacts / timing influences impacts:

Windows of opportunity open up in every process and can be anticipated from the temporal system dynamics. They often appear when system entities come to an end, for example when technical utilities reach the end of their life span or a contract has a specific end. Regional actors can make use of these opportunities. For example, nuclear power plants will need to be deconstructed in the coming years. This may open up discussions on the future of the German energy system and the advantages and disadvantages of renewable energy more intensely again. Many regulations, funding programs, and policies related to the energy system have specific durations, the same is true for contracts with energy suppliers or grid companies. Several German cities and rural regions were prepared when such a contract ended, bought back their distribution networks and manage it now again themselves (see e.g. Energienetz Hamburg, 2018; EWS Schönau, 2018).

3. Acknowledge or reduce delays

The energy transition is a long-scale process (Göpel, 2016; Schmid et al., 2013). Because temporal and spatial scales are related (Gibson et al., 2000), one can deduce that the energy transition in a smaller space may happen quicker. Also, perception and reaction may be slower in larger systems (Pahl et al., 2014). This suggests that regional energy transitions may be easier to realize and oversee than energy transition dynamics on the level of the nation state.

The perception and understanding of the present situation in relation to developments in the past and future might be influenced by the position, power, and experience of a decision-maker (Pahl et al., 2014; Weiser et al., 2017). A group of people with varied experience and expertise is therefore able to perceive a wider range of risks and potentials. This thought agrees with the experience of the practitioners in the study regions, who stated that an intensive exchange of expertise in with actors from higher administrative and political levels, science and economy can be very beneficial, especially to deal with complexities (Lutz et al., 2017a).

6.2 Implications for regional energy transition strategy design

In order to realize the idea of the region's network scenario, the regional use of renewable energy would ideally complement each other and transition strategies would be coherent with national *Energiewende* policies and politics (Umweltbundesamt, 2010). In the following, I discuss how the set of findings and thoughts developed in this dissertation can possibly contribute to designing generic regional energy transition strategies for an efficient and concerted approach toward *Energiewende*.

Strategic decisions related to, for example, climate mitigation policies, resource availabilities, or implications for land use and spatial planning are taken on the national level by experts and politicians. They have the responsibility to guide the energy transition and give clear goals and orientation for the realization of policies on the lower levels (Morgan, 2004). These decisions could find expression in the nine generic regional energy transition strategies suggested above, for example in the form of concrete aims of renewable energy supply and a portfolio of approaches regarding the implementation process. This would allow to steer regional energy transition processes in such a way that regional activities complement each other in their contributions to realize *Energiewende* policies and in that national goals on renewable energy use are distributed between the energy context types according to the types' socio-economic and natural potentials and constraints. The nine generic regional strategies could provide clear political orientation each region, which is crucial for activities related to Energiewende (ISOE Institut für sozial-ökologische Forschung, 2016). Given that these strategies would include transparent goals and milestones and are embedded in reliable political and economic conditions, they could be a tool to meet the main challenges of local and regional renewable energy implementation (Lutz et al., 2017a). On the regional level, the generic strategies would need to be deepened and tailored to fit to each region individually (Lutz et al., 2017b). Regional and local actors therefore ideally have the responsibility for and experience with the concrete implementation and use of renewable energy in the context of 'their' region and could thus consider past and present experience and performance. Moreover, regions can exchange on challenges and successful practices concerning the use and implementation of renewable energy with other regions of the same energy context type, or with one that works under different contextual conditions (Lutz et al., 2017a).

A transdisciplinarity approach towards generic strategies

As discussed in Lutz and Bergmann (2018), transdisciplinary research is a promising approach to meet many of the challenges of realizing *Energiewende* (see Appendix of this dissertation). It allows to include practitioners in the research process which is important for substantive, normative and instrumental reasons (Fiorino, 1990), in order to create socially robust knowledge (Nowotny, 1999), societal relevance and acceptance (Thorburn et al., 2011) and finally the actual application of the strategies. For the purposes of this article, I use the definition of Lang et al. (2012) below, because it underlines that transdisciplinary research focuses on societally relevant problems, enables mutual learning of researchers from different disciplines and people outside of academia, and aims at creating knowledge that is solution-oriented, socially robust, and workable both in science and practice:

> "Transdisciplinarity is a reflexive, integrative, method- driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge." (Lang et al., 2012, p. 26 f)

Developing generic regional energy transition strategies necessitates to find innovative solutions. From its design and thinking, transdisciplinary research offers a robust solution-orientation which goes beyond the analysis of the problem and works on practical solutions that can be applied in the real-world context (Clark and Dickson, 2003; Lang et al., 2012; Wiek et al., 2012b; Wiek and Lang, 2016). Moreover, transdisciplinary research generates knowledge within and for a specific context and thus allows us to understand change processes in relation to their temporal and spatial contexts (Bergmann et al., 2010; Funtowicz and Ravetz, 1993; Gibbons et al., 1994), which is relevant for the development of contextualized strategies.

Sovacool (2014a) found that decisionmakers of energy companies ignored energy research, they did not seem to think that it is worth considering. This can have many reasons, but it shows the necessity to find a common language and work mutually on challenges. In a transdisciplinary research process, both scientific and practical knowledge and experience are valued in order to find innovative solutions. It enables mutual learning of people with differing perspectives, knowledge types and thinking styles (Lang et al., 2012; Lutz and Bergmann, 2018; Pohl and Hirsch Hadorn, 2008; Scholz et al., 2006) and offers many methods for knowledge integration (Bergmann et al., 2010; Jahn, 2008) that allow for the development of socially robust knowledge. Socially robust knowledge (Nowotny, 1999) can help create acceptance for the necessary changes. Transdisciplinary processes also offer transparent communication and decision making (Gralla et al., 2015) which may help create acceptance by actors from the energy system, the political-administrative system, and the public.

In the light of the above, I suggest an interconnected transdisciplinary process on the national and regional levels to develop generic regional energy transition strategies. Considering the complexity of the task, a step-wise approach seems to be necessary. In a first step, detailed system knowledge on contextualized use of renewable energy could be developed on the national level. This corresponds to the right side of the ISOE-model for transdisciplinary processes (see fig. 3.3 in Lutz and Bergmann, 2018 in Appendix). Following processes on the national level might then include practitioners and work on system and transformation knowledge, which corresponds to both sides of the model (see fig. 3.1 in Lutz and Bergmann, 2018 in Appendix). The regional processes might in the following concentrate on the application of existing system knowledge and work predominantly on transformation knowledge. This would then mean that the processes predominantly follow the left side of the

ISOE model (see fig. 3.2 in Lutz and Bergmann, 2018 in Appendix). Ideally, the expertise and activities on all levels feed into each other so that knowledge and experience travel both from the national to regional levels and from regional to the national level.

Examples for participatory and transdisciplinary approaches in the energy system

There has not yet been a transdisciplinary research process to develop energy transition strategies in an interconnected process on the regional and national levels in Europe. Nonetheless, there is a number of examples that may inspire the process suggested above, and that can serve as a resource for inspiration.

The "Trialog Energiewende" of Humboldt-Viadrina Governance Platform is a series of discussions between stakeholders from politics and administration, companies, civil society and academia (Leopoldina Nationale Akademie der Wissenschaften et al., 2018). It aims to bring together a wide variety of controversial positions and offers a platform for respectful, open-minded discussion (Vollmer, 2015). The discussion series may offer experiences on how to deal with the broad spectrum of topics related to *Energiewende* and of stakeholder positions.

One example for an interconnected decision processes on the regional and national levels is the site selection process for nuclear waste disposal in Switzerland and Germany. In Germany, the *Standortauswahlgesetz* suggests to work with a national committee and regional conferences on those regions that have been identified as possible locations. This suggestion is inspired by the Swiss process, which has a comparable structure (Drögemüller and Kuppler, 2017). Here, the national committee consists of experts from energy companies, politics and academia. One of its tasks it to identify possible locations , where local stakeholders from civil society can join the decision making process in a dynamic approach (Krütli et al., 2010). The swiss example may offer experiences considering the intensity and dynamic of involvement of the public and of other groups, which should be structured along the phases of the process (see also Stauffacher et al., 2008).

6.3 Discussion of methods and potential for further research

The empirical parts of this dissertation relate to a specific context, which means that the results cannot be generalized easily. Nonetheless, the same methodological approach might be applied rather easily in other countries with strong administrative and technological infrastructures. For example, the statistical analysis of all German regions was mostly based on open-source data and used only open-source software. Still, political-administrative cultures vary between countries and the approach should always focus on the level on which energy policies are implemented. The regional approach to energy transition of this work fits to countries with federal structures such as Germany, although this might not be the crucial governance level elsewhere (Hall et al., 2016). If energy policies are implemented on the municipal level, challenges might arise related to the sheer number of units of analysis. If it is a higher level, intra-unit differences might be rather high, so that the results would have to be tested against that. This approach would not be appropriate in countries or areas with less developed electricity grids. If electricity grids do not supply all villages or households, renewable energy use mainly offers the opportunity of grid-independent, localized energy supply, comparable with the possibilities and impact of mobile phones instead of land-line based telecommunication (Sathaye et al., 2011).

The conceptual work on time in transformations has not been country-specific, but spanned scales and governance levels from global systems to specific sites. The time-in-transformations-approach is designed to gain and operationalize an understanding on temporal dynamics of systems and has no conceptual limitation to a specific system. Although it was developed at the mineral-energy-nexus, it should be applicable to any system or field, independent whether this would include a single sector or two sectors that overlap and cross-influence each other, such as food and energy, or minerals and information technology.

Finally, besides the empirical and conceptual research discussed below, I discuss the idea of generic regional energy transition strategies as an effective approach towards realizing a concerted use of renewable energy sources as contribution to *Energiewende*. This can be understood as one approach to optimize the current situation and provide clear orientation for regional activities. The more I read and work, the more questions came up. These can be summarized as such: If the idea of generic regional energy transition strategies was to be followed, more research would be necessary (i.) that brings together more of the existing knowledge and findings on regional and local renewable energy use and transition dynamics, (ii.) that focuses on how we can make use of temporal dynamics in societal transformation processes, and (iii.) that allows to test the idea of generic regional energy transition strategies and how these can contribute concretely to realizing *Energiewende*.

7. Conclusions

The implementation and use of renewable energies as part of *Energiewende* is a challenging endeavor that aims to bring about societal change. However, the German climate change mitigation goals (*Klimaziele*) for 2020 will most probably not be met and political effort needs to be strengthened again (Graichen et al., 2017). This delay creates important concerns. More than a decade ago, the Stern review argued for strong and early climate mitigation because their results will outweigh the costs of the measures taken (Stern, 2006). A new analysis on the economic impacts of climate change underlines the importance to keep global warming below

1.5°C (Burke et al., 2018). One measure to mitigate global warming is the use of renewable energy. In Germany, the regional level is important for the concrete implementation of renewable energy. So far, however, regional energy transition strategies are not designed for the concerted and dedicated effort that would be necessary to realize *Energiewende*.

With this dissertation I present empirical and conceptual contributions that can feed into a pragmatic, efficient approach towards regional energy transition strategies which would still allow for considering the strong differences between German regions: generic regional energy transition strategies. The approach is based on a spatially explicit analysis of the natural and socio-economic contextual conditions for the use of renewable energy across all German regions, which resulted in nine energy context types (Lutz et al., 2017b). The development of one generic energy transition strategy for each of the nine types is a compromise between a one-fits-all approach and the resource-intensive development of individual strategies. It aims to provide clear orientation and the necessary stable political and economic framework conditions for a successful implementation and use of renewable energies as part of *Energiewende* (see e.g. ISOE Institut für sozial-ökologische Forschung, 2016; Lutz et al., 2017a).

My work adds its findings to research on energy transitions and transformation dynamics. The spatially explicit analysis of German regions adds to research on energy geography (see e.g. Calvert, 2016; Pasqualetti, 2011), the discourse on space and place in socio-technical transitions (see e.g. Becker et al., 2016; Bridge et al., 2013; Wang et al., 2016), and research on the context of renewable energy use (see e.g. Asheim and Coenen, 2006; Trutnevyte et al., 2012a). Findings on the implementation of renewable energy in regional and local settings adds to the understanding generated in other case- based research such as the analyses on energy regions (see e.g. Binder et al., 2016; Hecher et al., 2016; Karpenstein-Machan and Schmuck, 2007; Späth and Rohracher, 2010) or community energy (see e.g. Klein and Coffey, 2016; Walker et al., 2010; Walker and Devine-Wright, 2008). The *time-in-transformations-approach* presented in chapter 4, which is to be understood as a first step to operationalize a temporal understanding for transformation processes, can add to the understanding of time in research fields dealing with time as system entity and those dealing with system change. Examples for the former are time ecology (see e.g. Adam et al., 1997) or time geography (see e.g. Massey, 1999; Shaw, 2012). The latter is the field of socio-technical systems and sustainability transformations (see e.g. Abson et al., 2016; Brandt et al., 2013; Fazey et al., 2018; Göpel, 2016; Schneidewind and Augenstein, 2012).

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Chapter 2

Facilitating Regional Energy Transition Strategies: Toward a Typology of Regions

Lotte M. Lutz, Daniel J. Lang and Henrik von Wehrden

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Abstract:

The regional level is essential for the use of renewable energies since on this level national political goals are harmonized with implementation activities. Hence, regional strategies can, we argue, be useful. Yet, these strategies must be tailored to meet a variety of contextual conditions. Within this study, we identified natural and socio-economic conditions that need to be considered when developing regional strategies for Energiewende. Focusing on these conditions, we conducted a multivariate statistical analysis of all 412 German districts (Landkreise). We identified nine energy context types characterized by different renewable energy potentials and socio-economic conditions. We propose to develop one generic regional energy transition strategy for each of the energy context types. These can serve as a governance tool that operationalizes and allocates national Energiewende goals according to regional contextual conditions. Moreover, the energy context types may support regional decision makers by allowing them to prioritize steps in the transition process, to establish networks with, and to learn from, similar regions.

1. Introduction

The growing use of renewable energy (RE) is an innovative practice that arose from the need to radically change the energy system in order to minimize GHG emissions. It aims to meet the social need to supply society with energy in a sustainable way, now and for the future [1–4]. In Germany, the incumbent energy companies have generally reacted to the trend rather late [5]. Instead, the growing use of RE has often been facilitated and diffused by organizations whose main purpose is social, not profit-oriented: governance bodies, social movements, community energy initiatives etc. [5–7]. Regions are one relevant level for RE implementation and use in Germany, as the political system is strongly based on federalism. Historically, the energy system developed in decentralized nodes and is still often structured locally and regionally [8,9].

The implementation of RE in regional or local settings has been examined in empirical studies, especially case studies, and in more theoretical papers focusing on energy or sustainability transitions. A survey of the empirical literature indicates that there is considerable heterogeneity concerning the contextual conditions for using RE. For example, a comparative analysis of all municipalities of one Swiss canton (state) showed that there is no single ideal energy strategy for municipalities, but, due to the different conditions in each of the municipalities, a broad range of possible options needs to be considered [10]. The authors concluded that these differences need to be considered when developing energy strategies. It is safe to assume that this is also true not only at the municipal, but also at the regional level: regional innovation studies also argue to consider contextual differences in innovation policies [11]. The significance of context for the use of RE is also emphasized in a spatially explicit analysis of conflicts between traditional landscape services and the use of the energy resources wind, photovoltaics (PV), and forest biomass for Switzerland [12]. This insight has important implications for those tasked with developing strategies for implementing RE at the regional level, as these strategies will have to integrate context-specific conditions into a broader framework. This is a very complex and challenging task, and the literature has so far only focused on some of the conditions that would need to be considered.

Several case studies on single regions in different European countries such as Austria [13–16], Switzerland [17,18], Germany [19], and Slovenia [20] mainly focused on rural municipalities or regions that largely rely on bioenergy. This emphasis on the distinct conditions for implementing bioenergy can also be observed in the literature on bioenergy villages in Germany. An interdisciplinary study on, for example, the village Juehnde integrated the perspectives of agriculture, soil science, economics, sociology, and psychology [21]. Other studies have considered socio-economic conditions for implementing RE. These are, for example, community-ownership of renewable energy utilities (e.g. [22,23]) or citizen cooperatives financing RE (e.g. [24,25]). The acceptance of wind power installations and the NIMBY-effect (not in my backyard) have also been studied (e.g. [26,27]).

The empirical literature on implementation of RE in regional or local settings is complemented by research that opens up a boundary between sustainability transitions and geography, the geography of sustainability transitions [28] and energy geography [29]. In geography, regions are discussed as key drivers for innovations [30,31]. The space and place of transitions in general and energy transitions in particular has received considerable attention [32–34]. Most publications in this emerging field exist on urban and regional visions and policies, while only few articles deal with the significance of local resources for the use of RE [28]. Späth and

Rohracher argue that regions provide social contexts and apply socio-technical innovations that differ from the dominant regime. They thereby test and demonstrate whether and how technical alternatives are feasible [35]. Transitions research stresses that conditions underlying larger dynamics determine the outcome of transition processes. In the literature, these conditions are also often referred to as contextual, landscape, or environmental conditions (Berkhout et al., 2004; Geels and Schot, 2007; Jacobsson and Lauber, 2006; Smith et al., 2005). The analysis of landscape service conflicts named above is not framed within this research field, nonetheless, it can offer fruitful inspiration for spatially explicit empirical energy transition research. For example, it combines different energy potentials with a set of social and environmental factors relevant for the acceptance of RE use [12].

As this cursory survey of the empirical literature shows, many specific conditions have been identified in distinct national, regional, or municipal contexts, but the insights of these studies have yet to be fully synthesized into a general framework or typology that could be used to develop regional strategies for implementing RE.

German energy transition policies, summarized under the term *Energiewende,* have been developed and decided on the national level [5,36,37]. Even though there has been no concerted effort to achieve the policy aims at the regional and local level, the German Association of Towns and Municipalities called for a coordinated approach [38]. Regions can share the responsibility to contribute to national *Energiewende* goals, as suggested in the region's network scenario by the Federal Environmental Agency according to their potentials and challenges [39]. This is supported by the finding that regions are the governance scale where national policies are actually realized and implemented [40]. Regions differ, for example in their RE supply potentials and demand for energy services [39]. Still, we expect that there are similarities between regions that can be used to allocate shares of *Energiewende* goals. In the light of limited temporal and financial resources to realize RE use, we suggest to develop generic strategies for regions. These would supply a basic structure and basic contents that fit to all regions with comparable contextual conditions for RE use (see [41] for a generic modelling approach of energy demand of buildings). For concrete RE realization, the generic strategies would need to be tailored specifically for each region, but each region would not have to start from zero.

With this paper, we aim at contributing to the need for spatially explicit, empirical analyses on regional energy transition contexts. We analyze a.) how regions differ in their contextual conditions and b.) whether and how regions can be grouped for generic regional RE implementation strategies.

In section 2 we clarify our understanding of contextual conditions of regional RE use and present the contextual factors used for analysis. Section 3 presents details on spatial scale, data, and analysis. We employ principal component analysis to identify correlations between all contextual conditions and cluster analysis to identify groups of regions. After presenting the results in section 4, section 5 discusses the results in the light of generic regional energy transition strategies. Section 6 concludes and binds the findings back to the challenges of realizing energy transition.

2. CONTEXTUAL FACTORS OF REGIONAL RE USE

We understand regional energy systems as complex systems that are composed of natural, technological, and societal units. According to Scholz and Tietje, complex systems can be described by three dimensions: function, structure, and context. These three dimensions can be defined as follows [42]:

- *Functions* are the goals and demands that are imposed on a system. In the case considered here, the most important function of a regional energy system is to provide energy services – heat, electricity, and mobility – using renewable energy sources.
- *Structures* are defined as the relevant "spatial and temporal relationship, connectedness, partitioning and modularization of the system units" ([42] p. 309) that serve to fulfill the functions of a system. Structures are regularly altered and shaped from within and from outside the system. The structures of regional energy systems are, among others, energy infrastructure such as solar panels or electricity grids or relationships between public energy services and their customers.
- *Context* "includes all environmental constraints that are permanently relevant system or impact factors" ([42] p. 309) that influence the processes in the system and cannot be easily influenced from within the system. The context of a regional energy system includes natural and socio-economic conditions, which both underlie larger dynamics and cannot or can only partly be influenced by actors at the regional level, e.g. wind speed for wind power.

In this study, we focus on the context of regional energy systems. As discussed above, recent developments concerning the use of RE primarily take place at the local and regional levels and within the confines of a given region (*Landkreis*). For this reason, we assume that these regions meaningfully bound RE systems for fostering sustainability transformations. It is important to note here that there are a few exceptions, for example Aller-Leine-area, a cooperation of municipalities from three adjacent regions [43], but for the most part, this approach allows us to examine the wide range of and spatial patterning concerning RE systems in Germany with regards to transition strategies.

In order to propose a corresponding typology of regions, it is necessary to identify, first, contextual factors for the regional use of RE and, second, groups of regions which encompass similar regions with regards to these factors, which show strong differences to regions in other groups. Therefore, we do not include contextual factors that affect regions in an equal manner, but only those that can be used to distinguish between regions. For example, national legislation and policy developments are two relevant contextual factors of regional energy systems, but in general, they apply to the entire country and do not differ between regions.

For this study, we identified a range of contextual factors from the transition literature and energy studies, which meet the criteria mentioned in the section above (see Table 1). Compared to the transition literature, energy studies have a more practical perspective, as they depict future energy system options for fostering specific kinds of transitions (e.g. [44]). Having identified contextual factors, we then assigned these factors to two categories: 'natural context' and 'socio-economic context.' The natural context corresponds to the natural environment; factors in this category can be used to assess the potential supply of RE. The socio-economic context corresponds to the social environment and includes factors that can be used to estimate the demand for energy and a set of factors describing select societal characteristics that need to be considered when implementing strategies at the regional level. We do not consider technical aspects because we understand technologies for the use of RE as part of the structure of a system, not its context. The contextual factors are presented in greater detail below, and their operationalization is discussed in section 3.

Natural context: In this study, we include the three renewable energy sources with the currently largest shares in electricity and heating in Germany. These are sun, biomass, and onshore wind [45]. Moreover, these sources are being mainly used in decentralized installations, and can therefore be part of regional energy transition strategies. We only consider the use of waste biomass in this study. According to the German Advisory Council on the environment, energy crops include several sustainability challenges in agriculture and forestry apart from the discussions on 'food or fuel' [46]. For example, (German) forests serve as sink for CO_2. Intensified harvesting for energy purposes changes forest structures and lowers the potential to bind CO_2, which conflicts with the aim of *Energiewende* to reduce GHG emissions [47]. Energy from biomass can, in the form of biogas, be used to flexibly even out the fluctuations from wind and sun and is therefore important for stabilizing RE electricity generation [48]. We do not consider offshore wind in this study, because its share in electricity from RE was less than 5 % in 2016 [49]. Additionally, offshore wind farms are a field in which regions or regional energy providers can invest, but there are no regional differences to be considered. We also do not consider the potentials of water and geothermal energy here, although they can provide essential base-load power [50]. The use of water power has a long tradition [51], and the installed capacity of water power in Germany has not increased significantly in the last 15 years [45]. Shallow geothermal energy can be used anywhere, so there are no regional differences to consider. The use of deep geothermal energy does not (yet) play a role in German electricity and heating. According to the considered renewable energy sources, we defined contextual factures that essentially influence their suitability in certain regions.

Table 2.1: Contextual factors considered in this study. Factors from natural and socio-economic context are operationalized in variables and proxies.

	Contextual factor	Variable	Proxy	References
Natural context	solar radiation	global radiation	annual average global radiation [Wh/m²]	[39,52,53]
	wind speed	wind speed	annual average wind speed at a height of 80m [m/s]	[39,52]
	waste biomass potential	from crops	harvest residues [GJ]	[54]
		from meadows	meadow residues [GJ]	[54]
		from forestry	forest residues [GJ]	[10,54]
		from livestock	zoomass [GJ]	[54]
		from households	waste [GJ]	[54]
Socio-economic context	population density	population density	number of inhabitants per km² built-up area	[44,52]
	population growth	population growth	total population growth up to the year 2025 [%]	[44,52]
	property rate	property rate	property rate [%]	[55]
	economic structure	forestry and agriculture	earners in forestry and agriculture [%]	[10]
		industry	earners in industry [%]	[44,52]
		commerce and services	earners in commerce and services [%]	[44]
	economic strength	tax income	municipal tax income from households [€]	[44]
		unemployment	unemployment rate [%]	[44]

Socio-economic context: We use population density to indicate a.) the demand for energy from private households, b.) the possibility to employ small-scale shared facilities like heating networks [56], and c.) built-up surfaces such as roofs and facades where the use of solar energy receives feed-in tariff [57]. For developing a realistic future energy system, it is vital to consider the future energy demand pattern from the population; we therefore implement population growth in our analysis. Because more than 40 % of solar energy technology is owned by private households [55], we take the property rate into account; here meaning whether the inhabitants live on rent or own the place they live in. The basic structure of the regional economy is included to indicate a.) the demand for energy from industry and commerce and b.) the potential to make use of waste biomass from land use (e.g. skilled workers). The economic strength of each region covers the ability to finance infrastructure projects related to the use of RE. Investments by private households represent a considerable share of all the money that is spent on decentralized renewable energy facilities, for instance rooftop solar panels or financial citizen participation in energy cooperatives or comparable models [25,58]. Therefore, unemployment was considered as a second variable related to this context factor.

3. Materials and Methods

Spatial scale: The study covers all German regions. These include 110 city regions (*kreisfreie Stadt*), which are, essentially, one larger city each, and 302 rural regions (*Landkreis*), which encompass several smaller cities and rural municipalities. It is important to note here that these are legal designations that may but do not necessarily reflect the actual character of these regions in terms of population density.

Proxies: Measurable proxies for each variable were chosen. We consider theoretical energy potentials regardless of technical options; in this case, the annual average wind speed at a height of 80m, the annual average global radiation, and the amount of energy in the available waste biomass. The theoretical energy potentials were normalized for each region for the area on which the land use allows the implementation of the different considered energy sources. For this, CORINE (Coordination of Information on the Environment) land cover data was used, a set of satellite data publicly available for all EU member countries that differentiates between land use classes [59]. We consider all fractions of waste biomass that were used in a material flow analysis for a sustainable use of biomass for energy purposes [54], except for industrial wood. This was excluded because we could not find reliable, spatially explicit empirical data. Values refer to the year 2010. Energy potentials of the waste biomass fractions harvest residues, meadow residues, and forest residues were normalized for area. Energy potential of the biomass fraction zoo mass was normalized for livestock units, and the fraction household waste for the number of inhabitants. For each region, the mean annual wind speed was calculated for areas covered by land use types on which wind turbines are common (arable land, pastures) and on which wind turbines are possible without nature conservation conflicts (coniferous forest) [60,61]; i.e. CORINE land cover classes 211, 231, and 312. For each region, the mean annual global radiation was calculated for surfaces on which solar energy is supported by the feed-in tariff [57]. These are buildings (CORINE land cover classes 111,112,

121) and disturbed surfaces (CORINE land cover classes 122, 132, 131). Population density is included because predominantly rural and predominantly urban regions have shown very different activities concerning the use of RE. We use the total population growth up to the year 2025. To assess economic strength, we use the unemployment rate and the municipal tax income from households because the latter is an indicator of the financial resources available to private households and municipalities. In contrast, GDP is an indirect proxy. The investments by private households represent a considerable share of all the money that is spent on decentralized renewable energy facilities [25,58]. The share of home ownership is included as the variable property, because regional RE strategies would need to address the needs of different stakeholders such as private home owners or public and private housing associations with different incentives and tools. Data on earners per economic sector (agriculture and forestry, industry, services) are used as proxies for the strength of each sector.

Data: Socio-economic data from the Federal Institute for Research on Building, Urban Affairs and Spatial Development was used for the year 2010 [62]. Data on livestock units from the German statistical database [63] was also used for the year 2010. For the regions Aschaffenburg, Bremen, Bremerhaven, Darmstadt, Offenbach, Schwerin, and Stralsund data on livestock units was only available for 2005, which was subsequently included in the data set. No original data on livestock units was available for the regions Wismar, Schweinfurt, and Neubrandenburg; here we used the mean value of all regions. Data on mean annual global radiation and mean annual wind speed at a height of 80 m are both raster data with 1 km x 1 km resolution from the German National Meteorological Service. For land use biomass fractions and the normalization of wind and radiation potentials we used CORINE land cover 2006 raster data with 250 m x 250 m resolution. The administrative borders in the conditions of 1.1.2009 are from GeoDatenZentrum [64]. All data is publicly available and mostly open source, we hope that the approach can thus be reproduced in other locations with comparable data.

Analysis and software specifications: Principal components analysis (PCA) in R (R 64 2.15.1 GUI 1.52) was used on standardized data, to analyze the correlation between all contextual factors across the data set and determine the gradients along which the types of regions change. The analysis was done with standardized data in order to make different variables comparable regardless of the scaling of the data. Cluster analysis was used to identify types of regions with similar contextual characteristics. Clusters in the standardized data were identified and analyzed in R with the cluster package version 1.14.2. We used hierarchical agglomerative clustering (agnes) with Euclidean distances and Ward's method. Dendrograms were used to determine an appropriate number of clusters. Types and single variables were mapped in ArcGIS (ArcGIS Desktop 10 Education Edition) to visualize and compare spatial patterns.

4. RESULTS

The following section presents the results of the PCA as well as the larger spatial patterns of select contextual conditions for the use of RE in the regions. After that, we describe the characteristics of each energy context type as suggested by subsequent analyses.

4.1 Spatial patterns

The PCA showed that the variation in the set of 15 variables across all regions can be explained by different gradients. Principal Component 1 (x axis) corresponded to the variable population density and explained 32 % of the variance. A shown in Figure 2.1, population density correlated on this axis closely with the variable earners in agriculture and forestry. Based on our dataset, we recognize a gradient from regions with very high population density to regions with very low population density that are characterized by an above-average percentage of earners in forestry and agriculture. Figure 2.2e shows the differences in population density. Principal Component 2 (y axis) corresponded to the variable unemployment, and this axis explained another 22 % of the variance in the data set. The tax income is here negatively correlated to the unemployment rate based on the results shown in the principal component analysis. We interpret this in a way that the y axis widely corresponds to the regions´ economic strength. Together with the variable population growth, which is closely correlated on the y axis, it described a socio-economic gradient from regions with a high unemployment rate and strong population decrease to regions with a low unemployment rate and population increase. The gradient of unemployment was oriented east to west (see Figure 2.2d). The variables global radiation and unemployment are closely correlated, but we do not see a causal relationship here. The variables show similar trends in the data on the regions, because the spatial patterns of unemployment and global radiation show some similarities. This is due to the strong economy in southern Germany, as more jobs are available here than in northern and eastern Germany. This pattern overlaps with the one for global radiation (see Figure 2.2b), but again, we urge caution as this is only a correlation and no causal relationship. It is possible to discern a spatial pattern of wind speed (see Figure 2.2c), which suggests a gradient from north to south, displaying high wind speeds on the coasts of the North and Baltic Seas. Further south, the regions with higher elevations are again characterized by higher wind speeds. Gradients for global radiation and wind, are, as indicated by the PCA, diametrically opposed. It is important to note here, however, that there are several notable exceptions, for example regions along the coast or those in higher elevations that show both high wind speeds and strong solar radiation.

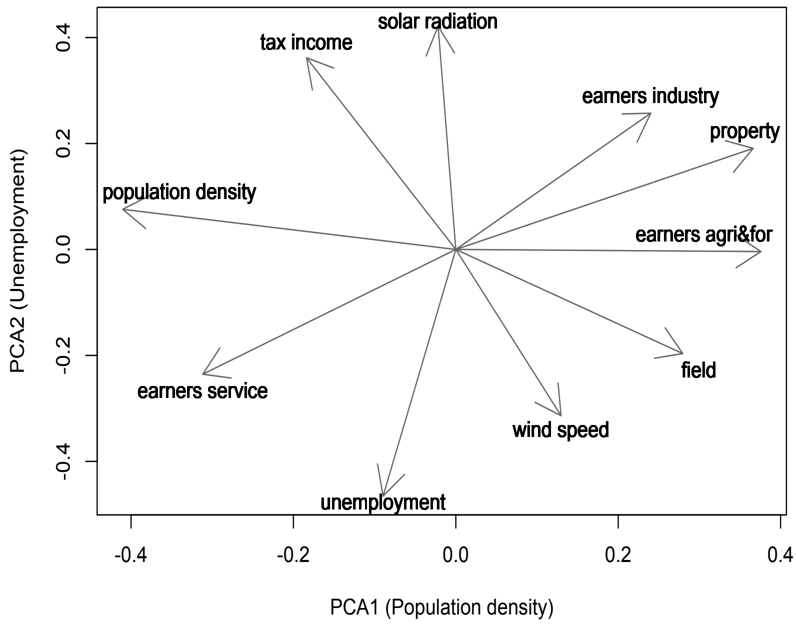


Figure 2.1: Principal Component Analysis. Principal Component 1 is displayed on the x-axis (which explains 32 % of variance) and Principal Component 2 on the y-axis (which explains 22 % of variance). The variables are shown as arrows; the longer the arrow, the higher its explanatory power. For reasons of visual clarity, the following five variables, which had no or hardly an additional explanatory power, are not included in the figure: meadow residues, zoo mass and forest residues (closely correlated to jobs in agriculture and forestry), population growth (closely correlated to mean radiation and unemployment), household waste.

4.2 Energy context types

Nine clusters of regions were identified (see Fig. 2.2a), which represent specific energy context types that differ in terms of their socio-economic and natural contextual conditions (see Table 2.2). The energy context types reflect the spatial patterns identified in section 4.1. In accordance with PC1, the population density strongly defined how regions were clustered. The three urban types T1, T4, and T8 include all city regions and the rural regions of the densely-populated areas Rhine valley and Ruhr area. The other six types include only rural regions. Regarding the socio-economic conditions, it is possible to observe a gradient from the economically weak and primarily rural Northeast to the economically strong and predominantly urban South. The latter corresponds to a high potential for the use of solar energy, whereas the former is associated with a high potential in wind energy. Detailed information on the variation of parameters evaluated for all energy transition types are given in the boxplot figure in Appendix A (at the end of this chapter).

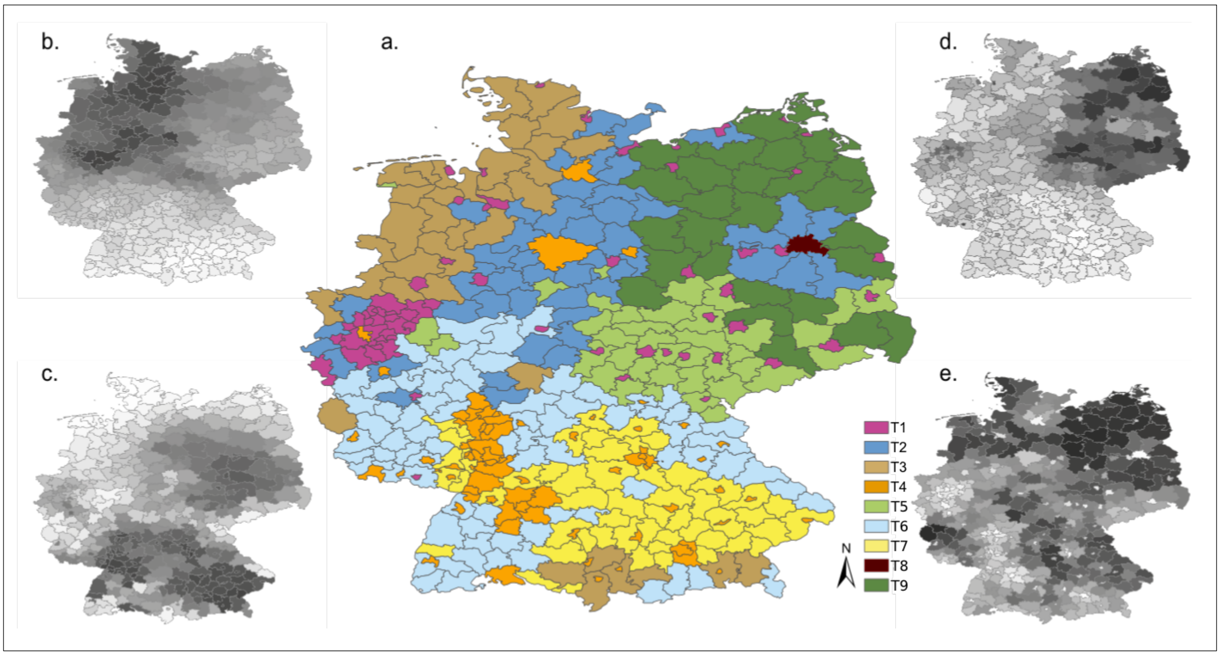


Figure 2.2: Contextual conditions for using renewable energy sources in all German regions. Maps show a. the energy context types, b. mean annual global radiation, c. mean annual wind speed, d. employment and e. settlement density. In maps b-e, light colors indicate high values, dark colors indicate low values.

In the following we have summarized key characteristics of the 9 types including respective “spotlights” with regards to potential consequences for transition strategies. A detailed overview of the characteristics of the types can be found in Table 2.2:

T1, Urban North: The city districts in northern Germany and the rural districts in the Rhine-Ruhr area are characterized by an above-average share of earners in services, a high unemployment rate and sharply decreasing population. The energy potential from waste and the mean wind speed are quite high. Spotlight: Motivation for and ownership of the transition process in the light of tense economic situation and population loss.

T2, Rural North: This type in the middle of Northern Germany shows average socio-economic contextual conditions. The districts are characterized by high wind speeds and biomass potential from land use, especially harvest and forest residues. Global radiation is quite low. Spotlight: Supply of adjacent city-districts.

T3, Livestock belt: This type consists of districts in the North-West and in mountainous areas that are traditional areas of livestock farming and have the highest mean wind speed. Spotlight: A concerted use of the diverse strong energy potentials may even out fluctuation, high potential to supply city districts.

T4, Urban South: The city districts mostly in southern Germany and the rural districts in the Rhine valley have a strong economy with the highest tax income, a growing population and, for urban areas, high residual property. The major energy potential is the strong global radiation. Spotlight: Combine the high potential from radiation in the cities with the energy potentials of adjacent rural areas.

T5, Industrial East: The rural districts mainly in Eastern middle Germany have the highest share of earners in industry and are characterized by a weak economy and strong population decrease. The wind speed and radiation have average values, the potentials from forest and harvest residues as well. Spotlight: Financing and ownership of the transition process.

T6, Rural South: This type encompasses rural districts with average socio-economic contextual conditions, a large industrial sector, strong radiation and high mean wind speeds. The strongest fraction in the mix of biomass potentials is forest residues. Spotlight: A concerted use of wind and solar energy may even out fluctuations, supply of industry.

T7, Sunny South: The rural districts are characterized by a strong economy with a large industrial sector, show the lowest unemployment rate and highest population increase; have very strong radiation and considerable potentials from land use. Spotlight: Synergy between population dynamic and transition dynamic.

T8, Global City: This type contains only Berlin, Germany´s capital and largest city. It is by far the densest city with a specific socio-economic context, e.g. very low residual property. The largest potential is waste, radiation is average. Spotlight: Challenge through low residual property, focus on financing and ownership of the transition process.

T9, Rich but Poor: The rural districts in the North East have the weakest economy and strongest population decrease. They are also characterized by very high energy potentials from land use, high mean wind speed, and average radiation values. Spotlight: Make use of energy abundance to create motivation for and ownership of the transition process in the light of tense economic situation and population loss.

Table 2.2: Energy context types: Summary statistics. Mean values of non-standardized data are given. Cells are colored dark gray for values more than 1 SD above average, and light gray for values more than 1 SD below average.

Variable	Energy context type								
	Urban North T1 (N=64)	Rural North T2 (N=50)	Livestock Belt T3 (N= 36)	Urban South T4 (N=69)	Industrial East T5 (N=38)	Rural South T6 (N=75)	Sunny South T7 (N=52)	Global City T8 (N=1)	Rich but Poor T9 (N=27)
Population density	2.916,8	1.345,4	1.162,4	3.128,1	1.338,4	1.371,2	1.438,1	5.503,3	810,5
Property	30,0	58,3	63,8	39,9	50,8	62,6	61,9	14,9	49,0
Tax income	543,3	527,7	547,3	811,1	402,5	561,7	664,5	513,6	330,1
Unemployment	8,8	6,1	4,6	5,3	9,3	4,3	3,2	10,0	11,0
Earners agri.+fores.	0,7	3,4	5,5	0,8	3,3	3,3	5,1	0,3	5,5
Earners industry	19,4	24,5	26,5	24,0	34,8	32,9	32,9	12,9	24,6
Earners services	79,9	72,1	67,9	75,1	62,0	63,9	62,0	86,8	69,8
Population growth	-7,9	-0,1	1,9	2,1	-13,3	-2,0	4,7	0,9	-13,4
Wind speed	5,8	5,8	6,3	5,1	5,7	5,8	5,1	5,3	5,8
Global radiation	1.017	1.008	1.034	1.105	1.030	1.081	1.136	1.035	1.034
Harvest residues	27.413	239.325	227.512	36.040	219.017	85.821	164.582	18.187	491.340
Meadow residues	7.765	48.905	182.927	7.147	30.603	57.577	33.867	3.343	101.253
Forest residues	49.852	485.553	291.896	112.371	445.870	625.863	355.525	236.318	765.317
Zoo mass	48.419	249.758	1.030.417	31.780	175.590	181.885	300.392	7.586	378.915
Household waste	422.402	360.245	324.317	446.452	275.217	271.564	246.332	6.059.108	250.054

All types have RE potentials for the three sources analyzed in this paper, i.e. biomass, wind, and solar. Even though the actual potentials and challenges for the use of RE are determined by different contextual conditions, our study indicates that it is possible to identify basic patterns and energy context types. In other words, each of the nine types identified here represents a distinct set of potentials and challenges for implementing RE.

The analysis has shown that each type contains regions with wind speeds above 5 m/s (see boxplot diagrams in the Supplementary material). Nevertheless, wind speeds are generally higher in northern Germany with 6.3 m/s for T3 and about 5.8 m/s for T1, T2, T5, T6, and T9.

Global radiation is generally stronger in southern Germany than in the north. With the mean value being 1053.3 Wh/m², the energy context types T4, T6 and T7 show above-average values. Regarding the parameters wind speed and global radiation, the urban types do not differ from the rural ones. In contrast, there are major differences when it comes to biomass. The highest total biomass potential can be found in T8, Berlin, which is due to the high energy potential of household waste (see also Appendix A). T3 and T9 also show high biomass potentials; here, the latter result from agriculture and forestry. The other rural energy context types hold considerable biomass potentials as well, whereas the smaller city regions of the urban types T1 and T4 show relatively low potentials from all waste fractions.

Regarding the socio-economic conditions, the strongest differences appear between rural and urban types. This is true for population density, which is, in all three urban types, more than one standard deviation above average. Moreover, the urban types show lower shares of property ownership and earners in agriculture and forestry. The latter is very closely related to the land-use related biomass parameters. Regarding unemployment rate and population growth, the data shows considerable differences between the rural regions of eastern Germany (T5 and T9) and the urban and rural regions of western Germany. To a lesser extent, this is also true for tax income. T5 and T9 show the highest expected decrease in population until 2025 (>13 %), and unemployment rates of 9.3 % and 11 % respectively. Berlin, T8, is also characterized by a high unemployment rate of 10 %, but it differs from T5 and T9 in many respects. For example, the data suggests that Berlin´s population will grow slightly until 2025. There are differences concerning the municipal tax income between urban and rural regions and between southern Germany and northern and eastern Germany. The tax incomes of T4 are more than one standard deviation higher than the average, while they are more than one standard deviation lower in T9. All other types are distributed along this gradient from the rich urban south to the poor rural northeast.

5. Discussion

In the following, we discuss the relevance and interrelations of our results according to the research questions and present an outlook on possible further research related to this study.

5.1 Discussion of results

The analysis showed that the socio-economic context changes along an East-West-oriented gradient. This gives evidence for a still existing imbalance between the two former German states: energy context types T5 and T9 encompass the rural area of the former German Democratic Republic. Major discrepancies between these two types and the remaining seven types become apparent in economic strength, population density and property rates. The

North-South gradient displays the interplay between high mean wind speeds on the coasts of the North and Baltic Seas and strong global radiation in the South. The biomass potential is independent from this gradient; it is rather a function of space and inhabitants, with space increasing the energy potentials from agriculture and forestry and the number of inhabitants increasing the energy potential from household waste. The total energy potential from waste biomass in this study is 475 PJ, which is 50 PJ lower than in the original data [54]. This difference mainly results from omitting the fraction industrial wood in our analysis, which represents 55 PJ in the data source. The remaining difference of 5 PJ can be explained as the result of not calculating the total amount directly, but from mean values per type.

The data on all analyzed renewable energy sources allows assessing to which degree these sources should be considered in the generic regional energy strategy of each type. According to the 'region's network scenario' of the German Environmental Agency, Germany can be supplied by 100 % renewable electricity by 2050 if all rural and urban regions use their local potentials [39]. Potentials of the analyzed RE sources are high in some energy context types, and less high in others. The study considers theoretical energy potentials. Wind speeds and solar radiation were therefore only assessed for areas on which the use of wind energy or solar energy is possible. Still, the analysis does not consider the total area on which wind turbines or solar panels can be mounted. Other factors in the analysis allow a careful guess of the feasibility to use an energy potential. The values of harvest, meadow, and forest residues (see tab. 2.2 and Appendix A at the end of this chapter) mirror the total area of these land use forms and thus allow to roughly assess the area on which wind farms can be mounted. The potential rooftop area for solar energy use can be cautiously derived from the variable settlement density. A comparison with the region's network scenario shows a similar spatial pattern of the PV potential [39].

In the region's network scenario, wind speeds of 5 m/s are regarded as sufficient [39]. This analysis offers a conservative assessment of areas with sufficient wind speeds, because we use 80 m as the reference height for wind speed. Wind turbines are usually higher than 100 m, and wind speeds are generally increasing with height [65]. With mean annual wind speeds of 5.1 m/s, wind energy use may not be a main strategy element in T4 and T7, for instance. Nevertheless, also these regions host areas with wind speeds considerably higher than 5 m/s (see boxplot diagrams in Appendix A). All other rural energy context types offer, according to our analysis, a high number of locations with adequate wind speed for energy generation. Here, wind power can be a viable RE source, and these types can thus contribute considerably to national RE targets. We conclude that wind energy can be used cost-effectively in every energy context type, and that especially types T2, T3, T5, T6, and T9 host considerable wind potentials. For the use of solar energy and biomass, a comparable pattern is visible. Practical experience shows that solar devices can be used in all parts of Germany regardless of energy context type.

Still, the use of solar energy is more resource-effective for regions with stronger radiation and might thus be favored there. These are found in southern Germany, especially in the energy context types T4, T7, and T6. T4 is an urban *energy context type* with high population density and relatively high property rates, this allows the assumption that considerable area for solar power devices exist here. T6 and T7 are both rural types with the highest share of earners in industry, which allows to assume that industrial infrastructure offers rooftops and so-called disturbed surfaces, on solar devices can be installed on the ground. We thus conclude that solar energy can be used in all parts of Germany, and that especially types T4, T6, and T7 host considerable potentials. For the use of biomass, the potentials from household waste and from land use waste need to be considered separately from one another. The energy potential from household waste is related to the number of inhabitants and especially high in urban areas. The biomass from land use waste is related to different forms of agriculture and forestry and is, depending on the characteristics of the material, processed in different ways. Urban and rural types, therefore, may need to consider very different technical options. All considered forms of biomass share the characteristic that they can be stored as fuels and further processed to electricity and heat when it is needed. This is considered important for regulating fluctuations from wind and solar energy [66]. Summing up, all energy sources can be used in all energy context types, but their significance in the generic strategies for each type differs. Also, the technical options to make use of the energy potentials differ.

5.2 Implications for generic regional energy transition strategies

The generic strategies should include both the socio-economic and the technological perspective. For example, generic strategies can offer different options to realize a strategy element such as shared facilities to supply homes with electricity and heat. For this, the strategies should consider different ownership models or organizational models that allow to adapt to different economic situations of private households and different property rates. In urban areas where most people live on rent and thus invest less in their homes, shared facilities can, for example, be owned and managed by housing companies or communities [67]. Cooperatives may be an option for both urban and rural types, while privately owned shared facilities in neighborhoods can be an option for rural areas with high property rates. Shared facilities can consist of different technological options. For example, combined heat and power plants are a cost-effective and resource-efficient system for small-scale applications [68], that can be fueled by biogas from land use or landfills, or by wood chips [18]. District heating systems can also be fueled by these sources.

For example, the generic strategy of type 9 would build on the high potentials for RE use and recognize the challenge of high unemployment and population loss. In this situation, it may be wise to focus first on those steps of RE implementation that can bring a positive effect to the people in these regions. A more intense use of RE will probably not automatically lead to the creation of jobs or to local revenues [69,70]. Still, a combination of different funding sources for regional RE projects and a close collaboration with formal networks seem to contribute to successful RE implementation and a general positive influence on the regional economy [71]. Breaking this down to the generic strategy for type 9, it may be interesting to use waste biomass from forestry and agriculture in decentral combined heat and power plants. While the generated electricity can be sold and contribute to supplying other regions, the heat can be used locally in district heating systems. It can be expected that many homes in type 9 need to modernize their heating soon, because a great number of homes invested in new heating after reunification of Germany. The generic strategy could thus set incentives and offer an option to guide investments that are anyway necessary to solutions based on RE, which might additionally contribute to realizing the necessary improvements of the older building stock [72].

The typology may set the basis to operationalize national energy transition policies, especially concerning the use of RE, for the regional level. It offers a structured picture of regional socio-economic and natural conditions for the use of RE, which may allow to allocate shares of national RE goals to *energy context types*. For example, the aim to install a capacity of 2800 MW onshore wind energy per year [73] can be distributed between and allocated to energy context types according to wind speeds and space: urban types can, for example, use small wind turbines as resource-efficient option to generate electricity [74]. However, effects and challenges of small-scale and micro wind turbines in urban areas are not sufficiently understood yet [75,76]. Many German regions are already experienced with the use of RE, but they may have used different planning procedures, ownership models or technologies. The typology may enlarge the potential of interregional learning, because, by having comparable contexts, successful projects can be reproduced in other regions of the respective energy context type.

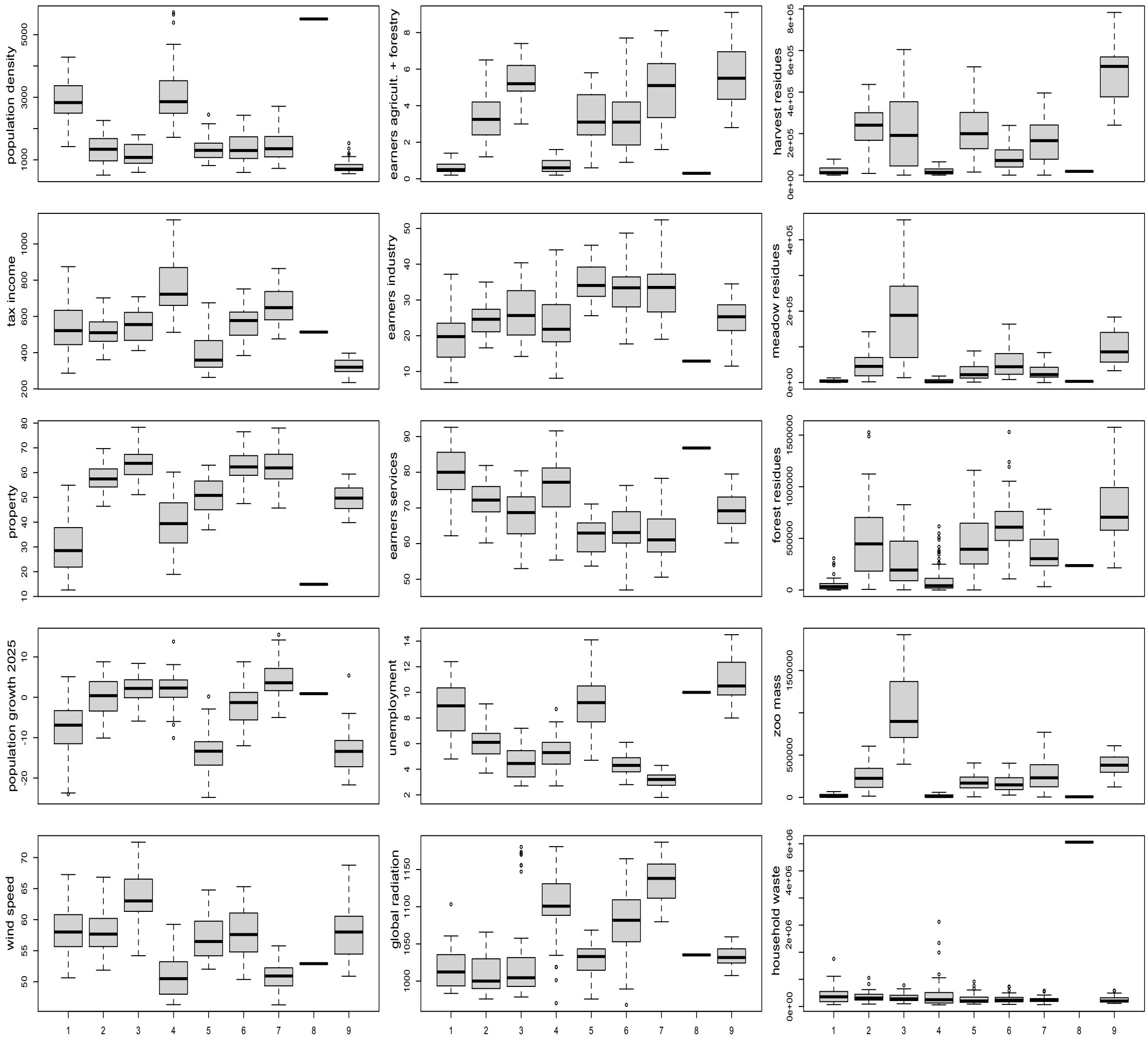
The envisioned generic regional energy transition strategies can be adapted to the major differences between the German regions. Still, each region will have to adapt the generic strategy of their type to the specific regional conditions and current situation. Although belonging to the same context type, regions may differ substantially in their experience and maturity concerning RE use. To fully develop these generic strategies, further research on fostering structural change is necessary, e.g. on actors, institutions and regulations. The generic strategies need to be flexible to differences in the maturity of regions with regards to the implementation of RE. While one region might just be starting to use renewables, others of the same type might have a long tradition or show a dynamic development in using renewable energy sources recently. Furthermore, it would be interesting to test this approach on different scales (municipality, state) or in other countries. We believe that large parts of the conceptual framework concerning the natural and socio-economic context are also valid for other energy systems; but expect considerable differences in the implementation process between countries due to different legislation, institutions and traditions.

6. Conclusions

This paper presented an approach to inform the development of generic regional transition strategies for the use of RE, which is based on multivariate analysis. Building on the contextual conditions for the use of RE in all 412 German regions, we identified nine energy context types. These energy context types differ in their natural and socio-economic contexts. Therefore, the approach fulfills its purpose with regards to the goal of informing the development of generic regional energy transition strategies.

The structured picture of regional characteristics can support the operationalization of national and international energy transition goals by adapting regional energy transition strategies to the respective natural and socio-economic contexts. Generic regional energy transition strategies can guide regional decision makers to prioritize action options in the complex field of energy transition. Moreover, the energy context types enable networking with and learning from other regions with comparable natural and socio-economic conditions. In the light of the above discussion, we are confident that generic regional energy transition strategies based on the natural and socio-economic context can serve as innovative tool to inform governance and operationalize national and international goals on the regional level. This may then contribute to realizing energy transition policies and GHG reductions.

APPENDIX A



Variation of parameters evaluated for all energy transition types. Boxes display the information of one parameter, each encompassing one boxplot per energy transition type as indicated on the x-axis. Outliers are only shown for the variables settlement density, forest residues, population growth, unemployment rate, radiation and waste.

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Chapter 3

Driving factors for the regional implementation of renewable energy - A multiple case study on the German energy transition

Lotte M. Lutz, Lisa-Britt Fischer, Jens Newig, Daniel J. Lang

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Abstract:

Understanding what drives the regional implementation of renewable energy is a prerequisite for energy transitions toward a post-fossil-based energy economy. This paper presents an empirical analysis of driving factors for the regional implementation and use of renewable energy. We tested literature-derived driving factors in a comparative analysis of 18 selected study regions using Rough Set Analysis and performance analysis. We paid special attention to common combinations of driving factors, which we understand as established practices concerning the use and implementation of renewable energy. Our findings confirm most of the driving factors identified in the literature, for example the existence of key actors, knowledge exchange, or the use of goals and milestones. We also observe differences in key driving factors between highly successful and less successful regions, especially regarding funding opportunities. The results may support policy makers who aim to successfully implement renewable energy at a regional level.

1. Introduction

Increasing the share of renewable energy (RE) to 45 % of the total electricity production by 2025 is one of the primary goals of the German energy transition ('Energiewende') (Bundesministerium der Justiz und für Verbraucherschutz, 2014). In the discourse on energy transitions, decentralized energy production is an important issue (Hecher et al., 2016; Späth and Rohracher, 2010). A large share of biomass, solar, and wind power plants has been installed at the regional level since the liberalization of the electricity market in 1998 (Geels et al., 2016). In 2010, regional actors such as private households, farmers, and municipalities owned more than 65 % of decentral RE installations in Germany (trend:research, 2011). Regions, therefore, have an important role in the Energiewende.

Regional energy transitions have been discussed extensively in the sustainability transitions literature (see, e.g., Grin et al. 2010). The multi-level perspective (MLP) is often used as framework to describe and analyze historical and current cases. Many of these focus on technical niche-innovations (see e.g. Hielscher et al., 2011; Kemp et al., 1998; Lopolito et al., 2011). Other publications on regional energy transitions deal with specific aspects of the analyzed processes or cases. For example, several studies examine specific energy sources such as bioenergy (Karpenstein-Machan and Schmuck, 2007; McCormick and Kåberger, 2007), wind energy (Musall and Kuik, 2011), or solar energy (Dewald and Truffer, 2012; Linder, 2013). Further studies focus on socio-economic contextual conditions affecting regional energy transitions. The involvement and participation of local actors and civil society have, for instance, been addressed in the literature (Müller, 2014; Musall and Kuik, 2011; Trutnevyte et al., 2011).

Some studies such as Blumer et al. (2013) and Domac et al. (2005) on bioenergy projects have sought to offer a more nuanced perspective on socio-economic drivers or success factors, respectively. Still, a more comprehensive approach to the use and implementation of RE, i.e., one that integrates socio-economic conditions as well as the participation and involvement of different actor groups, and that does not exclusively focus one RE source, is still missing from the literature. Also, comparative studies on regional RE implementations and use are still rare. This study addresses both of these aspects and follows a more comprehensive approach, integrating relevant aspects from four areas of activities of regional RE managers: planning and process, actors and networks, exchange and participation, and economic circumstances concerning the use and implementation of different RE sources in a region. This study is informed by successful regional practices from 18 study regions. We believe that it is helpful to consider potential interdependencies of driving factors for a successful implementation and use of RE. Our attention thus not only lies on singular driving factors; we also consider patterns, or combinations, of driving factors that can be observed in regional practice. More specifically, this paper aims to answer the two following research questions:

1. Which governance-related driving factors contribute, according to the literature, to a successful implementation of renewable energy at the regional level, and how can these factors be categorized?
2. Which driving factors and which patterns of driving factors can be identified based on an empirical analysis of regions, and how do they contribute to the successful implementation of renewable energy at the regional scale?

To answer these questions, we analyzed established practices concerning the use of RE in a sample of regions that aim at a 100% supply with RE. This analysis focuses on how RE has been implemented in a sample of regions, e.g. which processes were used and which actors were involved, independent from the concrete RE project or the regional RE potential. For doing so, we first identified driving factors for the regional implementation of renewable energy in particular and for transitions in general, drawing on the literature (Section 2). We then tested these driving factors in a comparative analysis of 18 selected study regions that have comparable natural and socio-economic contextual conditions regarding the use of RE. To do so, we collected data from professional experts in the regions via a detailed questionnaire and processed the resulting data with Rough Set Analysis and performance analysis. These methods are described in Section 3. We present the results on the driving factors and the related patterns in Section 4 and discuss them in Section 5. In the last section, we summarize our findings and propose policy implications.

2. Driving factors for the regional implementation of renewable energy

Driving factors promoting the implementation of renewable energy in local and regional settings have been analyzed from different perspectives in the literature, although they might not always be named as such. We focus here on governance-related factors from the literatures on socio-technical transitions governance, which included local and regional case studies concerning the implementation of RE. We looked at the general search areas of 'regional implementation of renewable energies' and 'renewable energy transitions' using the bibliographic database Scopus, as well as google scholar. We concentrated on the situation in Germany and added some ideas from international, mainly European, studies. We identified a total of 19 driving factors for a successful regional implementation of RE, which we grouped into four clusters that correspond to fields of activities in which regional actors might engage: 1.) planning and process, 2.) exchange and participation, 3.) actors and networks, and 4.)

economic circumstances. The list of factors is presented in Table 3.1, including short definitions and corresponding sources for each factor. Planning and process

Regional energy plans help to integrate and coordinate the decentral activities with national goals and thus perform an important function in the unfolding of the Energiewende. According to an inventory, 233 regional energy plans existed in 2014 (BMVI Bundesministerium für Verkehr und digitale Infrastruktur, 2015). The literature discusses several ways to facilitate the complex process of implementing RE in local and regional settings. Specific plans that concentrate on the energy system have proven to have a positive influence (Musall and Kuik, 2011), while Coutard and Rutherford (2010) stress the importance of comprehensive regional planning for policies concerned with energy, emissions and climate. A very common planning concept in German regions is the *Integrated climate protection concept* (icpc), which is co-funded by the national climate protection initiative (BMUB Bundesministerium für Umwelt, Naturschutz, 2015).

Actors and networks

A rich body of research is devoted to how actors and networks shape and influence transition processes. Many different actors and social groups are being involved in transition processes (Farla et al., 2012; Fischer and Newig, 2016; Geels, 2012), which have different skills, roles and resources. Actor networks can fulfil certain functions such as confidence building, decrease of uncertainty, building consensus, negotiations, providing decision making structures on a regional level, motivating local actors to get involved in common regional interests and providing a platform for identifying problems and to define new fields of action (Fürst and Schubert, 1998). The lack of a network can lead to very weak interactions which in the end hamper RE development (Negro et al., 2012).

Exchange and participation

The literature underlines the importance of communication between the numerous actors in charge of RE implementation and between these and civil society. A knowledge exchange between local actors is said to be important because of the high complexity of RE development, not only in regard to the new technologies itself, but also in regard to funding, legal issues, and operational arrangements (Walker, 2011). Regional actors in the 100ee regions expressed a need for consultation regarding specific topics such as evaluation and monitoring, or the development of a network (Projekt 100%-Erneuerbare-Energie-Regionen, 2009). Communication with the civil society and local participation is considered to be significant to meet public perception and acceptance of renewable energy.

Economic circumstances

Funding of RE development is crucial since new infrastructure and working routines need to be financed. Economic viability can be one of the reasons why a RE project or development fails (Walker, 2011), but it has also been a crucial driver for implementing RE development (Blumer et al., 2013). Funding structures are found to be quite heterogeneous, which means that regional projects usually rely on more than one funding source (Hecher et al., 2016; Walker, 2011). Related to our research questions the main interest of this study are the actors involved in the funding of regional RE implementation, and the perceived share of funding from public sources, private actors and business investments. In many German regions, community energy initiatives (CEI) are influential actors. We understand CEIs as local or regional initiatives mostly constituted by citizens, which follow the aim to sustainably produce renewable energies and/or to sustainably consume energy. In 2012, CEIs were responsible for 30 % of the investments in RE electricity generation, and owned 47 % of the total installed RE capacity (Holstenkamp and trend:research, 2013; Yildiz, 2014). The successful involvement and establishment of CEIs has benefits such as a financial return and the provision of a sense of satisfaction (Walker, 2011), and utilizing contextualized local knowledge which leads to sustainability benefits (Seyfang and Smith, 2007).

Table 3.1: Driving factors of renewable energy implementation processes as identified from the literature and how these are analyzed in this study. Factors are presented according to the clusters Process and Planning (P&P), and Exchange and Participation (E&P). The column "Analysis" indicates whether the factors are analyzed via RSA or performance analysis (P).

Cluster	Driving Factors identified in the literature	Analysis	References
P&P	**Duration of the Process**: Time is one major aspect in the gradual change of routines, rules and technology use, therefore the duration of a process of change is significant.	RSA	Geels, 2005
	Comprehensive regional planning is especially important for policies concerned with energy, emissions and climate. The *integrated climate protection concept* (icpc) encompasses public, private, industrial and business perspectives on aspects of energy use, water, waste and mobility and is a very common regional planning tool.	RSA	Coutard and Rutherford, 2010; Projektträger Jülich, 2016
	Energy specific planning: Regional concepts which, in contrast to comprehensive regional planning, specifically concentrate on the energy system positively influence the use of RE.	RSA	Musall and Kuik, 2011
	Monitoring of Goals: Setting goals and specific targets is crucial for transforming the energy sector. Goals and targets provide orientation and thereby facilitate the coordination of the different (private and governmental) actors involved in a transition. Also, targets can be measured and assessed, and they allow to identify policy needs.	RSA	Lipp, 2007; Späth, 2012
	Use of Milestones: The use of clearly defined milestones was found to be of relevance in a recent study about bioenergy.	RSA	Blumer et al., 2013
	Support by decision makers In a comparative case study of Denmark, Germany and the United Kingdom, "time and a clearly stated government commitment is named as the most critical element in transforming the RE market". Also, a sense of urgency concerning the process on the side of government representatives is supportive (Schreuer et al., 2010).	RSA	Boon and Dieperink, 2014 ; Bulkeley and Kern, 2006; Musall and Kullig, 2011; Schreuer et al., 2010; Lipp, 2007
	Consistent legal and policy conditions: Inconsistencies in legal or policy conditions are challenges that can possibly hinder the process of RE development. Policy continuity and stable legal conditions lead to an assurance of process conditions, such as certain market conditions, which influences participation of different actors. Inconsistency in policy has proven to be fatal as for the case of Denmark. Centers of research that initially played a very important role in wind power development struggled to continue their work because of a lack of funding.	P	Negro et al., 2012; Walker, 2008; Boon and Dieperink, 2014; Lipp, 2007; Rydin et al., 2013; Hekkert et al., 2007
E&P	**Use of various information channels**: Blumer et al. (2013:394) found that using several information channels was found to increase transparency by conveying information from the project to the public.	RSA	Blumer et al., 2013
	Participation and public involvement: Local participation is considered to be significant for the public perception of renewable energy. This is important in regard to financial involvement, political involvement, and the formation of fundamental trust which is then functioning as a basis for further work.	RSA	Devine-Wright, 2005; Musall and Kuik, 2011; Rydin et al., 2012, 2013; Späth, 2012; Walker, 2011; Karpenstein-Machan and Schmuck 2007; Walker et al. 2007
	Knowledge exchange with experts and experienced practitioners: Knowledge exchange is crucial for communities because of the high complexity of RE development, not only in regard to the new technologies, but also in regard to funding and legal issues, installation and operational arrangements. Developing high quality relationships between various actors can lead to knowledge exchange and the sharing of insights that can eventually change the socio-technical regime.	P	Boon and Dieperink, 2014 ; Bos and Brown, 2012; Projekt 100%-Erneuerbare-Energie-Regionen, 2009; McCormick and Kåberger, 2007; Negro et al., 2012 ; Rydin et al., 2012; Smith, 2012; Späth,

			2012; Walker, 2008, 2011
A&N	**Key actors**: The presence of key actor(s), both persons or institutions, seems to increase the possibility of a successful outcome.	RSA	McCormick and Kåberger, 2007; Späth and Rohracher, 2010; Walker, 2008
	Networks: Actor networks can fulfil certain positive functions such as confidence building, decrease of uncertainty, building consensus, negotiations, providing decision making structures on a regional level, motivating local actors to get involved in common regional interests and providing a platform for identifying problems and to define new fields of action. Under certain conditions they can also positively contribute to regional economic development. A missing network can lead to very weak interactions which in the end hamper RE development.	RSA P	Fürst and Schubert, 1998; Smith, 2012; Späth and Rohracher, 2010
	Actor heterogeneity: In transition processes, many different actors and social groups are being involved; there is never just a single (type of) actor involved in the transformation process. Authors suggest that governance strategies should include a wide range of different actors.	RSA	Farla et al., 2012; Geels, 2012; Lipp, 2007; Rydin et al., 2013; Firscher and Newig 2016
	Specific skills of key actors: Certain features are listed as potential essential characteristics of key actors: providing direction and leadership, being involved and supporting a network, giving expert knowledge, having an environmental consciousness, being in the position to the transfer and exchange resources.	P	Bos and Brown, 2012; Kratz, 2007; Boon and Dieperink, 2014; Fürst and Schubert, 1998; Jansen and Wald, 2007
	Supporting/opposing actors: Actors opposing change are considered to be a systemic problem of RE diffusion. Regarding the supporting actors, it is important that there is a commitment from all sectors of society. Also support from external parties is mentioned as being helpful.	P	Negro et al., 2012; Lipp, 2007; Boon and Dieperink, 2014
EC	**Funding sources**: Funding of RE development is crucial since new installations and new coherent working routines have to be financed. Funding structures are found to be quite heterogeneous, which means that projects usually rely on more than one funding source. In the UK public funding from central government departments and agencies was for instance not sufficient, which required community energy initiatives to draw on further sources of financing, such as European, local authority, charity and private sector sources.	RSA P	Bulkeley and Kern, 2006; Hecher et al. 2016, Lindner, 2013; Musall and Kuik, 2011; Rydin et al., 2012; Rydin et al., 2013; Walker, 2011
	Community Energy Initiatives (CEI) are reported to have a positive impact on RE development: The German energy transition is based considerably on such CEI. The successful involvement and establishment of CEI has benefits such as a financial return and the provision of a sense of satisfaction, as well as utilizing contextualized local knowledge which leads to sustainability benefits.	RSA P	Boon and Dieperink, 2014; Holstenkamp, 2013; Seyfang and Smith, 2007
	Positive influence on regional economy: Economic viability can be one of the reasons why a RE project or development fails, but it has also been a crucial driver for implementing RE development. In general, a positive RE development that demonstrates the benefits for the regional economy is of great value for transitions since these processes can be used to legitimize and support decision makers in upscaling RE development.	RSA	Karpenstein-Machan and Schmuck, 2007; Späth and Rohracher, 2010; Blumer et al., 2013; Walker, 2011

3. Study design and methods

In the following, we describe how we applied the literature-based driving factors in a sample of 18 regions.

3.1 Sample of regions

We sampled regions from the German 100ee-regions-network. This network has been established in 2008 in order to support regional RE initiatives and to connect those that aim to supply their region with 100% renewable energy (Institut für dezentrale Energietechnologien, 2016). The network is coordinated by the Institute decentralized Energy Technologies in Kassel (IdE) and supported by the University Kassel and the Federal Environmental Agency. It comprises 150 '100ee regions' (Institut für dezentrale Energietechnologien, 2015). 100ee regions need to fulfill a range of criteria to qualify as members of the network (Hoppenbrock and Fischer, 2012). Usually, a region first becomes a so-called starter region before becoming a full member (Buschmann et al., 2014). Both starter and full member regions were included in our sample.

To allow for a meaningful comparison, we restrict our analysis to a group of regions that share comparable contextual conditions, i.e. comparable RE potentials. According to a multivariate analysis of the socio-economic and natural contextual conditions concerning the use of RE, the selected regions can be assigned to a specific *energy context type* and are, in comparison to all German regions, characterized by rather low settlement density, medium incomes and little industry. Also, they show relatively high potentials for wind energy and bioenergy use. We include both municipalities and administrative districts in the analysis. Districts ('Landkreis') are an administrative and political subdivision between the municipal governments and federal states. They take over responsibilities from the municipalities, for example concerning road and energy infrastructure. When we do not distinguish between municipalities and districts, we use the term 'region' in this article.

Applying these selection criteria yielded 27 regions in total, which we all contacted via e-mail and phone. 18 of these provided the necessary data and were thus included in the analysis (participation rate of 67%). Short introductions to each of the 18 regions can be found in section 1 of the Supporting Information.

3.2 Data

The data collection involved a questionnaire sent out to one case expert for each of the selected regions in July 2014. Online and paper versions of the questionnaire were available. We contacted one case expert per region who, at the time of the data collection, worked in the region´s administration on a position related to climate protection measures or renewable energy use. If these positions did not exist, we contacted the mayor. We called each case expert to ensure that they had received and understood the material. The questionnaire was organized according to the clusters of driving factors (Section 2) and included questions to be answered by single choice, by multiple choice or on a five-point Likert scale, as well as single open-ended questions.

An interview with the project leader of the 100ee-regions-network completed the data collection in that he rated each of the 18 region's overall performance (telephone interview on 25 July 2014). He has been part of the project team from the beginning in 2008 and has since then contributed to the conceptual foundation and quality control of 100ee regions. He has also supported the network in giving hands-on practical advice in the regions as well as in organizing conferences and workshops. His perspective is very valuable for this study as he is familiar with all the case study regions and is able to expertly compare them from a professional distance. Questionnaire and interview were in German. English translations of all questions can be found in sections 2, 3, and 4 of the Supporting Information.

3.3 Analysis

The data was processed in two separate analyses. We used (i) Rough Set Analysis (RSA) to identify patterns in the data that indicated established successful practices. Here, we used the part of the data that could be handled in RSA without losing explanatory power. The part of the data that was too complex to be converted in rough scales was used in the (ii) performance analysis. In the latter, we compared regions with higher and lower performance. Some driving factors could be included in both, e.g. in RSA we included the number of networks a region is a member of, while in performance analysis we were specifically interested in which networks each region is a member of. Table 3.1 lists for each driving factor, how the data was analyzed. More detailed information on the driving factors can be found in the Supporting Information sections 3 and 4.

RSA Methodology

Given the high number of attributes and the relatively low number of cases in our study, standard statistical tools are not appropriate for the analyses. We chose to apply RSA, because it is an exploratory method that extracts useful information from small sample sizes and enables a structured analysis of quantitative and semi-quantitative data. RSA is a clearly structured method using few presumptions on the data, that was developed by Pawlak in the 1980s (Pawlak, 1997, 1982). According to Düntsch and Gediga (2000), RSA only reveals correlations in a basic sense. Therefore, RSA does not derive causal linkages in the data;

instead it identifies patterns of co-occurrences and thereby reveals clues about causal mechanisms that might be worth investigating. RSA bears resemblance to Qualitative Comparative Analysis (QCA), which is also a structured, but not statistical method to identifying patterns in data. However, the latter is a more theory-driven approach that seeks to test hypotheses. Whereas in QCA the number of attributes is more limited (Rihoux and Ragin, 2009), RSA allows to analyze a large number of attributes with a small sample size.

Analyses using RSA start from a decision table, containing the objects (in this case the different case study regions) as rows, and the attributes that characterize the cases as columns. We selected four decision attributes, i.e. indicators of success (Table 3.3), and 21 independent condition attributes, i.e. the driving factors identified from the literature plus two attributes that define each region's administrative status and the type of membership in the 100ee-regions-network (Table 3.2). As a preparatory step, the data needed to be discretized and converted into rough scale, which was done manually. Details for each attribute can be found in the Supporting Information, Sections 2 and 3. Depending on the nature of the attribute, we chose two to four levels. Attributes with *either/or* or *yes* and *no* options had two levels (1, 2), attributes that were measured on 5-point scale were reduced to 3 levels (1, 2, 3). Four attributes could not be answered by five case experts; we coded this as 'no answer', which led to a fourth level (0). These attributes were MIL (1 region), GOL (1 region), CEI (2 regions), and ECO (3 regions). High values indicate that this factor should be, according to the literature, beneficial for a project's success.

The decision table (Supporting Information 5a) encompassing the rough data was then analyzed using the ROSE.2 software (Predki et al., 1998). The first step called 'reduction' derives those condition attributes that are necessary to identify patterns in the data. The second step, 'rule induction', is central to this analysis and discerns patterns in the data set. The rules identify co-occurrences between condition attributes and decision attributes. They consist of one or several condition attributes which are organized in a logic string: e.g. *if* condition attribute A=x *and* condition attribute B=y *then* decision attribute P=z. Only rules that apply to four or more regions were further considered, in order to focus on practices that are established in several regions. In order to further condense the patterns, all rules that could be linked with the logical operators *and* and *or* were merged (for more detail on the merging of rules, see Supporting Information section 5b).

Definition of Attributes

The cases are described by condition attributes (Table 3.2), which relate to those driving factors marked with 'RSA' in Table 3.1. The decision attributes measure the performance of the cases related to different dimensions of success (Table 3.3). Following (Walter and Scholz, 2006), we departed from the following five success dimensions:

- Efficiency: To what extent do regional projects stay within their time and budget planning?
- Effectiveness: To what extent do regional projects reach the goals that they have set for themselves?
- Relevance: To what extent do the measures in the region contribute to supra-regional energy transition and climate protection efforts?
- Overall internal rating: How do case experts from each case estimate the success of their region?
- Overall external rating: How does the project leader from the 100ee-regions-network rate the success of each region?

After collecting the data, we excluded *effectiveness* from the analysis, since the results showed that this attribute is highly dependent on the regions' individual goals (see Table 3.3). Also, we did not consider financial resources in the attribute *efficiency*, because only three case study regions indicated that they use some kind of budgetary planning. Therefore, we changed the decision attribute to *time efficiency*.

Performance analysis

In order to get more in-depth insights into the patterns of different driving factors, we compared the characteristics of the regions with highest performance rating (HR) to the regions with lowest performance rating (LR). We identified the two groups by summing up the values of all four decision attributes. Because the performance values change gradually we split the sample in two groups of 9 regions each. For each analysis, we give the respective number of answered questionnaires. For this comparison, we analyzed those driving factors marked with 'P' in Table 3.1. We conducted the Student´s t-Test in R on this data, in order to test whether the HR and LR regions significantly differ from each other. We assumed that the values are normally distributed. We also used the T-Test on the decision attributes to test whether the regions significantly differ in the analyzed dimensions of success.

Table 3.2: Condition attributes used to assess the 18 study regions. Attribute details are given when necessary. The listed abbreviations are used in the rules. For scale questions, attribute values were converted from a 5 point scale to three levels. In case the additional option 'don´t know' (listed in the table as '?') existed, it was defined as 0.

Cluster	Attribute	details	abbr.	0	1	2	3
Planning and Process	duration of the process	in years	YEA		< 5	5-10	10-20
	comprehensive regional planning	use of integrated climate protection program	IKK		no	yes	
	energy specific planning		ESP		no	yes	
		total number of plans used	TNC		1 plan	2 plans	
	monitoring of goals		GOL	?	no	yes	
	use of milestones		MIL	?	no	yes	
	support by decision makers	timing of support	SUP		late	medium	early
Exchange and Participation	use of various information channels	heterogeneity of information channels	INF		low	medium	high
	participation and public involvement		PAR		low	medium	high
Actors and Networks	key actors	existence of key persons or actors	KEY		no key actors	either or	both
	networks	importance of informal networks	INE		low	medium	high
		importance of formal networks	FNE		low	medium	high
	actor heterogeneity	heterogeinity of actors in intraregional networks	HNR		low	medium	high
		heterogeinity of actors in expert networks	HNX		low	medium	high
Economic Circumstances	Funding sources	share of funding from public capital	PUB		low	medium	high
		share of funding from business capital	BUS		low	medium	high
		share of funding from private capital	PRI		low	medium	high
	community energy initiatives	Influence of CEIs on process	CEI	?	low	medium	high
	Influence on regional economy	influence of the use of renewable energies on regional economy	ECO	?	negative	neutral	positive
Region´s Status		membership status in 100ee network	TYP	starter region	full member		
		administrative level	ADM	district	municipality		

Table 3.3: Decision attributes to measure regions' performance. Each indicator measures a different dimension of success. Indicators use a rough 3-point scale between 1 (low success) and 3 (high success). Data is based on ratings provided by case experts for the attributes TEF, REL and OIR, and by an external expert for the attribute OER.

Attribute	Short Name	Indicator	0	1	2	3
Efficiency	TEF	Time efficiency of implementation measures in accordance with planning	no time planning	delayed	in time	faster
Relevance	REL	Contribution of regional implementation measures to supra-regional energy transition und climate protection efforts		low	medium	high
Overall internal Rating	OIR	Rating of overall success by case experts		low	medium	high
Overall external Rating	OER	Rating of overall success by project leader of 100ee network.		low	medium	high

Workshop

We discussed the advantages and disadvantages of selected driving factors in a workshop at Leuphana Energieforum (Leuphana Universität Lüneburg, 2015) in order to gain a practitioner's perspective on our findings. These insights contribute to the discussion in section 5.1.

4. Results

We first compare how the regions performed according to the four considered success dimensions. Based on these insights, we present how the driving factors appear in established practices as they are indicated by RSA and performance analysis (section 4.2).

4.1 Success dimensions

The success dimensions mostly measure significantly different aspects of the RE implementation process (Table 3.4), which also indicates that the case study regions' performance differed regarding the four dimensions of success analyzed here. The decision attribute *Relevance* was calculated from several questions concerning the region's contribution to energy transition and climate change mitigation. The case experts considered their region´s contribution to the sustainable development of their region, and to their region´s supply with heat and electricity from RE, to be very important (mean ratings ≥ 4.5 of 5). However, contributions to national and global challenges were assessed to be of minor importance (ratings between 2.6 and 3.2 of 5) (details on the rating in Supporting Information section 4).

Table 3.4: Comparison of the success dimensions analyzed here. For each decision attribute, the mean value is given. Results of the t-test are given for each pair of decision attributes. Significant results (p<0.05) are marked with an asterisk.

	mean	Overall internal rating	Overall external rating	Time efficiency
Overall Internal Rating	3,7			
Overall External Rating	2,7	t(31.32)=2.68, p=0.01*		
Time Efficiency	2,1	t(30.91)=4.40, p<0.001*	t(30.94)=1.45, p=0.16	
Relevance	1,9	t(32.23)=5.82, p<0.001*	t(27.54)=2.18, p=0.04*	t(27.37)=0.55, p=0.59

4.2 Patterns of driving factors

The data set derived from the questionnaire and fed in RSA can be found in Table 5a of the Supporting Information. The RSA step 'reduction' encompassed all attributes that we included in the analysis, because they all appeared in the rules. The RSA generated a total of 56 rules which mirror patterns of common, established practices applying to four and more regions (see section 3.3). Of these 56 rules, 16 were related to *relevance*, 18 to *time efficiency*, 13 to *overall internal rating*, and 9 to *overall external rating*. Merging of rules led to a reduced set of 29 rules (details in Supporting Information section 5b). Of these 29 rules, 22 related to high success values, eight to medium success values, and four rules to low success values (Table 3.5). Of all rules in the reduced set, only four included elements that contradict findings from the literature (rules #11, #16, #26, and #27). These unexpected findings related to the condition attributes participation (PAR), informal networks (INE), and information channels (INF).

Table 3.5: Main result of RSA: reduced rule set. Attributes linked with "AND" are displayed in the same row, attributes linked with "OR" are displayed in the row below. Rules contradicting findings in the literature are shaded gray. Rules #1 to #25 relate to high and medium success, rules #26 to #29 relate to low success.

#	IF	and/or	and/or	and/or	and/or	THEN	cases				
1	MIL = 2					Overall Internal Rating = 3	STY	HAR	ALT	GOE	
2	ESP = 1	IKK = 2	BUS = 2			Overall Internal Rating = 3	LDA	BHF	GOE	SAZ	TEF
3	ESP = 2	IKK = 1				Overall Internal Rating = 3	BAR	STY	SEK	LAU	ALT
						Efficiency = 2	BAR	STY	SEK	LAU	ALT
4	IKK = 1	TNC = 2				Overall Internal Rating = 3	STY	HAR	SEK	LAU	ALT
		INF = 2					STY	HAR	LAU	ALT	
5	TNC = 2	ADM = 0				Overall Internal Rating = 3	LDA	SEK	LAU	GOE	
6	YEA = 3	ADM = 0	PUB = 3			Overall Internal Rating = 3	GIE	SEK	LAU	GOE	
			BUS = 2				LDA	SEK	LAU	GOE	
7	GOL = 2	IKK = 1	TNC = 2			Efficiency = 2	STY	SEK	LAU	ALT	
			PRI = 2				BAR	STY	WET	SEK	LAU
8	IKK = 1	MIL = 1	PRI = 2	ADM = 0		Efficiency = 2	BAR	WET	SEK	LAU	
9	GOL = 2	MIL = 1	IKK = 1	TYP = 0	ADM = 0	Relevance = 3	WET	SEK	MIL	LAU	

10	KEY = 2						Overall Internal Rating = 3	HAR	LDA	SEK	GOE	TEF	
11	SUP = 3	PAR = 1					Overall Internal Rating = 3	HAR	LDA	LAU	TEF		
12	CEI = 3	ECO = 3					Overall Internal Rating = 3	GIE	BAR	ALT	GOE		
13	FNE = 3	TYP = 1	GOL = 2	ECO = 3			Overall Internal Rating = 3	BAR	STY	LDA	ALT		
14	HNX = 3	FNE = 3	IKK = 1				Efficiency = 2	BAR	STY	WET	SEK	LAU	ALT
		PRI = 2					Relevance = 3	STY	WET	SEK	LAU		
15	FNE = 2	YEA = 3	ECO = 3	PRI = 2			Efficiency = 2	SEK	LAU	GOE	WEM		
16	INF = 1						Relevance = 3	LDA	WET	SEK	MIL		
17	IKK = 1	ECO = 3					Efficiency = 2	BAR	STY	WET	SEK	LAU	ALT
		PUB = 3						WET	SEK	LAU	ALT		
18	IKK = 1	BUS = 2					Relevance = 3	STY	WET	SEK	MIL	LAU	
		PAR = 2	PRI = 2				Efficiency = 2	BAR	STY	WET	SEK	LAU	
19	BUS = 2	PRI = 2	TYP = 1				Efficiency = 2	WET	SEK	LAU	GOE		
			ADM = 0				Overall External Rating = 2	STY	GOS	BHF	GOE		
20	ECO = 3	PAR = 2	FNE = 2				Efficiency = 2	BAR	STY	WET	SAZ		
21	PUB = 3	ECO = 3	PRI = 2	ADM = 0			Efficiency = 2	WET	SEK	LAU	GOE	SAZ	
	BUS = 2			TYP = 0			Relevance = 3	GIE	WET	SEK	LAU		
22	PUB = 3	ECO = 3	PRI = 2	HNX = 3	MIL = 1	ADM = 0	Relevance = 3	GIE	WET	SEK	LAU		
23	FNE = 1						Overall External Rating = 2	GIE	HAR	GOS	BHF		
24	INE = 3	YEA = 2					Overall External Rating = 2	HAR	WET	BHF	SAZ		
25	PAR = 2	BUS = 2	MIL = 1	INE = 3			Overall External Rating = 2	WET	GOS	BHF	SAZ		
				ADM = 1				STY	GOS	BHF	SAZ		
26	INE = 3	CEI = 1	PRI = 2				Relevance = 1	HAR	OTT	BUS	WEM		
		INF = 2						HAR	OTT	WEM	GOS		
27	INE = 3	PRI = 2	BUS = 1	ESP = 1			Relevance = 1	HAR	OTT	BUS	WEM		
28	FNE = 2	MIL = 1	TYP = 0				Overall external Rating = 1	SEK	MIL	LAU	WEM		
29	CEI = 1	ADM = 0					Overall external Rating = 1	SEK	MIL	TEF	WEM		

Planning and process

All case study regions use structured planning processes. In the RSA patterns, the attributes from the cluster *planning and process* mostly related to the success dimensions *overall internal rating* or *time efficiency* (e.g. rules #1-8). Using an icpp (integrated climate protection program) appears in rule #2 related to *high overall internal rating*. Ten of eighteen case study regions do not use an icpp, which is in the patterns either related to being in time (TEF=2), to *high overall internal rating* or to *high relevance*. Although only four regions use milestones in their implementation process, this appears as a rule (rule #1), because all of these four regions have a high overall internal rating. Monitoring whether and how regions meet their goals appeared in patterns related to high *relevance* (rule #9), *overall internal rating* (rule #13), and e*fficiency* (rule #7). The case experts seemed to consider the above mentioned aspects to be beneficial to the process, while they perceived changing political priorities, delays due to slow administrative processes, and changing regulations and laws as main challenges regarding RE implementation (Fig.3.1).

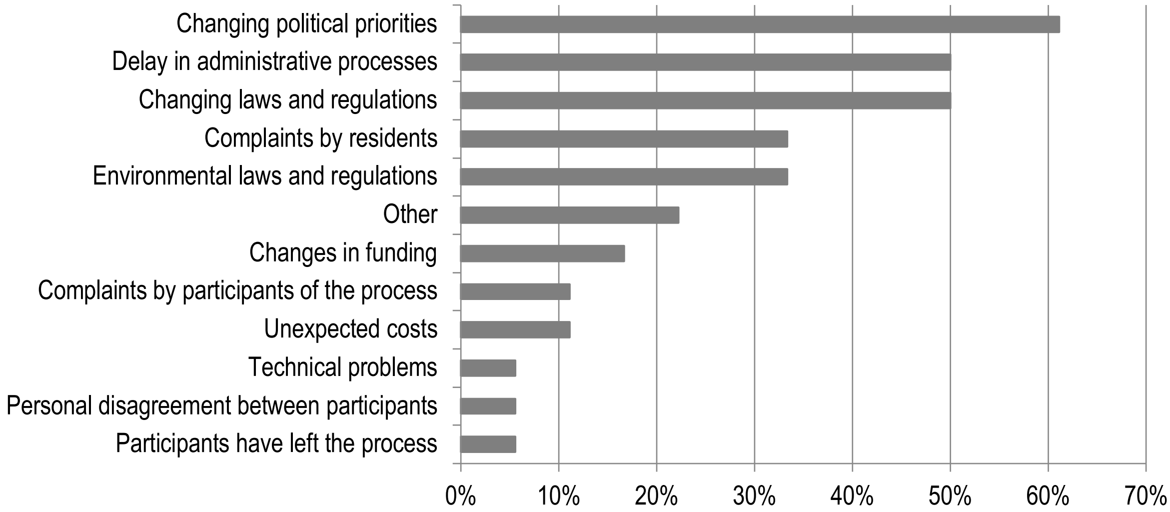

Figure 3.1: Perceived challenges during the implementation of RE in study regions. Data was provided by 11 of 18 case experts (n=11). Multiple answers were possible.

Exchange and participation

Knowledge exchange with experts from different sectors of society co-occurred (along with other condition attributes) with high *relevance* and high *efficiency* in rules #14 and #22 (7 of 18 regions). In the knowledge exchange with experts, high-ranked regions (HR) were generally more active than low-ranked regions (LR), differing significantly in the knowledge exchange with experts from politics (Table 3.6). HR regions were also in significantly stronger exchange with colleagues from the administration of other regions than LR regions (Table 3.6). The extent to which a topic is discussed varies between HR and LR regions (Fig. 3.2), especially funding is more discussed with experts and with other regions in HR regions (56% and 11%, respectively).

Actors and networks

Formal networks appear as a strong driving factor in the study regions, e.g. in rule #13, those regions in which formal networks are of great importance also monitor how they approach their goals, and the use of RE is perceived to positively influence the regional economy. This related to *high overall internal rating*. HR regions belong to at least one formal network, whereas only 5 out of 9 LR regions belong to a formal network besides the 100ee-regions-network. The LEADER network was often mentioned by case experts concerning HR regions

(7 out of 9) and only once in the LR regions. LEADER is an EU aid program, which supports development in rural areas.

Table 3.6: Knowledge exchange with experts and other (100ee) regions for regions with high performance rating (HR) and low performance rating (LR) each. Data was provided by all 18 regions. Mean value (mean), standard deviation (sd), t-test, and the corresponding p-value are given. Significant results (<0.5) are marked with an asterisk.

area	experts						other (100ee) regions					
	HR regions (n=9)		LR regions (n=9)				HR regions (n=8)		LR regions (n=9)			
	mean	sd	mean	sd	t-test	p-value	mean	sd	mean	sd	t-test	p-value
Politics	3,1	1,3	2,4	1,5	t(6) =7.55	0.0003*	5,0		2,6	1,2	t(11.82) =0.9	0,39
Administration	4,4	1,0	3,3	1,0	t(10.17) =1.85	0,09	4,3	0,8	3,2	1,3	t(13.99) =2.15	0.05*
Economics	3,6	1,0	3,0	1,0	t(8.5) =0.76	0,47	3,3	1,4	2,7	1,3	t(10.72) =1.07	0,31
Science	3,8	1,0	3,5	1,8	t(7.63) =0.75	0,47	3,3	1,3	2,9	1,6	t(7.06) =0.28	0,79
NGOs	3,4	1,1	2,8	1,3	t(7.47) =1.01	0,35	3,1	1,1	3,0	1,4	t(9.46) =0.74	0,48
Civil society	2,8	0,7	2,5	1,3	t(8.55) =-0.82	0,44	2,9	1,1	3,4	0,9	t(6.97) =0.41	0,7

In five regions, the presence of a key person or actor co-occurred with high *overall internal rating* (rule #10). 88% of the regions regarded a specific individual or multiple key persons to be of major importance for the implementation process, while 78% perceive single or multiple key actor(s) (political parties, companies, institutions, etc.) as important. The case experts (n=12) named expert knowledge (83%), environmental consciousness (80%), and networking skills (76%), as the three most important characteristics of key actors.

The case experts in both HR and LR regions perceived supporters as having higher levels of influence on the process than opponents have, except for civil society in HR regions. The case experts also indicated that they do not face resistance but have to cope with civil society's lack of knowledge of and interest in RE, which can adversely affect the implementation process.

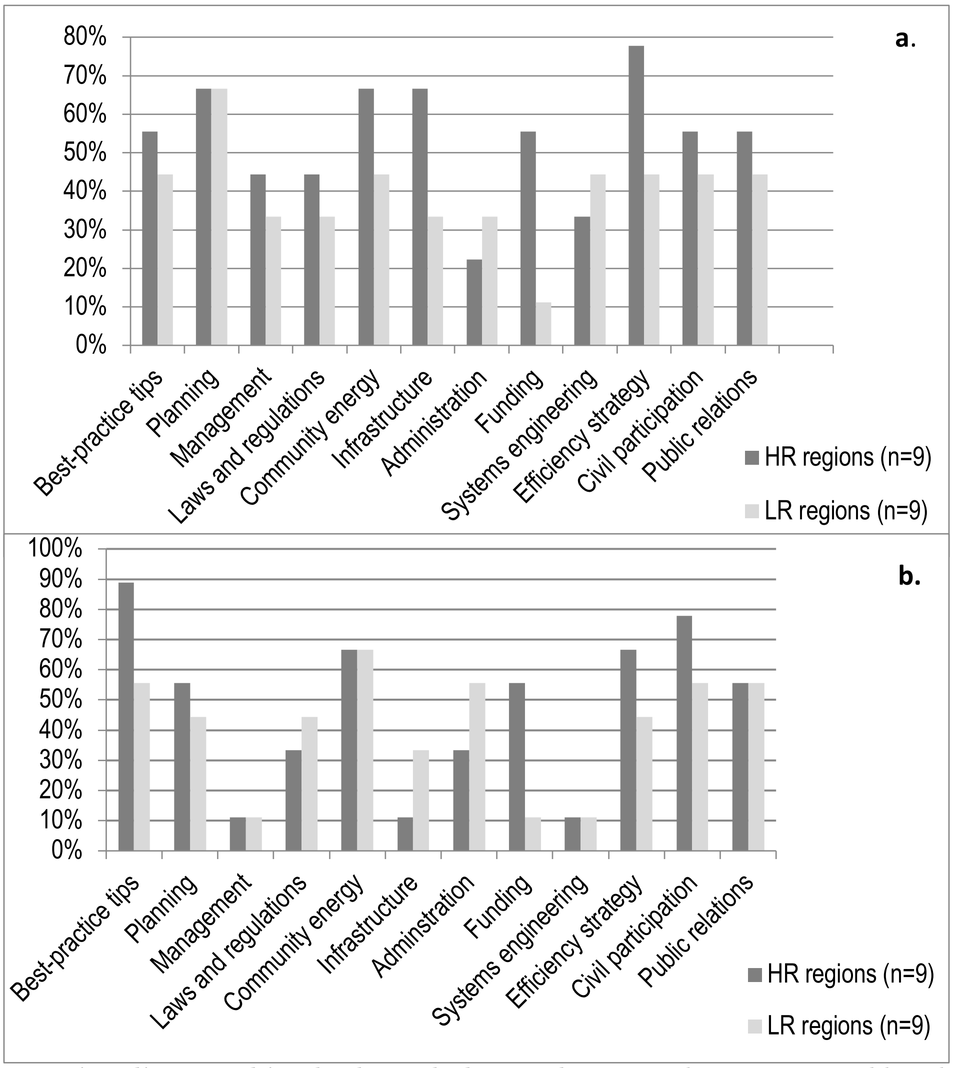

Figure 3.2: Topics discussed in the knowledge exchange with a. experts and b. other (100ee) regions on the regional implementation of RE. The importance of the topics is given as percentage of regions in which a topic is discussed intensively. Data was provided by all 18 regions.

Economic circumstances

In 12 out of 18 case study regions, experts stated that the implementation of RE had a positive effect on the regional economy. Attributes of the cluster *economic circumstances* occurred rather often in the rules and were always combined with other factors. For example, a *positive economic impact* (ECO=3) occurred, inter alia, with high *importance of CEIs* (community energy initiatives), high and medium *importance of formal networks,* or high *heterogeneity of expert network*. One or more funding sources often co-occurred with a positive regional impact on the economy (rules #15, #17, #21, #22). National or EU- programs are indicated as a main funding source in eight regions, while business and private sources are indicated as main funding source in one region each (see Supporting Information 5a). The availability of a wide range of different funding sources seems to contribute to the successful implementation of RE (see Supporting Information 5a, rules #6, #19, #21 and #22). HR regions generally state to have higher funding than LR regions.

Case experts of 12 regions listed a total of 34 CEIs that differ considerably in terms of their focus on technology, goals, or activities. Where CEIs are strong, the implementation of RE is perceived to have a positive impact on the regional economy (ECO=3), co-occurring with *high overall internal rating* (rule #12). Where CEIs have a minor influence on the implementation process (rules #26 and #29), this co-occurs with *low relevance* or with *low overall external rating*.

5. Discussion

In interpreting the findings, we first elaborate on the most promising practices found in the 18 study regions. Then we shortly touch upon the driving factors that did not appear corresponding to the literature and discuss the strengths and limitations of this study in the last section.

5.1 Insights on governance-related driving factors

Many patterns related to high performance are composed of driving factors from more than field of activities in which regional actors might engage. This indicates that being engaged in all four fields of activities – *planning and process*, *information exchange and participation*, *actors and networks,* and *economic circumstances* –might have supported the complex process of implementing RE or helped create a dynamic transition process in the study regions.

From the results we can deduce that three practices were especially relevant for a successful implementation of RE in the studied regions: a well-structured regional planning, engagement in formal networks, and diverse funding structures. In the following, we elaborate on each.

The results of the survey suggest that well planned and structured processes have a high chance to lead to success. They indicate that specifically formulated goals allow to monitor and assess the RE implementation process, which confirms Lipp's findings on RE process management (2007). The use of clearly defined milestones, as discussed by Blumer et al.(2013), might lead to a higher satisfaction with the process. These project management tools seem to help the case experts oversee and be in charge of the implementation of RE. Most likely for this reason, the case experts tended to rate the respective processes positively. Setting up a comprehensive climate protection plan such as an icpp can be a rather lengthy process, this is indirectly indicated by several appearances of '*No icpp'* with being *in time* (rules #3, 4, 7, 8, 9, 14, 17, 18). It seems that study regions with a strong interest in energy tend to use specific planning, whereas study regions with an interest in a more comprehensive regional development or with enough financial resources employ an icpp.

Our findings further suggest that an intensive cooperation with formal networks can potentially be a strong driver for RE development (e.g. rule #13, results of performance analysis). It seems that, as most HR regions belong to this network, LEADER has a positive influence on the case study regions and might fulfil several aspects that Fürst and Schubert attribute to actor networks (1998). As rule #14 suggests, formal networks offer the opportunity for an intensive knowledge exchange. An intensive knowledge exchange between actors of different regions and with experts also seems to drive regional RE implementation (see Tab. 3.6, Fig. 3.2). This might be due to the high complexity of processes relating to RE development, which necessitates learning and the exchange of experience (see also, e.g., Walker and Cass, 2007).

The findings indicate that the implementation is perceived to positively influence the regional economy in most study regions. This seems to be related to a diverse funding structure, which encompasses public sources such as the LEADER program, investments of regional businesses, and contributions of private households. We know from case studies in the UK that local and regional RE implementation necessitates a wide range of heterogeneous funds (see, e.g., Walker, 2011). Current research identified German decentral banking structures to be very helpful for investments in regional RE projects, and found that 'there was a substantially deeper appreciation of renewable energies as constitutive of citizen empowerment and regional economic development amongst our German respondents' in comparison to the British respondents' (Hall et al., 2016, p. 10). This might relate to our finding that CEIs appeared to be a driver for RE implementation, at least when they were in the position to influence the process.

Insights on the scope of regional RE activities

In addition to the insights on driving factors mentioned above, some findings are worth discussing. As the RSA results suggest, districts share more patterns than municipalities. This might indicate that districts share common practices, whereas municipalities are more likely to differ in their activities. This finding is further supported by the statement of a case expert from one of the study regions, who mentioned that there are few opportunities for making decisions on the district level, whereas municipalities have greater freedom when it comes to taking actions. Taken together, these findings suggest that municipalities and districts need different approaches for successfully implementing RE. Our findings further indicate that the main challenges concerning regional RE implementation (see fig 3.1) are beyond the local and regional scope and that actors and regional governments have limited influence on these levels.

This might also mean that the main challenges are to be found in the political and administrative spheres of the higher levels. The latter one is in line with findings stating that consistent legal and policy conditions are an important aspect for the development of RE (Boon and Dieperink, 2014; Negro et al., 2012).

5.2 Insights on inconsistencies with the literature

The results related to the driving factors *public participation* and *informal networks* did not correspond to the literature. To better understand these findings, we discussed the advantages and disadvantages of these factors in a workshop with practitioners who have a professional interest in topics related to regional RE use and implementation. In general, the workshop participants regarded public participation as crucial but identified several related challenges: Most administrations lack the knowledge to implement and coordinate an early participation process. As a result, citizens may only begin to show signs of opposition when changes become visible. Also, participatory processes may raise public awareness of future changes, which might possibly lead to conflicts and time-consuming processes. In the light of these experiences, the pattern of rule #11 might mirror processes in which administration and decision makers collaborated and pushed the respective project without including the public intensively. This may internally be rated as successful as long as the public accepts these changes. During the workshop, informal networks were described to be based on friendship and sympathy instead of knowledge and 'quality'. This can have advantages especially at the beginning of a regional implementation of RE but can also lead to a shortfall of competences or professionalism (true or anticipated). This experienced shortfall of competences seems to fit to our finding that informal networks are related to low relevance (rules #26, 27), as this decision attribute measures the contribution of the regional activities to supra-regional energy transition and climate protection efforts.

5.3 Strengths and limitations of this study

Due to the high response rate and high quality of the data, we were able to identify a set of patterns suggesting a wide range of established practices concerning the regional implementation of RE. RSA proved to be an adequate choice for the analysis of a dataset characterized by a relatively low number of cases, but a high number of decision and condition variables. In this study, we focused on rules observed in at least four regions, and by doing so, we disregarded rules that would only be observed in less than four regions. In other words, there might be other potentially relevant practices, but these are not identified here. In the following, we touch on three specific challenges we met using RSA. First, even though five case experts did not provide data for 1 or 2 attributes, we included these regions in the analysis and coded 'no answer' with a '0'. This can be regarded as being problematic as it suggests that the regions that provided no information are similar with regard to this attribute. In the analysis presented here, a complete data set would of course have been preferable, but the gaps in the data had no major consequences on the results. Because no attribute had four or more regions coded '0', these regions were not considered in the main element of the RSA, the rules. Second, the success dimension *time efficiency* was rated in light of each region's own time planning. Regions that had plenty of time and were thus able to reach their targets were rated positively. Regions that implemented more ambitious plans but failed to reach their deadlines were assessed negatively. This was done because the regions aim to realize very different projects, which makes it very difficult to assess the time efficiency objectively. This could be complemented with additional empirical data in a follow-up study, which might also include the aspect of financial resources. Third, it would also have been possible to use the condition attribute *Influence on regional economy* (ECO) as decision attribute. We decided to use the theoretical and empirical insights of Walter and Scholz (2006), in order to enable comparability with other studies. If we had used ECO as additional decision attribute, it is likely that the resulting patterns would have been different. Additionally, an influence on the economy is an indirect measure of the implementation and use of RE.

The comparison between HR and LR regions supported the results generated with RSA, as it allowed another perspective on the RSA patterns and thereby contributed to a better understanding. While it might be an unusual choice due of the small sample size, the T-Test nonetheless allowed us to identify those attributes in which the data set significantly differed. In general, this analysis was able to identify several aspects which seem promising to follow up with other methods or from other perspectives. This analysis is based on a survey of experts; in a follow-up study, the assessments of these experts could be complemented with additional empirical data on the implementation of RE.

6. Conclusion and Policy Implications

This paper presents an analysis of the implementation processes of renewable energy in 18 regions using a literature-based framework that integrates the insights of different fields of study. In general, most of our findings on established practices concerning the implementation of RE confirmed the driving factors identified in the literature. Our findings also indicate, however, that the factors *public participation, heterogeneity of information channels* and *informal networks* are not only less important than discussed in the literature, but also potentially limiting. Additionally, our results suggest that highly successful and less successful regions differ in regard to the presence or absence of specific driving factors.

Three implications for governance of energy transitions on a regional scale can be derived from our analysis: First, comprehensive and well-structured processes can contribute considerably to managing such a multi-faceted endeavor and to a successful implementation of RE in local and regional contexts. Although a comprehensive approach such as the integrated climate protection program (icpp) may require longer planning phases, regions using these approaches seem to be more aware of and, more importantly, to be better prepared to deal with, for example, national climate change mitigation policies. To succeed, regions need to pay attention to process management, as carefully choosing milestones, for example, seems to lead to greater efficiency.

Second, a strong engagement in formal networks can be very beneficial for the RE implementation process, especially when the networks offer intensive exchange of expertise. These drivers seem to contribute to successfully cope with the various and complex challenges related to RE implementation. For the regions studied here, it seems that the exchange with regard to funding was very helpful.

Third, a strategy combining funding from different sources seems to be beneficial. Regions with funds from different sources including, among others, community energy initiatives and public funding seem to experience a positive influence on the regional economy from the use of renewable energy.

Our results indicate that municipalities differ considerably in their activities concerning the implementation of RE, whereas districts share common practices. We believe that these types of administrative units need different approaches. Moreover, it might be possible to consider that districts, seeing that they share many patterns of activities, draw on generic strategies for the implementation of RE. This would allow an efficient strategy development for the use and implementation of RE for many German districts.

Identifying and combining the different driving factors in the context of the German energy transition made it possible for us to present common patterns for the regional implementation of RE. We hope to contribute to the research fields of transitions and regional governance with this comprehensive and multi-facetted approach and to give some guidance to practitioners involved in the regional planning and implementation of RE. In order to better understand the RE implementation process, future studies might address comparisons between regional administrative perspectives such as the one in this analysis with other regional perspectives e.g. of businesses or citizens, or with those at supra-regional levels.

SUPPORTING INFORMATION

1. Case study regions

The following short descriptions of all case study regions are headed with their respective abbreviation and include references for more detailed information (last date accessed: 6.4.2016). All case study regions are included on the map of the 100ee-regions-network (Institut für dezentrale Energietechnologien, 2015).

ALT: The 100ee-region Aller-Leine-Tal is a cooperation of eight rural municipalities with a total of 75.000 inhabitants. The region has a long tradition of bottom-up processes for the implementation of RE and won the German Solar award in 2007. The region aims at generating considerably more RE electricity than it needs for itself in order to be able to supply the neighboring town Celle.

http://www.alt-energieprojekt.haeuslingen.de
http://www.kommunal-erneuerbar.de/de/energie-kommunen/energie-kommunen/aller-leine-tal.html

BHF: Bad Hersfeld (fm) is a full member region and a municipality with approximately 29.000 inhabitants. It is also one of the few cities which is a member in the project 100ee-regions and since November 2014 it is also one of the first acknowledged European RE region. It provides a broad spectrum of advice and services concerning RE for its inhabitants such as providing information on energy savings. The region has also established an energy cooperation.

http://www.klimabuendnis.org/badhersfeld.0.html?&L=1
http://www.e-punkt-hersfeld.de
http://www.beh-eg.de
http://www.100-res-communities.eu/communities2

BAR: Barnim is a district and full member region in the 100ee network. The region follows a zero-emissions-strategy and therefore not only concentrates on electricity generation, but also on heat and mobility. For example, a car sharing system with e-cars and service stations for e-cars and e-bikes are in use. Also, education projects for kindergartens and schools are running.

http://www.erneuerbar.barnim.de
http://www.kommunal-erneuerbar.de/de/energie-kommunen/energie-kommunen/barnim.html

BUS: The municipality Buseck is a starter region. In 2008, the municipality decided to become the first climate neutral community in the administrative district of Gießen. Original plans foresaw building a local energy park on the former military area which has shown to be difficult.

http://www.buseck.de/~FILES/DOC/KlimaschutzkonzeptBuseck.pdf
http://www.giessener-anzeiger.de/lokales/kreis-giessen/hungen/klimaschutz-konzept-soll-als-fahrplan-dienen_14104808.htm

GIE: The 100ee starter region and district Gießen developed an integrated climate protection program. The need for energy efficiency, especially in the case of heating of private homes, but also public and commercial buildings, is emphasized. Gießen started a citizen dialogue and launched a yearly 'energy day' with workshops and discussion concerning regional energy topics.

http://www.region-giessen.de/fileadmin/grafiken_content/Aktuelles/neues_2014/endbericht-klischu-NEU.pdf
http://www.region-giessen.de/index.php?id=145

GOS: The municipality Goßlar is a full member of the 100ee-regions network. At the agency for energy resources (era) a variety of actors from administration and business convenes and provides advice for its citizens and businesses, but also for other municipalities. Goslar also participated in a research project on smart micro grids.

http://www.era-goslar.de
http://www.goslar.de/stadt-und-buerger/wohnen-bauen-energie/energie-klima/320-goslar-mit-energie-e-v
http://smig2013.de/index.php?id=357

GOE: The full member region Goettingen is a district encompassing the city of Goettingen and its rural hinterland. Together with Georg-August University Goettingen and Stadtwerke Goettingen AG (regional energy supplier) the city Göttingen is part of the project 'Masterplan 100% Climate Protection'. Main topics are urban development, sustainable mobility, heating, and wind energy use.

file://localhost/Integrated climate protection programme Goettingen/
http://www.landkreisgoettingen.de:staticsite:staticsite.php%3Fmenuid=498&topmenu=442
http://www.goettingen.de/staticsite/staticsite.php?menuid=1623&topmenu=1206

HAR: The municipality Hardegsen is a starter region with 8000 inhabitants. It is rich in forests and concentrates on energy generation from wood.

http://www.bioenergie.de/index.php?option=com_content&view=article&id=1002:stadt-hardegsen-ist-sieger-der-bioenergie-bundesliga&catid=14:branchennews&Itemid=26
http://www.stadt-und-werk.de/meldung_14854_Tabellenführer+bei+Bioenergie.html

LAU: The district and starter region Lausitz is part of the regional "Planungsgemeinschaft" Lausitz-Spreewald. This region faces severe population losses. Potentials for regional development and, closely related, potentials for RE are the areas of former brown coal mining. The regional activities are linked to the energy strategy of its federal state Brandenburg.

http://www.region-lausitz-spreewald.de/rp/de/planungsregion/portrait-der-region.html
http://www.region-lausitz-spreewald.de/klimzug/de/teil/projektbeschreibung.html
http://www.region-lausitz-spreewald.de/re/

LDA: Lüchow Dannenberg is the administrative district with the lowest population density in Germany. It is a full member region of the 100ee network. Due to the intermediate storage of nuclear waste in Gorleben, it has been a focal point in German energy politics for decades. Already in 1997 the district´s goal was to provide 100% of its energy consumption by renewables which has been realized in the following years with a multitude of projects. The district produces more electricity by RE than it can consume on its own and provides biogas for auto mobility. The region also co-developed and hosts an academy for professional education and training for RE-related professions.

http://www.bioenergie-wendland-elbetal.de/bioenergie-region.html
http://www.akademie-ee.de
http://www.luechow-dannenberg.de/desktopdefault.aspx/tabid-5529/10281_read-22966/

MIL: Minden-Lübbecke has several activities for climate protection such as the implementation of a bioenergy plant to heat public buildings and schools. Additionally, several buildings have been refurbished. Citizens, as well as regional companies, are eligible for energy consulting. The administrative district also established a climate and energy program which encompasses all measures.

http://www.minden-luebbecke.de/Service/Umwelt/Klima-und-Energie/index.php?La=1&NavID=1891.106&object=tx|1891.2138.1&kat=&kuo=1&sub=0

OTT: Ottersberg is a rural municipality with 12.000 inhabitants. The full member region cooperates closely with its local energy provider when it comes to questions of RE use and supply. The local government provides advice concerning energy efficiency and RE for private homes.

http://www.flecken-ottersberg.de/?Energieberatung
https://www.ewerk-ottersberg.de

SAZ: Salzhemmendorf is a municipality with 9.337 inhabitants. In 2008 it became member of the European climate alliance thus committing to reduce CO2 emissions by 10% every 5 years. It is also a founder member of the climate protection agency of the Weserbergland and has received a considerable amount of private investments in renewable energies in recent years.

http://www.salzhemmendorf.de/burgerservice/klimaschutz/

SEK: The starter region Schwalm-Eder-Kreis focuses on activities such as education programs and the refurbishment of public buildings. The administrative district is part of the bioenergy regions network.

http://www.klimaschutz-schwalm-eder.de/index.php?option=com_content&view=featured&Itemid=99
http://www.bioregio-holz-knuell.de/navigation/bioenergie-region.html

STY: The municipality Steyerberg is a full member of the 100ee network. The region is active in e-mobility fueled by solar and wind energy. Besides, there are initiatives concerning district heating systems based on different RE sources and tourism.

http://www.steyerberg100ee.info
https://www.lk-nienburg.de/portal/meldungen/tag-der-energie-entdeckerroute-am-20-5-in-steyerberg-1002361-21500.html?rubrik=1
http://www.steyerberg.de/portal/meldungen/gelungene-tagung-als-einstieg-ins-jubilaeumsjahr-des-bundesverbandes-solare-mobilitaet-e-v-bsm-25-geburtstagsfeier-im-lebensgarten-steyerberg--912001117-21600.html?rubrik=12000009

TEF: Teltow-Fläming is a starter region and an administrative district with about 160.000 inhabitants. Economically it is one of the most successful regions in Eastern Germany with a leading position in biotechnology, vehicle manufacturing and aerospace. Teltow-Fläming is a starter region in the 100ee-regions-network. Activities mainly address energetic refurbishment and efficiency measures for public and private buildings. The village Feldheim is self-sufficient in its electricity supply.

http://www.teltow-flaeming.de/de/landkreis/umwelt/klimaschutz.php
http://www.teltow-flaeming.de/de/aktuelles/2014/04/hauswende.php
http://www.teltow-flaeming.de/de/aktuelles/2013/08/energie-effizienz.php
http://www.maz-online.de/Brandenburg/Autark-in-der-Mark

WEM: The Werra-Meißner-Kreis is a starter region. The administrative district encompasses mainly rural areas defined by forestry and agriculture, thus many of its RE activities relate to the use of biomass. The region hosts two community energy initiatives dealing mainly with biomass and energetic refurbishment respectively.

http://www.werra-meissner-kreis.de/nc/fachbereiche-und-einrichtungen/fb-7-bauen-umwelt-und-gebaeudemanagement/75-abfallwirtschaft-und-erneuerbare-energien/erneuerbare-energien-energieberatung-klimaschutz/
http://www.deenet.org/nordhessen/regionale-partner/werra-meissner-kreis/portrait/
http://www.buergerenergie-wm.de/index.php/aktuelles/informationen/147-mehr-als-klimafreundlich-das-klimaschutzkonzept-des-werra-meissner-kreises

WET: Wetterau is a starter region and an administrative district in the Frankfurt Rhine-Main Metropolitan area. Its activities concentrate on education projects in cooperation with schools, and on energetic refurbishment of public buildings. Besides, the district cooperates closely with the local governments of its municipalities.

http://klimaschutz.wetterau.de/klimaschutz/?no_cache=1
http://klimaschutz.wetterau.de/fileadmin/klimaschutz/PDF/20121019_KLIMASCHUTZKONZEPT_Endfassung.pdf

2. Decision Attributes: Question, Scale and transformation to Rough Scale

Attribute short name	Attribute	Question	Scale	Transformation to Rough Scale	Respondent
OER	Overall External Rating	Please rate the success of each region with regard to the use of renewable energy.	5-point interval scale (1=very low, 5= very high)	1: rating 1 and 2 2: rating 3 3: rating 4 and 4	external expert
OIR	Overall Internal Rating	Please rate spontaneously how successful your region is with regard to the use of renewable energyö	5-point interval scale (1=very low, 5= very high)	1: rating 1 and 2 2: rating 3 3: rating 4 and 5	1 case expert per region
TEF	Time Efficiency	What is the region´s progress with regards to the time planning?	single choice with the following items: delayed, in time, faster than anticipated, no time planning	0: no time planning 1: delayed 2: in time 3: faster	1 case expert per region
REL	Relevance	1. In your opinion, how importnat are the following challenges? 2. With regard to all existing and planned renewable energy projects in your region, how big is the contribution of your region to the following challenges?	5-point interval scale (1=very low, 5= very high) for each of the follwing items: My region´s supply with electricity from renewable energy; My region´s supply with heat from renewable energy; My region´s supply with fuel from renewable energy; Sustainable development of my region; Our region as example for others; 100% renewable electricity for Germany; Reduce Germany´s Green House Gas emmissions; Reach the 2 degrees goal	Total project contribution / total challenges 1: below 0,75 2: 0,75 - 0,85 3: above 0,85	1 case expert per region

3. Driving Factors as Condition Attributes: Question, Scale and Transformation to Rough Scale

Attribute short name	Attribute	Question	Scale	Transformation to Rough Scale	Respondent
ESP, IKK, TNC	energy specific planning; integrated climate protection concept; total number of concepts	Which strategies does your region use for the use of renewable energy?	multiple choice with the following options: specific energy concept; integrated climate protection concept; part of integrated climate protection concept; no strategy; others. open ended response for "others"	ESP: 0=no; 1=yes IKK: 0=no; 1=yes TNC: 0= 0 concepts used; 1= 1 concept used; 2= 2 concepts used	1 case expert per region
YEA	years in the process	How long has the process to use renewable energy in your region been running?	single choice with the following items: less than 2 years; 2 to 5 years; 5 to 10 years; 10 to 20 years; longer than 20 years	1= less than 5 2= 5 to 10 years 3= 10-20 years	1 case expert per region
GOL	monitoring of goals	Are the goals being checked for achievement?	single choice with the following items: yes, no, don´t know	0= don't know 1= no 2= yes	1 case expert per region
MIL	milestones exist	Does the planning include clearly formulated milestones?	single choice with the following items: yes, no, don´t know	0= don't know 1= no 2= yes	1 case expert per region
HNR	Heterogeneity of intraregional network F1	How intensely does your region exchange on topics related to the use of renewable energy with persons and organizations from other regions?	5-point interval scale (1=not at all, 5= very intensely) for each of the following items: politics, administration, business, science, NGOs, civil society, others. open ended response for "others"	1= 1 to 3 ratings of 3 and higher 2= 4 ratings of 3 and higher 3= 5 to 7 ratings of 3 and higher	1 case expert per region
HNX	Heterogeneity of expert network F2	How intensely does your region interact with experts to foster the use of renewable energy?	5-point interval scale (1=not at all, 5= very intensely) for each of the following items: politics, administration, business, science, NGOs, civil society, others. open ended response for "others"	1= 1 to 3 ratings of 3 and higher 2= 4 ratings of 3 and higher 3= 5 to 7 ratings of 3 and higher	1 case expert per region
INF	Heterogeneity of information channels	How does your region inform the public on planned and current activities related to the use of renewable energy?	multiple choice with the following items: regional newspaper, municipal informations, information event, broschures, web site, newsletter, radio, notice board, not at all, others. open ended response for "others"	1= 0 to 2 channels 2= 3 to 5 channels 3= 6 and more channels	1 case expert per region
PAR	Civil Participation	Please rate how intensely the public is engaged in decisions concerning the public use of renewable energy.	5-point interval scale (1=not at all, 5= very intensely)	1=ratings 1 and 2 2= rating 3 3= ratings 4 and 5	1 case expert per region

KEY	Key Actors	Are there single or multiple key persons which have supported the development of the use of renewable energies in your region?Are there key organizations (parties, companies, institutions) which supported the development of the use of renewable energies in the region?	single choice with the following items: Yes, No, Don't know; each question was followed up on with an open ended response	1= no key actors 2= either person or actor 3= key actor and person	1 case expert per region
SUP	Support by decision makers	At which time in the process have the regional decision makers communicated their support for the use of renewable?	single choice with the following items: initiated the topic, from the beginning, after first success, after big success, not yet	1= not yet/after big success 2= after first success 3= from the beginning / initiated the process	1 case expert per region
INE	Importance of Informal Networks	How strongly did informal networks influence the process to use renewable energy in your region?	5-point interval scale (1=very weak, 5= very strong)	1= ratings 1 and 2 2= rating 3 3= ratings 4 and 3	1 case expert per region
FNE	Importance of Formal Networks		5-point interval scale (1=very weak, 5= very strong)	1= ratings 1 and 2 2= rating 3 3= ratings 4 and 4	1 case expert per region
CEI	Influence of Community Energy Initiatives on process	How strongly do community energy initiatives foster the use of renewable energy in your region?	5-point interval scale (1=not at all, 5= very strongly), alternative single choice: no CEIs in the region / don´t know	0= don´t know 1= rating 1 and 2 2= rating 3 3= rating 4 and 5	1 case expert per region
ECO	Economic Influence	How does the use of renewable energy in your region influence the regional economy?	5-point interval scale (1=very negative, 5= very positive), alternative single choice: none / don´t know	0= dont know 1= ratings 1 and 2 2= rating 3 3= ratings 4 and 5	1 case expert per region
PUB	Degree of funding from public capital	Please estimate how strongly the use of renewable energy is financed from the following sources.	5-point interval scale (1=not at all, 5= mostly) for each of the following items: federal or EU support programmes; regional funds, Community Energy Initiatives; local and regional business; supraregional business; private households; others	added rating of "federal or EU support" and" regional funds" 1= 4 and below 2= 5 to 7 3= 8 and higher	1 case expert per region
BUS	Degree of funding from business capital	Please estimate how strongly the use of renewable energy is financed from the following sources.	5-point interval scale (1=not at all, 5= mostly) for each of the following items: federal or EU support programmes; regional funds, Community Energy Initiatives; local and regional business; supraregional business; private households; others	added rating of "local and regional business" and "supraregional business" 1= 4 and below 2= 5 to 7 3= 8 and higher	1 case expert per region

PRI	Degree of funding from private capital	Please estimate how strongly the use of renewable energy is financed from the following sources.	5-point interval scale (1=not at all, 5= mostly) for each of the following items: federal or EU support programmes; regional funds, Community Energy Initiatives; local and regional business; supraregional business; private households; others	added rating of "Comunity Energy Initiatives" and "private households" 1= 4 and below 2= 5 to 7 3= 8 and higher	1 case expert per region
TYP	Region type	Identification of region		0= starter region 1= 100%region	1 case expert per region
ADM	Administrative level	Identification of region		0= district 1= municipality	1 case expert per region

4. Driving Factors in Performance Analysis: Question, Scale and Analysis

Driving factor		**Question**	**Scale**	**Transfer/Method**	**Respondent**
Consistent legal and policy conditions	Main challenges during the process	Which challenges and problems did appear during the process?	Single choice with the following items: Changing political priorities; Delay in administrative processes; Changing laws and regulations; Complaints by residents; Environmental laws and regulations; Changes in funding; Complaints by participants of the process; Unexpected costs; Technical problems; Personal disagreement between participants; Participants have left the process; Other	1= identified as a challenge 0 = not identified as a challenge each item was summed up over all regions and divided by the maximally possible sum to obtain relative values	1 case expert per region
Knowledge exchange with experts	Intensity of expert knowledge exchange	How intensely does your region interact with experts to foster the use of renewable energy?	5-point interval scale (1=not at all, 5= very strong) for each of the following items: Politics; Administration; Economics; Science; NGOs; Civil society; Other	Average over all regions by item. Due to an extremely low n for the item "Other" we have taken this item out. We further ran a t-test (with 95% probability).	1 case expert per region
	Topics discussed during knowledge exchange with experts	Which topics were being discussed during the knowledge exchange?	Single choice with the following items: Best-practice tips; Planning; Management; Laws and regulations; Community energy; Infrastructure; Administration; Funding; System engineering; Efficiency strategy; Civil participation; Public relations; Other	1 = identified as a topic discussed 0 = not identified as a topic discussed each item was summed up over all regions and divided by the	1 case expert per region

				maximally possible sum to obtain relative values	
Knowledge exchange with experienced practitioners	Intensity of regional knowledge exchange	How intensely does your region exchange on topics related to the use of renewable energy with persons and organizations from other regions?	5-point interval scale (1=not at all, 5= very strongly) for each of the following items: Politics; Administration; Economics; Science; NGOs; Civil society; Other	Average over all regions by item. Due to an extremely low n for the item "Other" we have taken this item out. We further ran a t-test (with 95% probability).	1 case expert per region
	Topics discussed during regional knowledge exchange	Which topics were being discussed during the knowledge exchange with regions?	Single choice with the following items: Best-practice tips; Planning; Management; Laws and regulations; Community energy; Infrastructure; Administration; Funding; System engineering; Efficiency strategy; Civil participation; Public relations; Other	1 = identified as a topic discussed 0 = not identified as a topic discussed each item was summed up over all regions and divided by the maximally possible sum to obtain relative values	1 case expert per region
Key actors/ specific institutions	Existence of key actors	Are there single or multiple key persons which have supported the development of the use of renewable energies in your region?Are there key organizations (parties, companies, institutions) which supported the development of the use of renewable energies in the region?	Single choice with the following items: Yes, No, Don't know; each question was followed up on with an open-ended response	1 = Yes key actors exist 0 = no key actors exist each item was summed up over all regions and divided by the maximally possible sum to obtain relative values. Content ananlysis of open ended response.	1 case expert per region
Specific skills of key actors	Specific skills of key actors	If you have pointed out key actors in your region, which of the following characteristics do they own?	5-point interval scale (1=not at all, 5= very strong) for each of the following items: expert knowledge; environmental consciousness; networking skills; material resources; leadership skills	each item was summed up over all regions and divided by the maximally possible sum to obtain relative values	1 case expert per region

Supporting/opposing actors	Supporters/ Opponents	Please estimate how actors from the following sectors have supported/opposed the regional development of RE implementation.	5-point interval scale (1=not at all, 5= very strong) for each of the following items: Politics; Administration; Economics; Science; NGOs; Civil society; Other; alternative single choice: Don't know	each item was summed up over all regions and divided by the maximally possible sum to obtain relative values 0= Don't know Due to an extremely low n for the item "Other" we have taken this item out.	1 case expert per region
Networks	Existence of networks, Type of network	In which networks is your region involved in?	Open ended response	Assign to HR and LR regions.	1 case expert per region
Civil commitment for/against regional RE use	Existence and type of community energy initiatives	Which community energy initiatives do exist in your region?	Open-ended response	Assign to HR and LR regions	1 case expert per region
Degree of funding from municipalities funds; private household's investment; Cooperatives/ alternative funding; Funding from SMEs/large companies/ Enterprises involved from different lines of business	Funding sources	Please estimate how strongly the use of renewable energy is financed from the following sources.	5-point interval scale (1=not at all, 5= very strongly) for each of the following items: National or EU; Regional; Community energy initiatives; Local and regional companies; Supra-regional companies; Private households; Others	Average over all regions by item. Due to an extremely low n for the item "Other" we have taken this item out. We further ran a t-test (with 95% probability).	1 case expert per region
	Local sector/ Supra-local support support	How strong did the following corporations support the use of RE in your region?	5-point interval scale (1=not at all, 5=very strong) for each of the following items: Building industry; Architecture offices; Systems engineering; Planning; Project developer; Craftsmen; Agriculture; Civil participation; Energy services; Financial services, Other	each item was summed up over all regions and divided by the maximally possible sum to obtain relative values 0= Don't know Due to an extremely low n for the item "Other" we have taken this item out.	1 case expert per region

a. RSA decision table

Decision table of RSA containing discretized data. The cases are described by decision attributes (dependent) and condition attributes (independent). Cells are shaded according to the rating: 1 is white, 2 light gray, 3 medium gray, 0 dark gray.

cases	decision attributes				Condition attributes																				
	OIR	OER	TEF	REL	ESP	IKK	TNC	YEA	GOL	MIL	HNR	HNX	INF	PAR	KEY	CEI	SUP	INE	FNE	ECO	PUB	BUS	PRI	TYP	ADM
GIE	3	2	1	3	1	2	1	3	2	1	3	3	2	3	3	3	3	1	1	3	3	1	2	0	0
BAR	3	3	2	2	2	1	1	2	2	1	2	2	3	2	1	3	3	2	3	3	2	3	2	1	0
STY	3	2	2	3	2	1	2	1	2	2	2	3	2	2	3	1	2	2	3	3	1	2	2	1	1
HAR	3	2	1	1	1	1	2	2	0	2	1	1	2	1	2	1	3	3	1	0	1	1	2	0	1
LDA	3	3	1	3	1	2	2	3	2	0	3	2	1	1	2	0	3	3	3	3	2	2	1	1	0
OTT	1	1	1	1	1	2	1	1	1	1	1	1	2	1	3	1	2	3	3	2	1	1	2	1	1
WET	1	2	2	3	1	1	1	2	2	1	3	3	1	2	1	2	3	3	3	3	3	2	2	0	0
BUS	2	3	0	1	1	2	1	1	2	1	1	1	2	2	3	3	3	3	3	0	1	1	2	0	1
GOS	1	2	1	1	2	2	2	3	2	1	3	3	2	2	3	1	3	3	1	3	3	2	2	1	1
SEK	3	1	2	3	2	1	2	3	2	1	3	3	1	2	2	1	2	2	2	3	3	2	2	0	0
MIL	2	1	0	3	1	1	1	2	2	1	1	1	1	2	3	1	3	2	2	2	1	2	1	0	0
LAU	3	1	2	3	2	1	2	3	2	1	1	3	2	1	3	0	3	1	2	3	3	2	2	0	0
BHF	3	2	3	3	1	2	1	2	2	1	2	1	3	2	3	2	3	3	1	1	2	2	2	1	1
ALT	3	3	2	2	2	1	2	3	2	2	3	3	2	3	3	3	3	3	3	3	3	1	3	1	1
GOE	3	2	2	2	1	2	2	3	2	2	1	2	3	3	2	3	3	1	2	3	3	2	2	1	0
SAZ	3	2	2	2	1	2	1	2	2	1	1	1	2	2	3	1	3	3	3	3	1	2	1	0	1
TEF	3	1	0	1	1	2	1	2	2	1	3	3	2	1	2	1	3	2	3	0	3	2	1	0	0
WEM	2	1	2	1	1	2	1	3	2	1	3	3	3	3	3	1	3	3	2	3	2	1	2	0	0

b. rule merging

Rules were merged if either the decision attribute value, or at least one condition attribute value were identical in two rules.

Identical condition attribute values in reduced rule #3:

Original rules	`if ESP = 2 and IKK = 1 then OIR = 3` `if ESP = 2 and IKK = 1 then EFF = 2`
Reduced rule	`if ESP = 2 and IKK = 1 then OIR = 3 or EFF = 2`

Identical decision attribute values in reduced rule #4

Original rules	`if IKK = 1 and TNC = 2 then OIR = 3` `if IKK = 1 and INF = 2 then OIR = 3`
Reduced rule	`if IKK = 1 and TNC = 2 then OIR = 3` `or INF = 2`

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Chapter 4

Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems

Annika Weiser, Lotte M. Lutz, Daniel J. Lang, Klaus Kümmerer

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Abstract:

The language of the global sustainability discourse in science and society is laden with time rhetoric, and time has been identified as one major contextual condition for sustainability transformations. Still, time and temporal dynamics are often not explicitly considered or conceptualized in research and strategy- building towards sustainability transformations in social-ecological and socio-technical systems: While existing approaches to time such as the concept of time ecology mainly inform system knowledge, many transformation concepts are found to lack an in-depth integration of time. This sets up the challenge to acknowledge and operationalize temporal system dynamics in transformation processes, in order to be able to plan and act purposefully towards long-term sustainable development. In this article, we take a first step to meet this challenge and propose an approach towards operationalizing and integrating the findings of time ecology for these sustainability transformation concepts. The presented time-in-transformations-approach consists of three subsequent steps. Each step informs specific features of the transformation process and is operationalized on the basis of insights from time ecology. By applying these steps to the exemplary case of the mineral-energy nexus, we show how our approach might enable a better temporal system understanding and support a structured reflection on human perception of change and typical temporal patterns. The approach leads to two main outcomes: First, it can inform how to design and carry out interventions in a way that they consider a system's temporal resilience and transformability. Second, an active consideration of temporal dynamics can inform strategy-building towards coherent sustainability transformations across sectors and regulatory levels, spatial and temporal scales. Therefore, it can contribute to a shared and operational understanding of temporal diversity and may thus meaningfully complement existing approaches to analyze, assess and purposefully intervene into systems across sector boundaries.

1. Introduction

1.1 Relevance

The language of the global sustainability discourse in science and society is laden with time rhetoric (van der Leeuw et al., 2012). Climate change mitigation calls for *immediate* action to avoid *long-term* adverse effects (COP 21, 2015; Stern, 2006). The dynamics of *ever-faster* growing impacts of human activities on the earth's system are framed as "The Great Acceleration" (Steffen et al., 2015). Goals have been set for *specific time horizons* such as 2020 (e.g. the two-degree climate mitigation goal (COP 21, 2015), 2030 (Sustainable Development Goals (United Nations, 2015) or 2050 (energy strategies (IEA, 2010; IRENA, 2014). Finally, already the Brundtland report (WCED, 1987) states that activities fostering a sustainability transformation need to be designed with a *long-term* perspective for generations to come. Despite this omnipresence of time-related language, time is often not explicitly integrated in the sustainability debate, neither in research nor decision-making and the public discourse (Held, 2001). Acknowledging this, Reisch and Bietz (2015) emphasize the significance of time and temporal elements for sustainability transformations. The authors present time and temporal elements as boundary condition and potentially powerful design variables for more sustainable lifestyles. Although scholars have identified these and other general time-related patterns of transformation processes, they are not (yet) embedded in a coherent theory (Olsson et al., 2014). Time is touched upon as a factor in transformation research, and the need for transformation is touched upon by time research. Yet both approaches are not explicitly linked in a way that allows to straightforwardly consider temporal aspects to inform decision-making and planning in a way that fosters transformations towards sustainability.

1.2 Motivation

The need for an explicit consideration of time is very apparent in the discourse on the transformation of the resources and energy sectors: Time horizons of interconnected processes behind resource and energy use range from short-term supply bottlenecks to the long-term needs of safely storing nuclear waste. We believe that a long-term perspective alone will not suffice to address future challenges at this *mineral-energy nexus* (Giurco et al., 2014). Rather, it must be assured that plans in both sectors are (temporally and spatially) aligned to plan and act purposefully towards long-term sustainable development. This calls for an explicit in-depth integration of temporal aspects in research and actions towards sustainability transformations.

1.3 Contributions

We postulate that a more explicit approach to temporal diversity could considerably enhance our understanding of transformation processes in highly interlinked systems. Beyond this, we could also make use of this more differentiated perspective on time to purposefully intervene into systems across sector boundaries. Time ecology as one of the most prominent examples of a more explicit and diverse approach to 'time' appears to be very helpful to elaborate on this issue because it emphasizes the temporal dimension and diversity of temporalities in understanding systems (Adam et al., 1997; Clancy, 2014; Held et al., 2000; Hofmeister, 2002; Kümmerer et al., 2010; Kümmerer and Hofmeister, 2008). In this paper, we analyze the practical relevance for and means of applying principles of time ecology to the sustainability transformation of interconnected systems, and discuss how a deeper and more explicit understanding and consideration of time in that sense can contribute to (i) improve our understanding of the dynamics behind such connected systems and related transformation processes and to (ii) assist designing interventions into complex and highly connected systems to purposefully navigate sustainability transformations.

1.4 Organization of the paper

Fig. 4.1 illustrates how the paper is organized and how the sections build on each other. At its core, we suggest the three-step time-in-transformations-approach that aims at developing an enhanced temporal perspective on processes of change across system limits. Each step relates to one of three key requirements (R1 to R3), which we identified in a survey of two bodies of literature: time (A) and transformations (B). To illustrate its potential practical relevance, we apply the suggested approach to exemplary processes at the mineral-energy nexus, namely the case of metal and renewable energy use. Following the logic of the three steps, we sketch out how the approach may inform decision-making and strategy design. We then synthesize our findings and reconnect them to both the literature on time and on transformations. Our key findings relate to the benefits we could gain from integrating the two mutually supporting perspectives on time and transformations for both understanding and purposefully intervening into systems.

Throughout the paper, we use the following terminology: (i) **temporal features** as technical term to differentiate between characteristics of time such as point in time, duration, or time lag; (ii) naturally occurring **temporal patterns** within a system such as the development of vegetation over or with the seasons; (iii) **interventions** into systems that notably disrupt and alter these temporal patterns; (iv) the overall sustainability **transformation** of a system, understood as a fundamental structural change towards a more sustainable state.

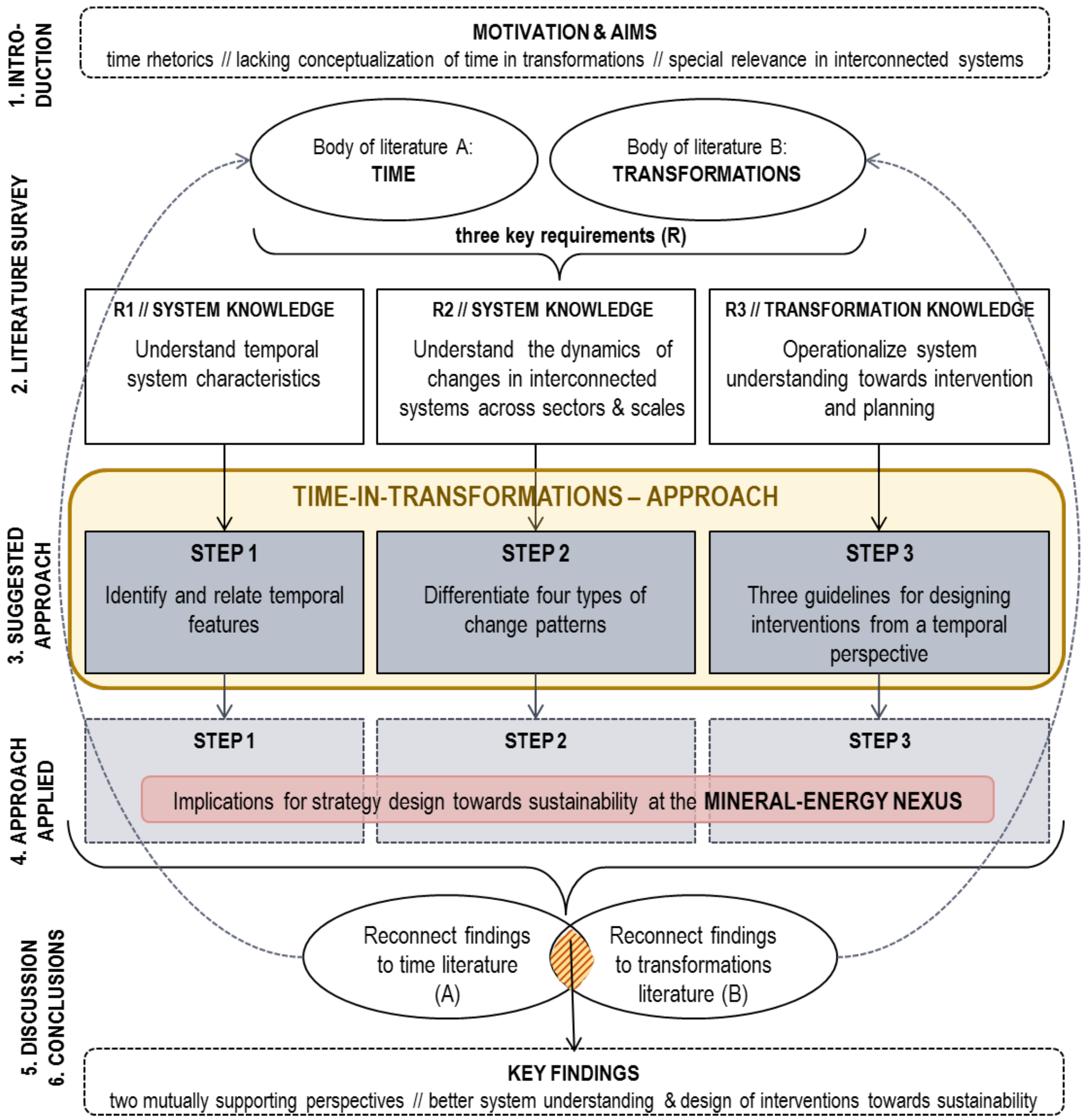

Figure 4.5: Schematic overview of the paper. A literature survey of two bodies of literature results in the definition of three requirements for a deeper understanding of time in transformations. We present the three-step time-in-transformations-approach that responds to each of these requirements and apply the suggested approach to the mineral-energy nexus as an exemplary case of a highly interconnected system. We reconnect our findings to the two respective bodies of literature and extract key findings relating to the positive effects of an increased conceptual integration of time and transformations.

2. Literature survey on time and sustainability transformations

We applied the general principles of a snow-ball search to survey the two bodies of literature of time and transformations, using Scopus and Google Scholar. For time literature, we focused on the time ecology approach to emphasize the aspect of temporal diversity. For literature on transformations, we focused on two of the most prominent approaches. In the following, we sum up our main findings with regards to aspects of transformation in time research (section

2.1) as well as aspects of time in transformations research (section 2.2), concluding with three key requirements for a closer integration and consideration of the two bodies of literature (section 2.3).

2.1 Time ecology and transformation

The time ecology concept understands 'time' as one major characteristic of a system (Kümmerer et al., 2010). It touches upon vital aspects of sustainability, but does not formulate a clear objective of actively inducing transformation processes towards sustainability. 'Time' is to be considered more diversely than in the purely quantitative, 'Newtonian' sense of time which is closely related to clock time and reversibility (Kümmerer and Hofmeister, 2008). Time measures are considered to have a descriptive and a normative component. The normative component refers to making proper use of time, and to finding the 'right' pace and point in time; it describes the right time for action as 'kairos' (Adam et al., 1997). Sustainable development is seen as an 'inherently temporal concept' (Held, 2001) with reference to future generations' own needs. A major objective is seen in finding suitable time measures for human action towards their environment. An explicit and integrative temporal perspective is considered necessary to understand how ecology, economy, and society interlink (Held, 2001). One example for a more explicit link of time ecology principles to governing system change is the temporal misfit approach. It states that systems may be irreversibly disturbed whenever the inherent system times or other temporalities of two or more coupled systems do not align, or when the speed of occurring change is inconsistent with the maximum possible adaptation rate of a system (Held and Kümmerer, 2004). As an example, temporal misfits may be created when regulative action is taken at the wrong time (i.e. too early or too late) or otherwise irrespective of the time frames or adaptation rate of the natural system. Munck af Rosenschöld et al. (2014) have identified a number of temporal misfits in the governance of endocrine-disrupting chemicals (EDC) such as between the production of new knowledge and the emergence of new impacts and adverse effects, or the 'cycles of regulation and impacts' (p. 6). Also, the point of time of an intervention is considered crucial for temporal fit (Kümmerer and Hofmeister, 2008).

2.2 Transformation research and time

Several theories, concepts and methodologies related to transformation research and the normative guiding idea of sustainable development have been developed over the last years. They share the objective to analyze or find appropriate pathways to tackle unsustainable trends in often complex human-environment systems and act towards long-term sustainability (Luederitz et al., 2016), but may relate differently to time as such. In the literature on sustainability transformations and in related fields, transformation processes are understood to be context-specific developments that happen over a specific period of time. Two prominent approaches and how they consider temporal aspects are introduced here: transitions of socio-technical systems (STS) (Grin et al., 2010) and transformations of social-ecological systems (SES) (Walker et al., 2004).

- Socio-technical transitions theory has mostly been applied to individual sectors such as energy or health. The transition of a STS in time is described as a sequence of four alternating phases: (1) pre-development, (2) take-off, (3) acceleration and (4) stabilization. The ideal-typical transition process is conceptualized as s-shaped curve (Geels et al., 2016; Rotmans, 2001; Rotmans and Loorbach, 2010). Transition processes depend on a variety of contextual factors (Geels and Schot, 2010, p. 26), which potentially open a 'window of opportunity' that facilitates change (Geels, 2005, p. 685). This enables radical innovations to influence the system. Once triggered, major changes may occur within short time frames, which will then lead to a new regime configuration or to the collapse of the system (Göpel, 2016).
- SES are perceived as complex and adaptive to internal and external influences. They are characterized by the capacities resilience (constantly changing yet remaining within critical thresholds), adaptability (adjusting to external and internal changes yet remaining in the current trajectory), and transformability (crossing thresholds into new development trajectories) (Folke et al., 2010). SES undergo a process of constant evolution, in which the speed of change varies considerably (Gunderson and Holling, 2002). Actively induced transformation processes of SES pass three main phases: (1) preparing for transformation, often at different scales of the social-ecological system and by different actors at the same time; (2) navigating the process step by step; and (3) building the resilience of the new system state, where several factors (such as leadership, funding and legislation) have been identified as helpful. Often, the first and second phases occur in a window of opportunity (Olsson et al., 2014, 2006, 2004).

Both approaches share a rough differentiation of three phases: (i) preparing system change, (ii) actual intervention and occurring change, and (iii) stabilizing the new system state. Both approaches mention that time may run unevenly or speeds might be very different in the course of transition or transformation processes (Göpel, 2016; Gunderson and Holling, 2002; Rotmans and Loorbach, 2010). Still, both do not explicitly consider this temporal diversity. In the following, we use the terms *(sustainability) transformation* and *transformation research* for both approaches introduced above.

2.3 Three requirements to support a deeper understanding of time in transformations

At present, the two bodies of literature evolving around temporal diversity and transformation are mostly treated separately. While the time ecology concept presents the temporal dimension as a valuable system component, it does not provide sufficient detail on how to apply this understanding to conceptualizations of transformation processes or to designing interventions into systems. Similarly, while transformation research provides some starting points in this respect, time is mostly neglected as a vital system component. We identified a need for understanding temporal diversity in systems under transformation, approaches to deal with different temporal and spatial scales across interconnected systems, and practical knowledge on how to design interventions in coherence with this understanding of temporal diversity. In order to overcome this gap and make full use of an improved and applicable understanding of temporal diversity in processes of or towards sustainability transformations, we therefore suggest addressing the following three requirements:

(R1) knowledge regarding the temporal system characteristics (i.e. understanding its components from a temporal diversity perspective),

(R2) knowledge with respect to the point of intervention and the potential dynamics of (desired and undesired as well as intended and unintended) changes in interconnected systems across sectors and scales (i.e. when and where to intervene to reach the desired outcome), and

(R3) knowledge in the sense of an operationalized system understanding towards intervention and planning (i.e. how to intervene in awareness of the temporal specificities of the systems).

While R1 and R2 target an improved understanding of system characteristics (*system knowledge*), R3 relates to the creation of knowledge that can be used to achieve progress or change behavior (*transformation knowledge*) (see (Brandt et al., 2013; Wiek et al., 2006) for the differentiation of knowledge types

3. A THREE-STEP APPROACH TO INTEGRATE TIME IN GOVERNING SUSTAINABILITY TRANSFORMATIONS

The three-step time-in-transformations-approach presented here aims at integrating and operationalizing the concept of time ecology (Adam et al., 1997; Held et al., 2000; Kümmerer and Held, 1997) with transformation research (Grin et al., 2010; Gunderson and Holling, 2002). As illustrated in figure 4.2, each step responds to one of the key requirements identified in the literature survey (section 2.3) and may inform one or several of the three main phases of transformation processes identified in section 2.2. The steps are subsequent and thus either form the basis for or inform the following one. While step 1 and 2 enhance system understanding and prepare for the intervention (*where and when*), step 3 informs the intervention itself (*how*). Step 1 leads to a temporal system understanding that may inform the preparation phase (phase 1) of transformation processes. Step 2 differentiates patterns of change and may thus inform the actual point of intervention (phase 2). The guidelines presented in step 3 may contribute to navigating the actual change process (phase 2) and thus indirectly support the process of stabilization (phase 3).

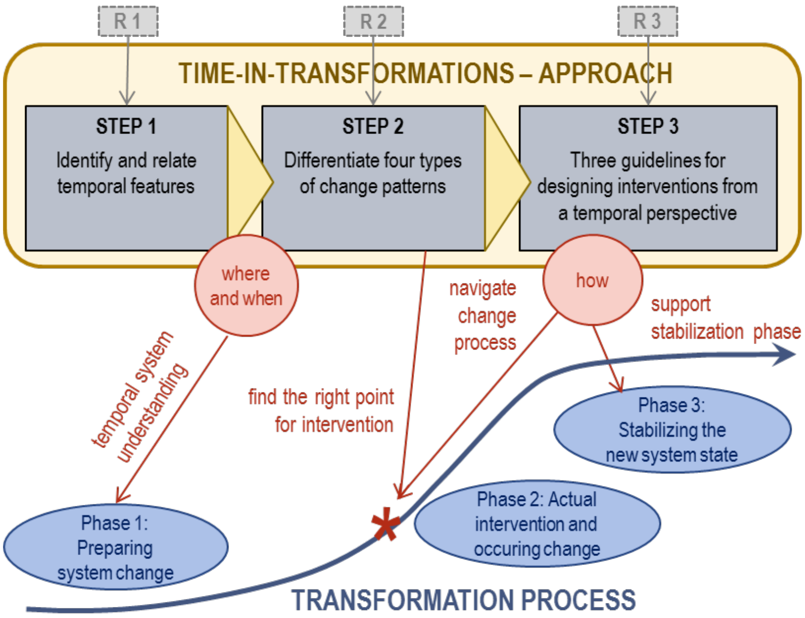

Figure 4.6: Interrelations of individual steps of the suggested time-in-transformations-approach and phases of the transformation process (approach with the three steps in yellow and grey, shared phases of transformation processes in blue, arrows (red) indicate how each step may inform one or several phases).

3.1 STEP 1: Identify and relate temporal features

AIM	Get an overview of the observed system(s), their temporal specificities, and defining components in terms of system dynamics. We suggest differentiating between the natural, the socio-technical and the regulatory spheres. The natural sphere encompasses natural processes such as ecosystem dynamics. The socio-technical sphere includes processes related to mainly economic activities such as mining, production and consumption, while the regulatory sphere encompasses processes related to governance and intervention measures such as policies and legislation. Step 1 also allows to consider several sectors that may be involved in an intervention.

APPROACH	Following the time ecology principles, systems or system components are usually characterized by a combination of several temporal features. These are constituted by the basic temporal elements point of time and timeline. In combination with the basic temporal relations 'before', 'after', and 'simultaneous', they allow for statements being made on, among others, the direction of time, temporal extension, time-scale, duration and change, or the unique times of past, present, and future (Kümmerer et al., 2010). Time exists as a variety of different temporal features with strongly differing characteristics (Adam et al., 1997; Held, 2001; Held and Kümmerer, 2004; Kümmerer, 1996; Kümmerer et al., 2010). Fig. 4.3 below lists and describes these temporal features (Kümmerer et al., 2010). Use this list to identify the relevant temporal features of the observed system for each sphere and sector. Take a temporally-focused perspective on the system to identify path dependencies or temporal elements that are necessarily sequential.
ADDED VALUE	The identification of the variety of temporal features inherent in a system is a necessary basis for an enhanced system understanding. A common consideration of all involved sectors provides a suitable basis for the identification of system features and underlying dynamics that might have an influence across sectors' limits. Action towards increasing sustainability in and across these sectors will have to consider all relevant temporal features and their interlinkages. In that respect, this step can complement system analysis and emphasizes a process-oriented perspective.

duration	*time scale specific for an organism, population, system, and/ or process' (a)* *informs 'how long an event, or its influence, lasts' (b)*
point in time	*the specific 'moment when an event occured' (b), incl. nonregular events; this has an 'influence on the effects of that event' (b); 'crucial for the development of a system: points in time when a system or organism is sensitive and insensitive to external input or change' (a)*
rhythm	*recurrence of the similar with variation, synchronized between processes and systems' (a)*
metronomic beat	*exact time scale and point in time: repeating the same action; intended to be invariant and uniform' (a; there is no metronomic beat in nature (b)*
speed, acceleration, deceleration	this dynamic conduct of a process is ; 'important for a system´s reactions on disturbances, problematic if not adequate' (a)
timing	*coincidence and / or synchronisation of events and processes' (a), may be intended or not*
time lag	*delayed damage or incomplete development; masking of time-related effects' (a); a triggered process may run over some time before the effect can be perceived*
temporal webs	*interplay of different time scales and points in time within systems and different systems and levels' (b)*

Figure 4.7: Terms and definitions to help navigate the identification of relevant temporal features of the observed system (as compiled by Kümmerer et al. (2010) (a) for the case of soils and (Kümmerer, 1996) (b))

Systems have very specific *Eigenzeiten* (inherent times) such as naturally occurring temporal patterns (Adam et al., 1997; Held and Geißler, 1995). These system-inherent times are embedded within organisms and ecosystems, but also non-biotic processes. Rhythms, for example, allow a system temporal flexibility and elasticity, which is a precondition for its resilience (Held and Kümmerer, 2004; Kümmerer et al., 2010). It is necessary to acknowledge a system's inherent times when planning an intervention into a system to avoid (temporal) misfits, but also to take advantage of their flexibility and the resulting resilience.

3.2 STEP 2: Differentiate four types of change patterns

AIM	Develop an understanding of underlying patterns of change and the degree of flexibility the system(s) at hand offer(s). This helps to make full use of 'windows of opportunity' and to determine promising entry points for intervention. Understand not only the inherent system times, but also the underlying processes and temporal patterns of constant change (intended as well as unintended), including 'naturally' occurring disturbances (Held and Kümmerer, 2004), to be able to determine where to rely on observations of the system and foresee or predict future behavior.
APPROACH	Identify and categorize system-inherent patterns of change to determine whether or not it is possible to observe or predict what is happening. Patterns are formed by specific points of time and time lines that result in a certain temporal irregularity and temporal extent. (Relative) Temporal irregularity describes how regular or irregular changes in a system are, ranging from the rigid metronomic beat to highly irregular specific points in time (events). (Relative) Temporal extent describes the time it takes for the according system element to change, which ranges from split seconds to millions of years and is defined by the time covered between specific starting and ending points. This results in four types of temporal patterns of change as described below.
ADDED VALUE	The step adds to understanding the dynamics and interactions of changes in systems and enables a more directed view on interplays and mutual reactions between different spheres and sectors. It helps to differentiate system-inherent patterns of change from on-going transformational change and allows estimating how long it might take until impacts of interventions become visible. It may sharpen the focus on features that may (unintendedly) trigger a development into an irreversible new state and thus need special attention.

We suggest that the following temporal patterns can be differentiated:

- *Type 1 temporal patterns* are short- to mid-term intervals of change with a low to medium temporal irregularity, i.e. they have a relatively regular pattern. Examples are day and night, regular maintenance intervals to keep machines in order, or legislative periods in politics. Here, changes are relatively easy to observe and predict.
- *Type 2 temporal patterns* are mid- to long-term changes, with a low to medium temporal irregularity. Examples include solar and lunar eclipses, but also the anticipated average life-time of technical devices such as power plants. Changes here, or the temporal pattern itself, are possibly harder to observe, but, once recognized, rather easy to predict due to their relative regularity.
- *Type 3 temporal patterns* characterize changes that are mid- to long-term in duration and show medium to high temporal irregularity. Examples are the process of recognizing ozone depletion due to CFCs and the formation of ore deposits within geological time scales. It is rather difficult to observe as well as to predict changes occurring here.

- *Type 4 temporal patterns* characterize shorter, or abrupt, change, with a medium to high temporal irregularity: One example occurring in nature would be the eruption of a volcano; in the context of the mineral-energy nexus similar patterns can be found in the volatility of resource prices. Such events may be rather easy to observe for humans, but are very difficult or impossible to predict.

The types strongly relate to the fact that the spatial and temporal scales of an observed system influence the time it takes to perceive some kind of change or disturbance (Held and Kümmerer, 2004; Kümmerer, 1996). Changes in larger systems are often observed much later than those in smaller systems, which emphasizes the close relation of spatial and temporal scales (Gibson et al., 2000). A perception lag might cause considerable delays before action is taken (Adam, 1998; Held, 2001; Kümmerer et al., 2010). Also, it is important to differentiate between the time it takes to recognize a specific change process for the first time from the temporal patterns the change process itself might have. For example: It took several decades to detect and understand the process of ozone depletion, but we can now observe and deal with annual variations of ozone depletion, i.e. changes that are rather short-term and relatively regular. While the former would be categorized as type 3, annual variations of ozone depletion would thus be categorized as type 1.

Whether or not a specific system feature may be an appropriate entry point for intervening into the system also depends on the degree to which it can be influenced by humans. This relates to two (temporal) factors. First, the less predictable a change process is, the more difficult it is to intervene at the right point in time and influence the system according to the desired outcome. Second, the time scales might just be too long to be influenced from an individual human perspective. With regards to changes that are both irregular and on long time-scales, interventions in the system must be flexible enough to adjust to this irregularity and must not overstretch the system's capacities to restore.

3.3 STEP 3: Guidelines for designing interventions from a temporal perspective

AIM	Design and plan interventions into a system in a way that does not cause irreversible harm but instead contributes to the desired transformation of a system, which can also support the stabilization phase and build resilience.
APPROACH	Apply general guidelines for the manner in which an intervention should be executed. Based on the principles of time ecology, three overall guidelines may be formulated that respond to the interconnectedness in temporal webs and the need for coherence with the limits of temporal flexibility, and are informed by an in-depth understanding of the relations of temporal and spatial scales (see Table 4.1).

ADDED VALUE Following these guidelines can inform the manner in which to carry through such an intervention. With increasing relevance and need to act towards sustainability across sectors, this may support policy making especially in complex environments, helping to incorporate temporal diversity into actual planning and practice.

Applying the following guidelines (Table 4.1) has particular relevance with regards to the different spheres and the regulatory level or spatial scale at which an intervention is taken. Interventions usually target a specific sphere of a system. The Paris Agreement following COP21 and the Montreal Protocol, for example, both aim to intervene into the national regulatory spheres of their member states. As response to these international treaties, national governments intervene into the socio-technical sphere with the aim to reduce greenhouse gas or ozone-depleting emissions, respectively. The guidelines of step 3, based on the temporal system understanding gained in steps 1 and 2, enable decision-makers to place interventions deliberately in the targeted sphere. Moreover, the guidelines may help to minimize negative impacts in spheres that should remain undisturbed.

Table 4.1: Guidelines for designing interventions.

Target	Approach & background	Conceptual basis
Avoid temporal misfits	Acknowledge the diversity of temporal features in a system & engage proactively to suit the purpose Temporal elasticity is limited and an intervention into a specific system might change its temporal characteristics. Including time into our thinking and action must therefore be informed by an understanding of the underlying temporal webs and the limits of a system's temporal elasticity and should aim for harmonization of times within these limits. Working at the nexus of two or more sectors creates even more complex temporal webs and increases the danger of misfits. It demands foresight and thoughtfulness to consider the relevant times of all system components into the design of an intervention, and to use this knowledge so that the intervention ensures functionality and follows the intended purpose. relevant temporal features: temporal webs, duration, speed - acceleration - deceleration	time ecology (cycles, frequencies, rhythms and their mutual relation) (Kümmerer, 1996) timescapes (Adam, 1998) environmental governance (misfits/ mismatches approach) (Dille and Söderlund, 2011; Munck af Rosenschöld et al., 2014; Pahl et al., 2014)
Minimize negative impacts	Find the right point in time to remain within or even improve a system's (temporal) elasticity. Irregularly occurring changes might challenge the stability of a system more than regular ones, since a system may adapt or even rely on regular change, but might not be 'prepared' for irregular events. The temporal patterns at the nexus of two or more sectors may leave room for only small windows of opportunity for action within the systems' temporal elasticity. relevant temporal features: timing, point in time, rhythm	time ecology (flexibility of a system, temporal impact assessment) (Held and Kümmerer, 2004; Kümmerer, 1996)
Acknowledge or reduce delays	Consider the role of context for the perception of change. Temporal and spatial scales are related, and perception and reaction may be slower in larger systems. The perception of the present situation in relation to the past and future might be influenced by the position, power and experience of a decision-maker, and might thus also differ depending on the sector one works in. This guideline aims to reduce delays in the perception and management of processes. It must be acknowledged, however, that delays in natural systems can also often be understood as buffers that slow down negative effects and leave time to maneuver. relevant temporal feature: time lag	time ecology (timescapes: 'to regain a sense of context'), psychological research (perception and delay) (Adam, 2004, 1998; Pahl et al., 2014)

4. Applying the time-in-transformations-approach to the case of the mineral-energy nexus

As shown in section 2, bringing time and transformation together is not just a question of defining short-, mid- and long-term objectives. To illustrate the added value of the explicit integration of time and temporal diversity, we applied the three-step approach to interventions towards sustainability in the interconnected sectors of metal use and renewable energy use.

Transformation processes can neither be understood nor guided properly by treating systems or sectors as separate entities, as it is currently often the case for actions taken to achieve a more sustainable resource and energy use. Both are 'inextricably-connected' and 'overlap[ping] with bidirectional influences' (Giurco et al., 2014). Generally, strong interlinkages make it difficult to oversee all system components and interactions of cause and effect can often not be easily distinguished (cf. e.g. Held and Reller, 2016). Most literature on mineral and/ or energy futures does not yet sufficiently address nexus issues (Giurco et al., 2014) and time is either largely disregarded or incorporated very differently. In resource (availability) estimates and depletion studies (Angerer, 2010; Graedel et al., 2015; Tilton, 2002), time mostly plays an ancillary or implicit role. Some practical approaches such as visioning and foresight explicitly take on a future perspective within a certain time-frame (Prior et al., 2013). Often the time-frames of studies cover not more than a decade, which will have to be considered as too short to adequately address the challenges of sustainable mineral resource use (Giurco et al., 2014). Compared to that, energy studies such as scenarios or models often take a longer perspective of several decades (ECF et al., 2010; IEA, 2016; IRENA, 2016).

In the following, we focus particularly on neodymium production and use as an illustrative example. Neodymium is a rare earth element (REE) that is needed for many renewable energy technologies such as high-strength permanent magnets in wind energy converters (Graedel, 2011; Nansai et al., 2015; Zimmermann et al., 2013). It ranks high among (especially short-term) criticality ratings and supply bottleneck estimates (Commission of the European Communities (EC), 2014; Moss et al., 2011; US Department of Energy (DOE), 2010) and is even considered to potentially delay broad-scale wind power implementation, even though supply would eventually cover risen demand (McLellan et al., 2016).

4.1 STEP 1 applied: Temporal features of metal use and use of renewable energy technologies

Relevant temporal features of the transformation process towards sustainable energy and metal use are compiled in table 4.2 (at the end of this chapter). It illustrates the temporal diversity that ought to be considered and reveals the large gap between the system-inherent time-scales of resource and energy use within as well as across sectors and spheres. The inherent time scales of metal use are much longer than those of renewable energy use, and the phase in which the metals are used for generating renewable energy is extremely short in relation to the whole metal life-cycle (see Tab. 4.2 at the end of this chapter). This temporal imbalance between the metal life-cycle and its in-use phase is aggravated by the fact that many rare earth elements (REE), including neodymium, are mined with radioactive elements such as thorium. The half-life of the most abundant Thorium isotope in nature (^{232}Th) is 14 billion years. In contrast, the preparation phase for generating renewable energy in a wind farm needs only months to a few years, and the life time of a wind turbine, which is also the in-use phase of neodymium, is 20 to 30 years.

Implications for strategy design: The different time horizons can be considered a major challenge for developing joint strategies that target a sustainable metal and renewable energy use. Relating the temporal features to one another helps to uncover sequential steps in a process, where a change in one would lead to a change in another. For example, less frequent maintenance (*rhythm*) might lead to a shorter overall lifespan (*Eigenzeiten/duration*) of a technological device.

4.2 STEP 2 applied: Temporal patterns of change in metal use and use of renewable energy technologies

We exemplify step 2 using the case of neodymium and thereby differentiate between the natural, socio-technical and regulatory spheres (Fig. 4.4). As described in section 3.2, we thereby differentiate four types of temporal patterns of change, depending on (i) the temporal extent of the change and (ii) its temporal irregularity. These are depicted in Fig. 4.4 below as a matrix with four quadrants. The matrix shows exemplary change patterns for each of the three spheres allocated to the respective type (i.e. quadrant); e.g., in the natural sphere (green circles), seasons are an example for rather short, rather regular change patterns (and hence allocated to quadrant 1), whereas habitat recovery takes considerably longer and is allocated to type 2. Processes of ore formation are both long and irregular (type 3). Reconnecting this to the general findings on temporal patterns (section 3.2), conclusions can be drawn on observability, predictability and (potentially) ability to control the processes mentioned here for the mineral-energy nexus: regular change patterns with short intervals (e.g. maintenance intervals for technical devices using neodymium (type 1), as well as for those with long intervals (e.g. nuclear half-life (type 2) are comparatively easier to predict. In contrast, it is more difficult to predict change with irregular patterns, again independent of whether they happen as an unforeseen single event (e.g. a mine waste spill, type 4), which might be followed by supply bottlenecks (type 4) or with a rather long time-frame (e.g. the process of ore formation (type 3).

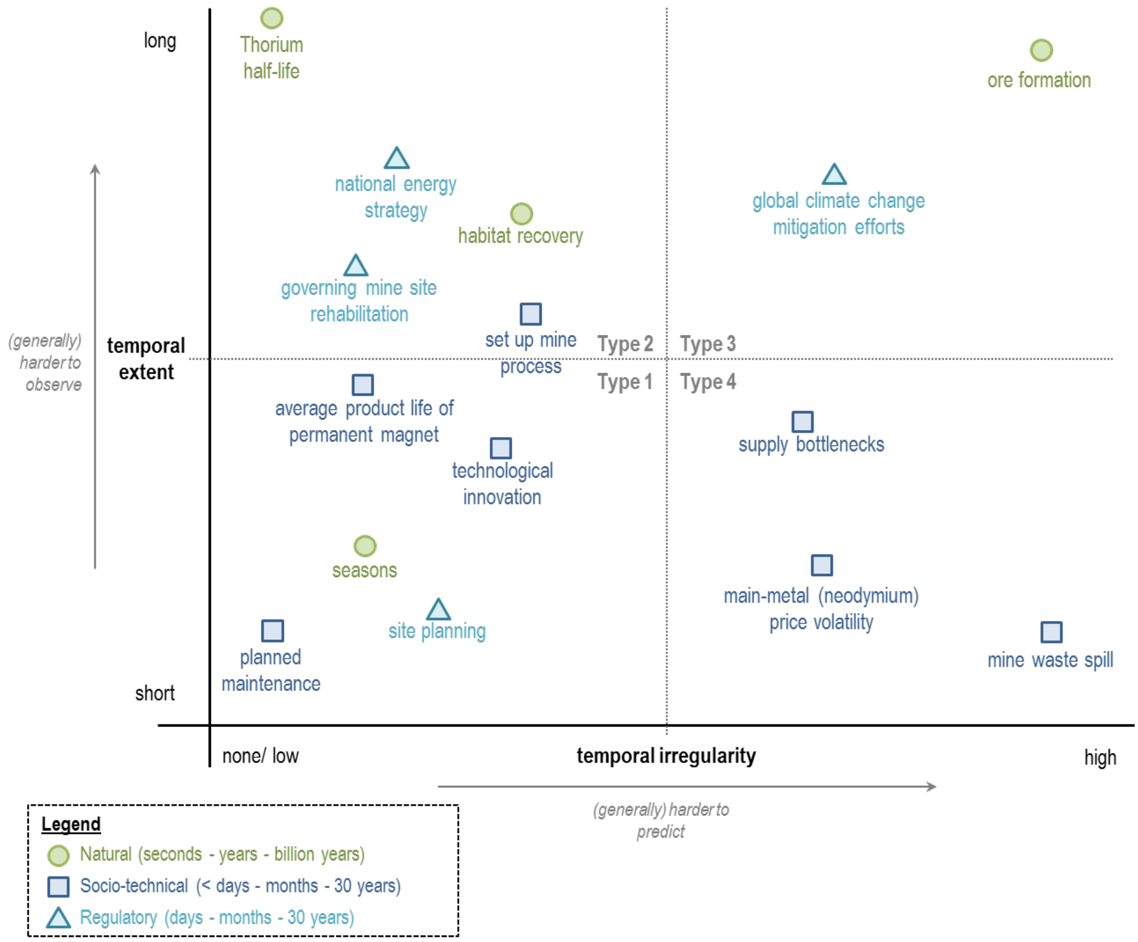

Figure 4.4: Matrix of (relative) temporal irregularity of a system and (relative) temporal extent of system-inherent temporal patterns of change with examples evolving around the use of neodymium (own illustration)

Implications for strategy design: Intervention points into a system may be considered promising when (i) it is easy to predict which change they will bring about on which time scale and whether and how it will affect others, (ii) change will occur within a relatively short period of time (if intended), so that effects can be observed and any necessary adjustments made in a timely manner; and/ or (iii) they are placed within a sphere that allows to exert influence on the system comparatively easy. For example, the growing use of renewable energy may increase pressure on neodymium availability. Since supply bottlenecks and price volatilities are rather difficult to predict, a joint strategy would have to consider these and could then also decrease price volatility. One option to reduce resource shortages is the exploration and setting-up of new mine sites. Here, as shown by the following example, the involved processes can go beyond time horizons that can be properly overseen by humans (Pahl et al., 2014): The life-cycle of a mine, which involves phases of exploration, mine-site development, the actual extraction of ore and finally its closure, usually covers a period of several decades (Environmental Protection Agency (EPA), 2012; University of Arizona, n.d.). While this prohibits a short-term reaction to supply shortages, the associated processes are still largely predictable. However, the actual operation phase is followed by various potentially very long-lasting processes. First, dealing with tailings and mine-site rehabilitation can be critical long-term issues, especially when radioactive by-products such as thorium are involved. Second, also unexpected and unintended events such as a spill of mining waste can considerably extend the temporal and spatial scale of (adverse) effects.

A second strategic option to address resource shortages is the development of more efficient recycling technologies or business schemes. The development of recycling approaches and their successful establishment in the socio-technical sphere may also take longer than the actual in-use phase of, for example, a wind turbine's magnet. Also, recyclability of products may be limited because materials are often mixed in very small concentrations (cf. e.g. Kümmerer, 2016; UNEP, 2013). Still, this second option would keep the impacts within a temporal range that can be better overseen by humans: Not only may the speed of innovation of recycling be increased through research funding; estimates based on average product life-time (i.e. potential recycling material) are generally less afflicted with uncertainty than those on resource estimates (Speirs et al., 2015). Even though the two intervention options emerge from a similar context within the socio-technical sphere and cover comparable time horizons for their implementation, the associated effects of the two options differ strongly in their temporal extents. Therefore, the temporal implications strongly favor the recycling option over the mining option.

Weighing up intervention options and thus contributing to better anticipatory governance (Guston, 2014; Nordmann, 2014; Weiser et al., 2017) may also be a question of the sectors involved, since change patterns might be easier to predict in one sector than in another. A joint strategy for expanding renewable energy production would then need to allow for room to maneuver for volatilities of metal supply, but could already embrace the known natural patterns of climate conditions.

4.3 STEP 3 applied: Design interventions into metal use and use of renewable energy technologies in coherence with time ecology principles

Also considering the findings from applying step 1 and 2, the implications given in table 4.3 aim to contribute to coherent strategy making for renewable energy and metal use.

Table 4.3: Guidelines for designing interventions applied to the case of the mineral-energy nexus

Guideline	Implications for strategy design
Avoid temporal misfits	Temporal misfits may arise, for example, between the availability of necessary materials and the choice of preferred technology options as well as the money and knowledge needed, for both renewable energy products and recycling. As a consequence, a high demand for new energy technologies might not be met over the time span covered by an energy strategy due to a lack of available materials and experts. A change in market conditions would necessitate a switch in technologies to adapt to resource shortages. Another example are the unconnected temporal patterns of energy demand and fluctuating energy provision from renewable energy sources. Solutions such as storage and smart grids allow a closer temporal fit of these patterns, but necessitate again specific materials, knowledge and experts. Strategy-building across sectors must thus consider potential misfits and bear enough flexibility for the system to adjust to these changing conditions. Strategy building should reflect this diversity of times and translate such understanding into suitable overall time horizons, concrete targets, and target years.
Minimize (negative) impacts	To minimize negative impacts, the strategy design should aim to reduce interferences in other spheres. For example, construction phases of wind turbines can be timed outside critical phases such as the breeding season. Such a thoughtful timing of an intervention reduces the impacts of felling trees, noise, and earthworks on the breeding animals. Similarly, the economic system may be more or less vulnerable to new regulations depending on the overall market situation, making it recommendable to time interventions accordingly.
Acknowledge or reduce delays	Designing a strategy at the mineral-energy nexus in awareness of wanted and unwanted possible delays, especially in large systems, emphasizes the role of precautionary approaches to be taken in situations inflicted by uncertainty. In other words, it might be wise not to wait until adverse effects have occurred, but to react to trends indicating unwanted dynamics as implied by (systemic) risk governance (Renn et al., 2011). Furthermore, as perception in general depends on position and experience, strategy-building processes should incorporate a diversity of perspectives. It may thus be useful to introduce interdisciplinary practice-science advisory boards at the national level that are inspired by institutions such as the Intergovernmental Panel on Climate Change to accompany and guide the strategy development and implementation process over the complete time span of the strategy. Similar suggestions regarding a global governance system for sustainable resource management have been made by Bleischwitz and Bringezu (2008). Besides the International Panel for Sustainable Resource Management, which was established in 2007, this should include an international convention and an international agency for sustainable resource management.

5. Discussion

Our work illustrates that time is a relevant functional component of analysis in the context of transformations. Its integration must not stop at understanding systems, but pave its way towards developing sustainability strategies based on a deeper understanding of the role and diversity of time(s). While time ecology principles mainly contribute to system knowledge and partly neglect transformation knowledge (Brandt et al., 2013), many transformation concepts are found to lack an in-depth integration of time. Also, this perspective is not yet thoroughly discussed for the future of the mineral-energy nexus. Any observation or analysis, however, cannot be fully understood - let alone serve as a basis to govern system transformations towards sustainability - without having grasped the dynamics behind these systems, including their temporal patterns. Besides the actual time-scales, this must also include system features such as recurring innovation cycles for new technologies. Considering time helps to operationalize comprehensive, joint analyses of two or more sectors and to cope with system-inherent times in a structured way, creating a greater awareness for dynamics across different sectors, i.e. at their nexus.

5.1 The "added value" of considering temporal diversity in sustainability transformation

Enhanced awareness for temporal diversity and potential path dependencies allows for a more detailed response to changes and interventions into the system. It demands a 'more process-oriented view' (Hofmeister and Kümmerer, 2009, p. 1382) that reflects the character of ongoing transformation processes and emphasizes that often unchangeable sequences (path dependencies) exist and must be considered when planning interventions into systems. This is closely connected to avoiding or minimizing (temporal) misfits, especially across several interconnected sectors and spheres. Misfits may be created between diverging time scales, but may also be an issue of timing, thus including other temporal features such as speed or point in time. Avoiding such misfits, or generally all patterns that might work adversely to sustainability, should be one central objective of all actions. Similarly, Munck af Rosenschöld et al. (2014) explicitly draw on the timescapes approach to address a lack of 'precision with regard to temporal complexity', emphasizing the importance of context as brought forward in the timescapes concept, in analogy to landscapes (Adam, 1998). To ensure coherence with the inherent time-scales of a system, decisions should be taken in awareness of the longest relevant times of the respective system (Graßl, 1993), which implies the need for careful system observation.

Hofmeister and Kümmerer connect measures and levels of effectiveness to differing time scales in their temporal assessment of environmental impacts. A focus on impact also forces decision-makers to consider that the time scales of implementation processes may influence the (temporal and spatial) effectiveness of measures, since a system's sensitivity to changes may differ depending on phenomena such as elections or the seasons (Hofmeister and Kümmerer, 2009; Kümmerer and Hofmeister, 2008). The point of time in which a decision is taken, a technology enters the market, or a technical device is installed, highly matters, and may considerably influence other factors (including temporal ones) such as a product's life-time. Additional factors include a technology's acceptance in society or whether its unintended adverse effects on the natural environment will be perceived and understood in time. Integrating temporal diversity into planning interventions, however, does not only refer to the question of "when" to intervene, but also to the "how". Acknowledging that systems are continuously changing and must do so to stay resilient (Gunderson and Holling, 2002; Held, 2001; Kümmerer, 1996), helps to consider system-inherent temporal patterns and, as a consequence, to design interventions into systems that maintain or enhance their resilience. There seems to be no one-fits-all approach to integrating and making use of temporal diversity. Still, such temporal considerations cannot replace but should complement other perspectives or approaches to system analysis or assessment in an integrative manner (Hofmeister and Kümmerer, 2009). For instance, we believe that the suggested time-in-transformations-approach has potential to expand and differentiate the temporal component of the leverage points concept (Abson et al., 2016; Meadows, 1999). For example, the guidelines (step 3) may support the design of interventions towards effective leveraging, as the consideration of diverse temporal dynamics can help to design interventions to suit the purpose for both shallow and deep leverage points.

Also, the relation to space and other contextual factors needs to be considered (cf. Kümmerer and Hofmeister, 2008), especially when time is not anymore reduced to quantification, but aims to include qualitative aspects ('making good use of time'). In that respect, we showed that reaction times differ across sectors. Complementing the spatial perspective, time can serve as a shared scale that offers an approach to accessing and making sense of the gap between urgency and long-term solutions and may thus also support transformation processes and according studies. The role of actors has not been in the focus of the work at hand. Nevertheless, it is not only important to consider who, based on their expertise and values, takes a decision. Also, the temporal implications of knowledge management and information flows between actors are relevant. An actor's individual context and position influences their perception of challenges and also the perception of their individual room to maneuver in relation to time. Perception is also discussed with respect to time: for time horizons extending 100 years, human perception is considerably limited, and rather the issue of imagination (Kümmerer, 1996; Pahl et al., 2014). This is an interesting factor for governing long-term sustainability challenges such as climate change. Considered to be a phenomenon that is 'long-term, delayed, with potentially rapid nonlinear changes' (Pahl et al., 2014, p. 385), climate change exemplifies a process that extends widely into the future and reveals long time-lags between cause and effect. According to Pahl et al. (2014), people connect less to outcomes or rewards in the distant future, and time orientation and perception may differ significantly between individuals. Similarly, Giddens's paradox states that many people will do nothing concrete about global warming as long as it is not visible or tangible in their everyday lives. Paradoxically, waiting until climate change becomes concrete in the form of catastrophes will often mean that it is too late to act (Giddens, 2011). This means that special emphasis should be put on explicitly including this 'limitation' in our thinking and action.

Summing up, explicitly carving out the temporal dimensions of an intervention and its potential impacts may be of particular relevance in situations where complex interactions make it difficult to oversee all relevant cause-and-effect relationships, thus complementing, e.g., established approaches to system analysis or sustainability assessment. At this stage, our suggestions remain rather abstract or general in large parts. Follow-up steps and research should therefore include a concrete application to specific cases that allows for a recognition of the whole intervention process in detail and that pays tribute to the perception and time horizon of the involved actors. Above that, focus should be put on a closer temporal analysis of policy documents, strategies and transformation plans to provide a basis for improving and harmonizing policies through a times lense, and to further elaborate and test the temporal component of institutional fit.

5.2 New insights into the study of transformation processes in relation to time

Phase 1 – the pre-development or preparation - of a transformation process prepares the actual intervention and change process and thus demands system understanding across spheres and, for many sustainability challenges, across sectors (cf. e.g. Díaz et al., 2015; Future Earth, 2014). In both socio-technical systems (STS) and socio-ecological systems (SES), many preparatory processes happen in confined niches; but also processes on other levels and scales as well as cross-scale and cross-level processes are shown to be relevant (Göpel, 2016; Olsson et al., 2004). Step 1 of the time-in-transformations-approach contributes to this system understanding across levels, scales, sectors, and spheres because it plainly shows system-inherent time scales, potential path dependencies that may need to be overcome, and long-term risks that may need to be considered in a sustainability transformation. This temporal system understanding may help to decide what to do where. "Where", in this sense, means the sphere and sector, the scale and level of an intervention. Step 2 of the approach complements this, because it helps to reflect on our human capabilities to perceive and influence processes. This step can add to the understanding of possible temporal impacts of human activities in complex adaptive systems. Phase 2 of a transformation process, the actual intervention and change, is informed by third step of the approach. This step guides the design of interventions in a way that they acknowledge the temporal diversity and temporal elasticity of a system, and potential gaps related to the perception of processes. It therefore informs when and how to intervene in a system. Step 3 builds upon the system understanding developed in steps 1 and 2 and contributes to interventions in a way that a stabilization of the desired outcome can be achieved.

The time ecology concept allows for a more differentiated understanding of the temporal dynamics of a transformation process. While transformation research acknowledges that change processes happen at specific periods over time, time ecology considers a development's specific points in time, the rate of change and the specific time period when the process takes place. Transformational change as such is not explicitly considered in time ecology. The latter rather aims to incorporate (human) activities into (natural) systems in a way that the system-inherent temporal patterns stay intact and the system stays within its dynamic equilibrium and resilience (Kümmerer, 1996; Kümmerer et al., 2010). According to Gunderson and Holling (2002), it is necessary to overcome a system's resilience in order to enable transformation. Social-ecological systems naturally undergo constant evolution in a process of four linked and recurring phases: release, reorganization, exploitation, and conservation, which is described as panarchy. In this cycle, the speed and rate of change vary considerably. Change is most rapid in the "creative destruction" that marks the shift from conservation to release, while the system slowly evolves from exploitation to conservation (Gunderson and Holling, 2002). Further work might combine lessons from time ecology with the system understanding of panarchy and study how impacts of interventions differ when they are placed in the four phases of constant renewal and decline. For example, the effort to transform a system to a different state may be much higher when the system is in the stable exploitation and conservation phases compared to the release and reorganization phases. It might also be interesting to analyze whether the creative destruction or the reorganization phase of a system can be understood as a window of opportunity. Bearing in mind a system's adaptability and transformability, it may be necessary to intervene into a system at a time when it is more fragile and path-dependencies can be overcome easier in order to contribute to transformational change. Here, the time-in-transformations-approach offers to differentiate between the three spheres and may guide the design of interventions in such a way that the impacts mostly affect the sphere(s) that is or are supposed to change. Sustainability transformations usually aim to protect the natural sphere and alter technical and regulatory system elements. Thus, an intervention might ideally be placed when the natural sphere of a system is in a resilient state, but the socio-technical and the regulatory spheres are more fragile and allow change to occur.

6. Conclusions

Without considering time and temporal diversity, we would miss an opportunity to take better-informed decisions that can contribute to sustainability transformations. For governing complex and vital challenges such as transformations at the mineral-energy nexus, coherent strategies across sectors and levels, spatial and temporal scales are needed. In these strategies, time in all its facets can serve as a shared perspective on the system. The literature survey highlighted that the concepts of time ecology and sustainability transformations are connected and complement one another. This connection allows for a more comprehensive and differentiated system understanding that we operationalized in the time-in-transformations-approach. It builds on an in-depth understanding of temporal system characteristics and the dynamics across sectors, scales, and spheres. It also takes intended and unintended system dynamics, including temporal ones, into account and allows for an operational understanding of how to design and implement interventions. Even more important, it teaches us to take uncertainties as given, since our understanding of temporal dynamics remains limited.

Key findings from applying the approach to the case of the mineral-energy nexus exemplify the usefulness of the approach.

- *Eigenzeiten* and other temporal characteristics of the two sectors are very different. Still, the suggested approach allowed considering both sectors' dynamics together.
- The temporal perspective adds another layer to inform decision-making. For example, recycling is to be favored over mining from a temporal perspective, because of the extremely long and thus often uncontrollable time spans related to mining side-effects.
- A temporal perspective also adds another argument for the relevance of transdisciplinary practice-science collaborations to meet sustainability challenges. Because a higher diversity of backgrounds, experiences and trainings minimizes perception lags, transdisciplinary practice-science collaborations may contribute to avoiding problematic long-term developments. This is especially relevant for strategy building and risk governance for complex transformation challenges at the nexus of two or more sectors.

The suggested time-in-transformations-approach offers two key contributions:

- First, the approach allows making use of temporal system understanding for studying and fostering transformation processes towards sustainability. It may be included in or adapted to transformation management approaches such as transition management or adaptive management. In this context, the design guidelines for interventions of step 3 seem to be of particular interest.
- Second, the combination of time ecology with conceptualizations of transformation processes and the differentiation between spheres of a system allows placing and designing an intervention according to its intended effect. This may either be to protect a system and strengthen its adaptive capacity, or to add to its transformative capacity to destabilize and thus overcome unsustainable path dependencies. The approach allows placing interventions in a way that they trigger change in the targeted sphere, while negative impacts on the other spheres can be minimized.

The time-in-transformations-approach suggested in this article may help to avert decisions with potentially long-term adverse effects and enable to use opportunities. In doing so, it can also contribute to moving the 'time rhetoric' of the global sustainability discourse from an implicit, one-dimensional understanding to a shared and operational understanding of time and a more precise wording regarding temporal diversity.

Table 4.2: Temporal features of metal use in renewable energy technologies - the example of neodymium. Features are chosen according to Fig. 4.3. Sectors are indicated with “metal” for metal use and “RE” for renewable energy use.

Temporal feature	Sectors	Example from the natural sphere	Example from the socio-technical sphere	Example from the regulatory sphere (governance, intervention measure)
duration	metal	time for formation of ore deposits, half-life of Thorium (is mined with Neodymium)	time needed for site development (mine/wind farm) or the development of recycling infrastructure	time needed for a new policy or legislation to be developed, agreed and implemented, possibly as a reaction to occurring change
	RE	period of specific wind conditions		
point in time	metal	eruption of a volcano (leading to copper mineralization via hydrothermal circulation)	specific moment for emission measurements of a mine	issuance of a new law, of new (regional) planning
	RE	solar eclipse	new turbine technology enters the market	
rhythm	metal	formation of sedimentary rocks	innovation cycles; market cycles (supply and demand); product life-cycles	legislative periods
	RE	seasons: rhythms of global radiation intensity and wind	repowering cycles of wind turbines, regular maintenance	
metronomic beat	metal	- not observed -	machines, e.g. in ore extraction	- not observed -
	RE		generator frequency	
speed acceleration deceleration	metal	speeds of hydrothermal processes that lead to ore deposits	increasing speed of technological innovation and product life cycles	increase in amount of information available to digest and react upon prolongs overall reaction times
	RE	wind speed, tempo of weather changes	inconstant wind speeds lead to fluctuating electricity generation	
timing	metal	availability of porphyry ore deposits at the surface: ores formed in the Phanerozoic and were subject to geologic processes since	collect materials on time for recycling; open new mine in time to react to increasing demand	issue a policy in accordance with others with which it interacts, e.g. EU raw materials initiative, national resource strategies
	RE	wind when electricity is needed	get biogas power plants running in time to even out fluctuations from wind and solar energy	start a wind farm project in timely reaction to spatial planning roll-outs
time lag	metal	groundwater contamination from mining only becomes apparent once the groundwater reaches the surface again	supply with critical metals, as by-products, is coupled to major metal demand, supply with critical metals might not meet demand and possibly lead to delays in supply	delayed perception of and reaction to (hidden) negative side-effects of mining
	RE	influences on species diversity when wind farms cause habitat changes	delays in construction because of the availability of materials or construction parts; delays because of long administrative processes	delayed perception of and reaction to e.g. spatial planning concerning the use of RE
temporal webs	metal	interplay of e.g. a volcano eruption and specific pressure and temperature that allow ore mineralization	interaction of supply and demand patterns (production and transportation times, raw material trade, ...)	connectedness of decisions and strategies/programs: issued to different points in time on different scales from global to local, time lags between decision taking and corresponding activities, differing durations of interlinked processes
	RE	interplay of weather conditions, e.g. intensities of wind and radiation, for RE generation	interaction of supply and demand patterns: daily, weekly, seasonal rhythms of demand <-> non-related rhythms of RE potential and supply	

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Transdisziplinarität: Forschungsansatz für die Energiewende

Lotte M. Lutz und Matthias Bergmann

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1. Einleitung

Die Energiewende ist eine der großen gesellschaftlichen Herausforderungen unserer Zeit (WBGU, 2011), die über einen Wandel des technischen Energiesystems weit hinausgeht. Sie bringt eine tiefgreifende Veränderung in der Energiewirtschaft mit sich, die sich unter anderem in der neuen Rolle der Energienutzer als Konsumenten und Produzenten von Energiedienstleistungen wiederspiegelt (sogenannte Prosumer: Gährs, Wieckowski, von Braunmühl, Wolfmaier & Hirschl, 2015). Der WBGU fordert eine integrierte Energie-, Umwelt- und Klimapolitik, um Rahmenbedingungen für die Gestaltung der Energiewende zu entwickeln, die diese neuen komplexeren Bezie- hungen abbilden und verlässlich strukturieren können (WBGU, 2012). Eine einfache Top-Down-Steuerung dieser Veränderungsprozesse ist aufgrund ihrer Komplexität nicht möglich (Brinkmann, Bergmann, Huang-Lachmann, Rödder & Schuck-Zöller, 2015). Transdisziplinäre Forschung ist ein erfolgreicher Ansatz, um Lösungen für solche komplexen Probleme wie die Herausforderungen nachhaltiger Entwicklung zu identifizieren und weiterzuentwickeln (Bergmann et al., 2010, S. 23 ff; Lang et al., 2012). Im Folgenden wird Transdisziplinarität als Forschungsansatz für die Energiewende konzeptionell eingeführt. Darüber hinaus werden beispielhaft einige Projekte aus Forschung und Lehre aus dem Themenfeld der Energiewende vorgestellt.

2. Transdisziplinäres Forschen

2.1 Entstehung – Zielsetzung – Prinzipien

Die historische Entwicklung des transdisziplinären Forschungsansatzes sowie eine Darstellung der verschiedenen Herangehensweisen und vielfältigen Methoden kann hier nur gestreift werden. Eine ausführliche Darstellung ist beispielsweise in Brinkmann et al. (2015) sowie Jahn, Bergmann und Keil (2012) zu finden; eine stärker wissenschaftstheoretische und -soziologische Betrachtung publizierte Stauffacher (2011). Der wissenschaftliche Diskurs zur Transdisziplinarität wird bereits seit mehr als 40 Jahren geführt (Jahn et al., 2012). Denkansätze wie die „post-normal science“ (Funtowicz & Ravetz, 1993; Ravetz, 1999) und insbesondere die „mode 2 science“ (Gibbons et al., 1994) waren prägend. Eng verknüpft ist die Transdisziplinarität in der deutschen Forschungslandschaft mit der Sozial-ökologischen Forschung (z. B. in der gleichnamigen Fördermaßnahme des Bundesministeriums für Bildung und Forschung) sowie der Entwicklung der Nachhaltigkeitsforschung (Jahn et al., 2012; Spangenberg, 2011). Die folgende Definition aus Jahn et al. (2012, S. 26 f.) formuliert eine gemeinsame Basis für verschiedenen Strömungen der transdisziplinären Forschung:

> „Transdisciplinarity is a reflexive research approach that addresses societal problems by means of interdisciplinary collaboration as well as the collaboration between researchers and extra-scienti c actors; its aim is to enable mutual learning processes between science and society; integration is the main cognitive challenge of the research process.“

Ausgangspunkt transdisziplinärer Forschung ist, dass einzelne disziplinäre Perspektiven nicht ausreichen, um komplexen gesellschaftlichen Herausforderungen, so- genannten „real world problems“ (Thompson Klein et al., 2001), wissenschaftlich zu begegnen und passende Lösungen zu entwickeln. Vielmehr ist ein Forschungsansatz notwendig, der neben dem Verknüpfen verschiedener wissenschaftlicher Perspektiven auch ausgewählte Akteure mit einbezieht, die sich durch eine besondere Betroffenheit, besonderen Einfluss oder besonderes Wissen über das Problem auszeichnen.

Die Zusammenarbeit mit Praxispartnern wird entsprechend der Problemstellung und der Zielsetzung des Vorhabens gestaltet. Dies betrifft Intensität und Methode der Zusammenarbeit, die Wahl der Praxispartner sowie die Abgrenzung des zu untersuchenden Themas (Jahn et al., 2012; Krütli, Stau acher, Flüeler, & Scholz, 2010). Strukturierte transdisziplinäre Forschungsprozesse durchlaufen mehrere Phasen, in denen die Zusammenarbeit mit Praxispartnern unterschiedlich intensiv ist (siehe folgenden Abschnitt zum ISOE-Modell). Auch Erfahrungen anderer Forschergruppen zeigen, dass die Intensität der Zusammenarbeit mit Praxispartnern im Verlauf des Projektes unterschiedlich hoch ist, da je nach Phase verschiedene Ziele verfolgt und dementsprechend verschiedene Methoden und Modi der Zusammenarbeit eingesetzt werden (Stauffacher, Krütli, Flüeler, & Scholz, 2012).

Das gemeinsame Lernen von Personen mit unterschiedlichen professionellen, also wissenschaftlich-fachlichen oder auch allgemein gesellschaftlichen Hintergründen und Interessen in Bezug auf das Problem erfordert einen sehr hohen Grad der Integration verschiedener Wissensarten oder von „Denkstilen“ (Fleck, 1983; Pohl & Hirsch Hadorn, 2008). Für transdisziplinäre Forschungsprozesse ist daher nicht nur eine Reflexion der Inhalte, sondern auch ganz besonders des eigenen Denkstils sowie eine selbstreflexive Vorgehensweise essentiell. Diese Herausforderung nimmt im ISOE-Modell eine hervorgehobene Stellung ein.

2.2 Transdisziplinarität als integraler Bestandteil sozial-ökologischer Forschung: das ISOE-Modell

Einen sicheren Rahmen bieten soll ein modellhaftes, idealtypisches Schema für einen transdisziplinären Forschungsablauf. Die Prozesse mit so heterogenen Partnern aus Wissenschaft und Gesellschaft, die oft mit Stichworten wie Co-Design oder Co-Production gekennzeichnet werden und in denen gemeinsames Lernen im Vordergrund steht, können eine klare und auf Methoden gestützte Rahmung gut gebrauchen. Doch es soll auch offen genug sein, um – bei aller Sicherheit – auch anpassungsfähig an die vielen Spielarten von Forschungsdesigns und -kontexten zu sein und sie alle gleichermaßen zu unterstützen.

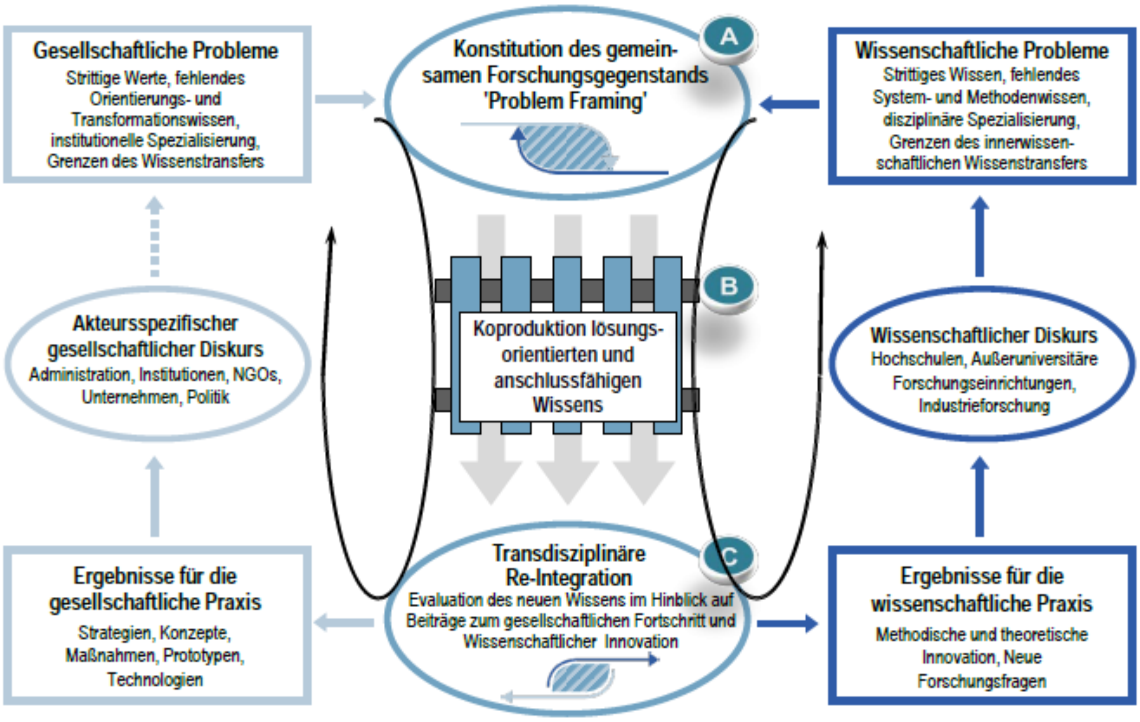

Abb. 5.1 ISOE-Modell eines idealtypischen, reflexiven transdisziplinären Forschungsprozesses*. Quelle: Jahn et al. (2012); eigene Übersetzung und Ergänzung.*

Das sogenannte ISOE-Modell des idealtypischen, reflexiven transdisziplinären Forschungsprozesses (Abb. 5.1) ist am Institut für sozial-ökologische Forschung (ISOE) aus der Reflexion der eigenen Praxis einer transdisziplinären sozial-ökologischen Forschung heraus entstanden und wurde im Rahmen verschiedener konzeptioneller Forschungsprozesse über Transdisziplinarität weiterentwickelt.

Das Modell geht von drei grundlegenden Erkenntnissen aus:

1) Zur Bearbeitung realweltlicher Problemstellungen bedarf es der Beteiligung verschiedener fachlicher Zugänge in der Wissenschaft und der Alltagsexpertise aus der Zivilgesellschaft, aus Wirtschaft und/oder Politik. Hier ist die erste ‚Bewegung' durch Differenzierung gekennzeichnet, also durch das Erkennen und Anerkennen der unterschiedlichen Wissensbestände aus Wissenschaft und Praxis, die für die Problemlösung bzw. -transformation herangezogen werden müssen und je eigene Beiträge liefern können. Dabei geht es um das gleichberechtigte Nebeneinanderstellen des jeweiligen Wissens und das Vermeiden von Leitdisziplinen oder fachlichen Hegemonien.

Notwendigerweise ist die folgende Aufgabe, die sich durch den ganzen Forschungsprozess hindurchzieht, die Integration, also das lösungsorientierte Zusammenführen dieser Wissensbestände mit dem Ziel, eine integrierte, das ganze Problem – und nicht allein disziplinbezogene Spezialfragen betreffende – Lösungsstrategien zu erarbeiten. Dabei gilt es, drei Dimensionen der Integration zu berücksichtigen:

- Eine kognitiv-epistemische Dimension der Wissensintegration, in der es um das Unterscheiden und Verknüpfen von disziplinären Wissensbeständen sowie von wissenschaftlichem und alltagspraktischem Wissen geht;
- eine Dimension der sozialen und organisatorischen Integration, in der das Unterscheiden und Verknüpfen von Ansprüchen, Aktivitäten, Wünschen, Erwartungen unterschiedlicher Individuen, Gruppen, Institutionen und zwischen Teilprojekten angestrebt wird;
- und eine Dimension der kommunikativen Integration, die das Unterscheiden und Verknüpfen der kommunikativen Praktiken und Begriffe der beteiligten wissenschaftlichen und gesellschaftlichen Akteure betrifft (Bergmann et al., 2010, S. 41).

Methoden für die Integration in diesen drei Dimensionen werden ausführlich in Bergmann et al. (2010) beschrieben. Diese reichen von theoretischen Rahmenkonzepten unter anderem über Modelle und Bewertungsverfahren bis hin zu integrativ wirkenden Kooperationsformen in Projektteams und der damit zusammenhängenden Formulierung der Forschungsfragen.

Am Ende des Prozesses steht der Vorgang der Intervention. Das heißt, mit den Forschungsergebnissen wird in das gesellschaftliche Problemfeld und in den wissenschaftlichen Diskurs interveniert, um zu Problemlösung und wissenschaftlicher Innovation beizutragen (Bergmann & Jahn, 1999, S. 258ff.).

2) In der Regel führt die Komplexität der gesellschaftlichen Problemlage zu einem sehr heterogenen institutionellen und personellen Setting. Wenngleich der Forschungsprozess in der Regel wegen der Aufgabe einer Problemlösung bzw. -transformation in einem gesellschaftlichen Handlungsfeld initiiert wird, treten doch spätestens beim Zusammenstellen des Teams aus Wissenschaft und Praxis zusätzliche Probleme auf – solche wissenschaftlicher Art, die insbesondere fehlende Methoden, disziplinäre Grenzen und fehlende Kommunikationsstrategien betreffen. Das Forschungsteam hat also die Aufgabe, während des gesamten Prozesses zwei Pfade parallel zu führen, die zudem epistemisch sehr unterschiedliche Charaktere besitzen. Diese werden in der Abbildung durch die beiden gekrümmten Pfeile gekennzeichnet. Die Besonderheit – und der Reiz – des integrativen transdisziplinären Forschungsprozesses ist es also, dass er gleichzeitig eine lebensweltlich-problembezogene und eine wissenschaftliche Herausforderung aufgreift. „Nur die Parallelführung erzeugt einen Mehrwert (...) und weist über eine reine Einzelfallforschung bzw. disziplinbezogene Forschung hinaus“ (Bergmann et al., 2010, S. 32).

3) Ein solcher Balanceakt zwischen wissenschaftlicher, interdisziplinärer Genauigkeit einerseits und gesellschaftlicher Nützlichkeit andererseits erfordert von allen Beteiligten ein hohes Maß an (Selbst-)Reflexivität. Insofern sind Verfahren der Selbstevaluation (Bergmann et al., 2005), der Iteration und Rekursivität sowie der gezielten und dauerhaften Kooperation zwischen Disziplinen bzw. zwischen Wissenschafts- und Praxisakteuren z. B. in Form von Tandems (Bergmann et al., 2010, S. 117 .) angebrachte Hilfsmittel, um insbesondere immer wieder den Problem- bezug der Forschungsarbeiten zu überprüfen.

3. Beispiele für transdisziplinäre Forschung zur Transformation des Energiesystems

Im Rahmen des Förderschwerpunkts „Sozial-ökologische Forschung“ des Bundesministeriums für Bildung und Forschung (BMBF) werden seit 2013 in der Fördermaßnahme „Umwelt- und gesellschaftsverträgliche Transformation des Energiesystems“ 33 Forschungsverbünde gefördert (https://www.fona.de/de/15980, 22.2.2016). In der Förderbekanntmachung zur Maßnahme hieß es, dass Vorhaben gefördert wer- den, „die inter- und transdisziplinären Forschungsansätzen folgen und auf diese Weise ökologische, ökonomische, soziale und technische Aspekte in einer problembezogenen Perspektive verknüpfen“ (BMBF, 2011). Es sei dabei eine enge Kooperation zu gewährleisten „mit Partnern aus der Praxis (kommunale Verwaltung, Wirtschaft, Unternehmensverbände, Verbraucherorganisationen, NGOs), die in die Konzipierung des Forschungsvorhabens einbezogen werden sollen“ (BMBF, 2011).

Damit wird ein weitreichender transdisziplinärer Forschungsansatz beschrieben, in dem sogar die Konzipierung der Forschung partizipativ geschehen soll. Forschungsfragen, Fragen der Zusammenarbeit und Wissensintegration werden also zwischen Wissenschaft und Praxispartnern gemeinsam formuliert und konzipiert.

Schaut man sich die einzelnen Vorhaben an, so stellt man fest, dass gerade Fragen der Beteiligung von Bürgerinnen und Bürgern, von zivilgesellschaftlichen Organisationen, von Verbänden, Genossenschaften, Kommunen, Energieversorgern und -dienstleistern u. a. m. als zentraler Forschungsgegenstand angesehen werden. Dabei gilt es zu unterscheiden zwischen Vorhaben, die partizipative Verfahren und Methoden selbst entweder initiieren oder durchführen, und solchen, die vorhandene partizipative Vorgänge beispielsweise in Kommunen beobachten, also über Partizipation forschen.

Begleitet wird die Fördermaßnahme durch ein Projekt der Wissenschaftlichen Koordination, in dem Synthese und Kooperation zwischen den Vorhaben und der Transfer der Ergebnisse unterstützt werden und eine Studie über die Methoden und Qualitätsmerkmale der Partizipation durchgeführt wird (http://www.fona.de/ de/15980, 26.11.2015). Zur Unterstützung dieser Zielsetzungen wurden die 33 Vorhaben in fünf Cluster zusammengefasst: Partizipationsstrategien, Governance, Entwicklungsoptionen, Gebäude & Siedlungen sowie Bürger, Verbraucher, Mieter & Geschäftsmodelle (siehe hierzu auch die Transfer-Plattform: http://transformation- des-energiesystems.de/, 26. 11. 2015).

Hier sollen zur Veranschaulichung nur einige wenige Projektbeispiele mit ihren zentralen Untersuchungsfragen genannt werden:

- Projekt Dezent Zivil: Wie können Planungs- und Genehmigungsverfahren von dezentralen Energieanlagen verbessert werden, um Konflikte zu verringern? (http://www.dezent-zivil.de, 11. 12. 2015)
- Projekt Energiekonflikte: Was sind die Motive und Argumente der Gegner von Projekten und Instrumenten der Energiewende? Wie können Beteiligungsprozesse soziales Lernen fördern? (http://www.energiekonflikte.de, 11. 12. 2015)
- Projekt Akzente: Welche Technologien können Schwankungen bei erneuerbaren Energien optimal ausgleichen? Wie lässt sich der Ausgleich so gestalten, dass er vor Ort auf Akzeptanz stößt? (http://fg-umwelt.de/index.php?id=195, 11. 12. 2015)
- Projekt DZ-ES: Welche Vor- und Nachteile bringt eine stärkere lokale Beteiligung an der Planung und Finanzierung von dezentralen Energieanlagen und den entsprechenden Stromverteilnetzen? (http://dz-es.de/, 11. 12. 2015)
- Projekt EnerLOG: Wie entstehen neue Organisationsformen aus lokalen energiepolitischen Kon ikten? Welche neuen Arten der Steuerung gehen mit ihnen ein- her? (http://www.zab-energie.de/de/Projekt-EnerLOG, 11. 12. 2015)

- Projekt Transparenz Stromnetze: Kann die Beteiligung von Bürgerinnen und Bür- gern an den Verfahren zum Netzausbau durch unabhängige, transparente Informa- tionen unterstützt werden? (http://www.transparenz-stromnetze.de, 11. 12. 2015)
- Projekt TransStadt: Wie nehmen Kommunen die Herausforderungen der Energiewende auf? Wie managen sie den Übergang zu neuen Energiesystemen? (http://www.difu.de/projekte/2013/transformation-des-staedtischen-energiesystems-und.html, 11. 12. 2015)
- Projekt Vernetzen: Kann die Integration von sozial-ökologischen Schlüsselfaktoren und Erfolgsfaktoren der Partizipation in eine bisher rein technisch-ökonomisch ausgerichtete Strommarktmodellierung den Netzausbau und den Anlagenneubau gesellschaftsverträglich befördern? (https://www.izt.de/projekte/pro ject/vernetzen, 22. 2. 2016)
- Projekt InnoSmart: Wie können Haushalte in ihrer Rolle als Energieproduzenten gestärkt werden? Sind Smart-Grids die Lösung? Wie können sie eingeführt werden? (http://www.innosmart-projekt.de, 11. 12. 2015)
- Projekt SoKo Energiewende: Welche finanziellen Belastungen hat die Energiewen- de für Haushalte? Was heißt Energiearmut und wie kann ihr vorgebeugt werden? (http://www.zew.de/soko2013, 11. 12. 2015)

Das BMBF hat also bereits mit der Ausschreibung der Fördermaßnahme den transdisziplinären Ansatz vorgegeben, um sicherstellen zu können, dass die sogenannte Bürger-Energiewende durch die Forschungsvorhaben neue Handlungsstrategien er- hält, dass also „sozial robustes Wissen“ (Nowotny, 1999), also Wissen, das auf Akzeptanz stößt und zur Anwendung gelangt, erzeugt wird, um die Energiewende vor Ort zu unterstützen.

Es gibt andere Herangehensweisen, die ebenfalls den Gedanken verfolgen, eine Nachhaltigkeitstransformation anzustoßen. Diese sind allerdings weniger auf bestimmte Akteure bzw. Akteursgruppen bezogen, sondern auf konkrete Orte. Dahinter steht – wie beispielsweise beim Ansatz des Transition Management (Loorbach & Rotmans, 2010) – der Gedanke, dass lokale ‚Nischen‘ gebildet werden, die dann bei erfolgreicher ‚Transition‘ als Good-Practice-Beispiel für vergleichbare andere Orte dienen.

Durch das Ministerium für Wissenschaft und Kunst des Landes Baden-Württemberg werden sogenannte Real-Labore gefördert. Im Ausschreibungstext dazu heißt es: „In Reallaboren lassen sich reale gesellschaftliche Problemstellungen und Wandlungsprozesse, wie z. B. die Sanierung von Stadtteilen oder die Einführung nachhaltiger Mobilitäts- oder Energiesysteme, in Realexperimenten initiieren und wissenschaftlich begleiten“ (Ministerium für Wissenschaft, Forschung und Kunst Baden

Württemberg, 2013). Wissenschaft begleitet also gesellschaftliche Entwicklungen. Eines der sieben Reallabore der ersten Staffel in Baden-Württemberg befasst sich auch mit Energiefragen: Das „EnSign Reallabor für einen klimaneutralen Innenstadtcampus“ (http://www.hft-stuttgart.de/Forschung/Projekte/Projekt131.html/de, 27.11.2015) stellt den Transformationsprozess zu einer klimaneutralen Hochschule in den Fokus, darin auch das Bereitstellen erneuerbarer Energien auf dem Campus der Hochschule für Technik Stuttgart. Neben zwei Hochschulinstituten sind 15 sehr unterschiedliche Praxispartner in dem von der Hochschule konzipierten Vorhaben involviert. Hier verschwimmen die Grenzen zwischen einer lokal begrenzten transdisziplinären Fallstudie und dem Reallabor Hochschule – jedenfalls vom Ansatz her. Wie sich das Vorhaben, das 2014 begonnen wurde, entwickelt, wie seine angestrebte Verstetigung über den Förderzeitraum hinaus gelingt, ob das Realexperiment in der Transformations-Nische gelingt, kann noch nicht beurteilt werden.

Es würde hier zu weit führen, den Diskurs darüber wiederzugeben, der Fragen dazu behandelt, ob das Forschung ist, ob nicht meist doch Wissenschaft und eher selten Praxisakteure Initiator der Prozesse sind (wie beispielsweise bei den Reallaboren in Baden-Württemberg), ob das dem Gedanken von Co-Design und Kollaboration näher kommt oder gerade nicht, weil nun die Wissenschaft nur begleitet und nicht kollaboriert, und andere mehr (hierzu: Wagner & Grunwald, 2015).

Eines steht außer Zweifel – ob transdisziplinäre Forschung, Transition Management, Reallabore, City Labs oder noch andere Ansätze – es handelt sich bei allen um Versuche, mittels partizipativer Vorgehensweisen gesellschaftliche Transformationen anzustoßen – ob es nun Forschung ist oder eher Entwicklung oder Prozessmanagement. Wie geeignet sie jeweils sind, hängt vom Charakter des Ausgangsproblems ab, vom gesellschaftlichen Kontext und den involvierten Akteuren und vor allem von der Frage, welches neue Wissen in solchen Prozessen zunächst fehlt und darin – mit welchen Methoden – erarbeitet werden soll.

Die idealtypische Antwort auf diese Frage gibt die Unterscheidung in

- Systemwissen, das benötigt wird, Wissen über Genese und mögliche Entwicklungen des Problems zu erhalten;
- Zielwissen, das den Veränderungsbedarf und erwünschte Ziele sowie bessere Praktiken im gesellschaftlichen Problemfeld beschreibt;
- und Transformationswissen, das Handlungsmöglichkeiten zur Veränderung bestehender und Einführung erwünschter Praktiken im gesellschaftlichen Problemfeld beschreibt (Pohl & Hirsch Hadorn 2006, S. 32 .).

Ist also das Wissen über das Ausgangsproblem relativ groß und unumstritten und gilt dies auch für die Zielzustände, die man mit der erwünschten Transformation im Problemfeld erreichen will, so kann sich der Forschungsprozess ganz auf das Er- arbeiten von Transformationswissen konzentrieren. Das beschreibt der linke Strang des ISOE-Modells (Abb. 5.2), denn hier muss allein der Pfad der Problemlösung beschritten werden. Das integrierte Modell von Abb. 5.3 wird also nicht mehr in Gänze benötigt.

Es gibt aber durchaus auch Problemlagen, bei denen schon die Verständigung über das Ausgangsproblem schwierig ist, die Sichtweisen für Ursachen und Entwicklungen höchst unterschiedlich sind und zunächst Klarheit darüber hergestellt werden muss.

Dann geht es also um das Erarbeiten von Systemwissen, um zunächst einmal das Problem klar und in allgemein akzeptierter Weise beschreiben zu können, bevor Schritte zu seiner Lösung bzw. Transformation unternommen werden können. Da- bei wird also zunächst allein der rechte Pfad des ISOE-Modells beschritten, in dem es noch nicht um die Lösung des Problems geht, sondern um die durchaus auch im transdisziplinären Setting zwischen Wissenschaft und Gesellschaft geführte Auseinandersetzung mit dem Ziel einer geteilten Ursachenbeschreibung (Abb. 5.3).

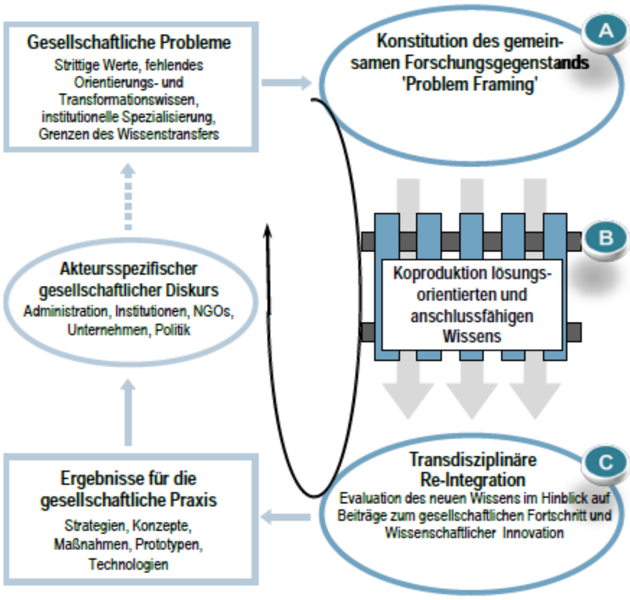

***Abb. 5.2: Erarbeiten von Transformationswissen** für die gesellschaftliche Problemtransformation / Problemlösung*

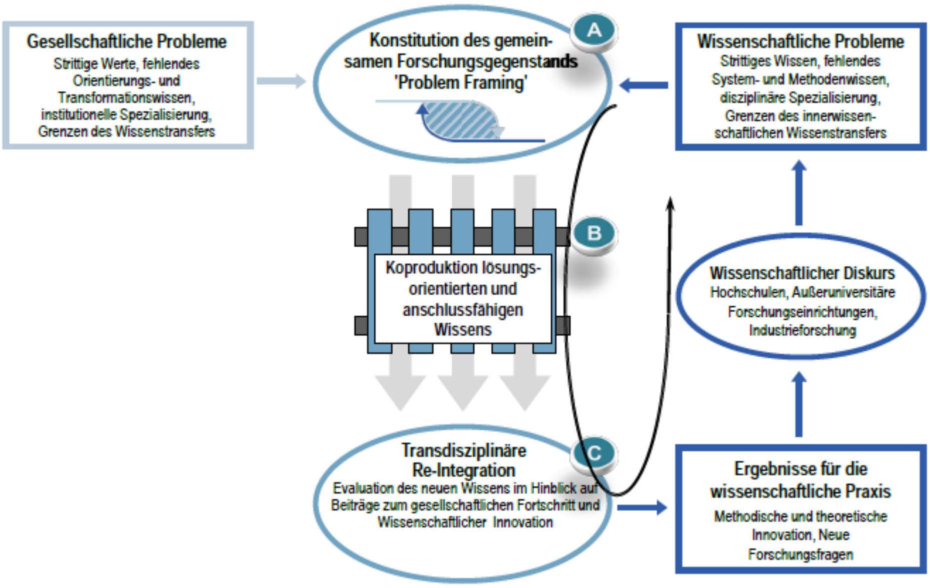

***Abb. 5.3: Erarbeiten von Systemwissen** für ein besseres Problemverständnis*

Die Energiewende scheint zunächst nur der Erarbeitung des Transformationswissens, also von Wissen darüber, wie man es machen kann, zu bedürfen. Denn das Ziel ist klar, Ausstieg aus fossiler und nuklearer und Ersatz durch erneuerbare Energie (wenngleich politische Szenarien für Zielkorridore durchaus in verwirrend vielen Varianten vorliegen). Schaut man genauer hin, so fehlt es doch an Systemwissen und teilweise auch an Zielwissen. Die Auseinandersetzungen beispielsweise über Trassenverläufe und unerwünschte Wirkungen und Einflüsse von Windkraftanlagen, vor allem aber auch über die Volatilität der erneuerbaren Energien und die damit verbundenen rechtlichen bzw. gesetzgeberischen Instrumente mit ihren Wirkungen auf den Markt und die Beteiligungsmöglichkeiten, aber auch über die sogenannte Energiearmut und Maßnahmen zu ihrer Verhinderung machen deutlich, dass nicht nur die Möglichkeiten der Zielerreichung noch stark umstritten sind, sondern dass Einigkeit über die Beschreibung des Ausgangsproblems und die Dringlichkeit der Transformation des Energiesystems noch nicht erreicht ist.

Wenn man zudem nicht nur den Stromsektor betrachtet, sondern die Bereiche der Wärmeversorgung und der Mobilität hinzunimmt, werden die Dinge noch komplizierter, denn hier geht es noch viel stärker um Fragen des Komforts, des Lebensstils, der alltäglichen Routinen, aber auch der technischen Machbarkeit von Fahrzeugen, so dass die Problembeschreibung noch viel stärker umstritten ist.

All das sind Hinweise darauf, dass die ‚Bürger-Energiewende' nur zusammen mit den Bürgerinnen und Bürgern durchgesetzt werden kann, dass Transformation ein partizipativer Prozess sein muss, wenn er gelingen soll. Die Forschung befindet sich also mit Programmen wie der Sozial-ökologischen Forschung des BMBF auf dem richtigen Weg, allerdings sind die großen Fördersummen und langfristigen Forschungsvorhaben noch immer vorwiegend im Bereich der Technik-Forschung zu verorten.

4. Transdisziplinarität in der universitären Lehre

Die Studierenden der Umwelt- und Nachhaltigkeitswissenschaften der Leuphana Universität Lüneburg führen inter- und transdisziplinäre Forschungsprojekte durch (Leuphana Universität Lüneburg, 2015), die sich an den drei Phasen des ISOE-Modells orientieren (Abb. 5.1). Für die Lehre wurde das ISOE-Modell in ‚12 Schritte des idealtypischen transdisziplinären Forschungsprozesses' untergliedert und Schritt für Schritt so beschrieben, dass die Studierenden einen Rahmen für Konzipierung und Durchführung ihrer transdisziplinären Projekte im Rahmen der Projektseminare zur nachhaltigen Entwicklung haben. Diese Projekte des sogenannten forschenden Lernens stellen Studierende wie Lehrende durch ihre immer wieder neuen inhaltlichen wie personellen Kontexte vor große Herausforderungen, bei denen ein Orientierungsrahmen willkommen ist. Die Studierenden arbeiten in diesen Projekten weitgehend selbständig und selbstorganisiert und werden dabei durch die Lehrenden unterstützt (Vilsmaier & Lang, 2015).

Im Folgenden stellen wir beispielhaft ein Projekt aus dem Bachelorstudiengang Umweltwissenschaften dar, das von April 2015 bis März 2016 stattfand.[1] Das Projekt begleitete die Implementierung von Integrierten Energetischen Quartierskonzepten für zwei Lüneburger Quartiere, die zu Projektstart neu vorlagen. Entsprechend war das Thema des Projektes "Nachhaltige Energiesysteme in Lüneburger Stadtquartieren: Chancen, Grenzen, Perspektiven." Praxispartner des Projektes war die Klimaschutzleitstelle (KSL) Lüneburg. Darüber hinaus war geplant, mit der Sanierungsmanagerin bzw. dem Sanierungsmanager zusammenzuarbeiten, leider wurde diese Stelle bis zum Ende der Projektlaufzeit nicht besetzt.

4.1 Phase A: Konstitution des gemeinsamen Forschungsgegenstands

Bereits vor Semesterbeginn hatten die Lehrenden Kontakt zur KSL aufgenommen und gemeinsam einen Themenbereich für das Projekt definiert. Innerhalb dieses Themenbereichs entwickelten die Studierenden im Seminar entsprechend ihrer Interessen unter Anleitung konkrete Fragestellungen. Eine besondere Herausforderung in dieser Phase studentischer Forschungsprojekte ist, dass die ganze Gruppe den Forschungsgegenstand ‚begreift' und ein

[1] Den Lehrenden des Seminars, Annika Weiser und Manuel Bickel, einen herzlichen Dank für Informationen und Material zu diesem Projekt.

gemeinsames Verständnis entwickelt. In diesem Projekt führten die Studierenden sogenannte „transect walks“ durch (Caniglia et al., 2016): sie liefen in kleinen Gruppen durch die beiden Stadtquartiere und nahmen, angeleitet durch Fragestellungen, nicht nur die Strukturen und Funktionen der Quartiere wahr, sondern auch deren Herausforderungen in Bezug auf die Umsetzung eines nachhaltigen Energiekonzepts. Bei einem gemeinsamen Treffen von Seminargruppe und Praxispartnern standen die entwickelten Forschungsfragen und mögliche Zielsetzungen für das Projekt zur Diskussion. Bei diesem Treffen wurde erfolgreich ein gemeinsames Verständnis des Problems und der Ziele im Projekt erarbeitet.

In solchen Projekten forschenden Lernens muss immer eine Abwägung zwischen dem Erlernen des Forschungshandwerks und der inhaltlichen Vertiefung stattfinden. In diesem Projekt wurde den Studierenden viel Zeit eingeräumt, innerhalb eines Themenfelds eine aus wissenschaftlicher und Praxissicht relevante Forschungsfrage zu entwickeln, die innerhalb der Projektlaufzeit beantwortet werden kann. Diese Phase der Entwicklung des gemeinsamen Problemverständnisses und der Gruppenbildung hat das Sommersemester in Anspruch genommen.

4.2 Phase B: Koproduktion lösungsorientierten und anschlussfähigen Wissens

Die inhaltliche Arbeit fand in drei Arbeitsgruppen statt, die sich untereinander in regelmäßigen Abständen über Vorgehen und Zwischenergebnisse austauschten. Die KSL wurde in den Sommermonaten kontinuierlich durch Ergebnisprotokolle der Seminarsitzungen über den aktuellen Stand des Projektes informiert. Darüber hinaus standen die Gruppen auch in telefonischem Kontakt mit der KSL, beispielsweise um Ansprechpartner zu vermitteln oder Daten auszutauschen.

Beispielhaft soll hier das Vorgehen einer der drei Arbeitsgruppen skizziert warden. Eine der Arbeitsgruppen untersuchte, inwieweit die Umsetzung der Quartierskonzepte zu einer nachhaltigen Entwicklung in den Stadtquartieren beitragen würde. Dazu identifizierten die Studierenden mittels Literaturrecherche Indikatoren für nachhaltige Energiesysteme auf Stadtquartiersebene. Das resultierende Set von Indikatoren diskutierten die Studierenden mit verschiedenen Praxisexperten: den MitarbeiterInnen der KSL, QuartiersmanagerInnen anderer Städte und den Autoren der Lüneburger Quartierskonzepte. Auf Basis der gemeinsamen fachlichen Diskussionen überarbeiteten die Studierenden das Set von Indikatoren und führten damit anschließend eine Nachhaltigkeitsbewertung der Quartierskonzepte durch. Dabei reflektierten Sie auch die Frage, welcher Beitrag zur Energiewende auf Quartiersebene geleistet werden kann.

4.3 Phase C: Transdisziplinäre Re-Integration

In diesem Projekt erarbeiteten die Studierenden sowohl Systemwissen (Abb. 5.3) als auch Transformationswissen (Abb. 5.2). Daher entstanden zwei ‚Produkte': Zum einen verfassten die Studierenden einen wissenschaftlichen Artikel, in welchem sie einen Fokus auf die methodische Herangehensweise und die Synthese der Ergebnisse hinsichtlich deren wissenschaftlichen Mehrwerts legen. Zum anderen entwickelten die Studierenden einen Leitfaden bezüglich der Anwendung der Energiekonzepte, welcher der KSL und der zukünftigen Sanierungsmanagerin bzw. dem zukünftigen Sanierungsmanager zur Verfügung gestellt wurde. Dieser Leitfaden beinhaltet detailliert all jene Ergebnisse mit besonderer Relevanz für die Umsetzung der Konzepte vor Ort. Bei einem Abschlusstreffen in der KSL stellten die Studierenden ihre Ergebnisse vor und übergaben den Leitfaden.

5. Fazit

Transdisziplinäre Forschung für die Energiewende ermöglicht es, Lösungen für die komplexen Herausforderungen zu finden, vor der die Gesellschaft zur Zeit steht und in den kommenden Jahrzehnten stehen wird. Wie wir gezeigt haben, müssen wir für eine Gestaltung der Energiewende nicht nur Transformationswissen erarbeiten, sondern uns auch fundiert mit einer genauen Beschreibung und einer Einigung über das Ausgangsproblem auseinandersetzen und die Ziele genauer bestimmen. Alle diese Fragen benötigen die durch Konzepte und Methoden transdisziplinärer Forschung geleitete Integration verschiedener Perspektiven.

Bisher ungelöste Aufgaben, wie das Problem der Mehr-Ebenen-Governance zwischen Bund, Land, Region und Kommune, ebenso auch die Frage danach, welche Energiewende wir denn wollen, ob eine, die Bürger/innen bei der Teilhabe unterstützt oder eine durch Politik und Wirtschaft geleitete Energiewende, die von oben herab ganz enge Grenzen setzt, können am besten durch partizipativ angelegte Forschung beantwortet werden. So weisen beispielsweise aktuelle sozial-ökologische, transdisziplinäre Forschungsergebnisse darauf hin, dass Voraussetzungen für gelingende Bürgerbeteiligung bei Infrastrukturplanungen durchaus auch mit der technischen Modellierung von Trassenplanung und Strommarkt zusammengeführt werden können. Auf diese Weise werden Politik und Projektträgern gangbare Wege für eine gesellschaftsverträgliche Entwicklung des Energiesystems aufgezeigt.

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Lüneburg, den 14. 06. 2018