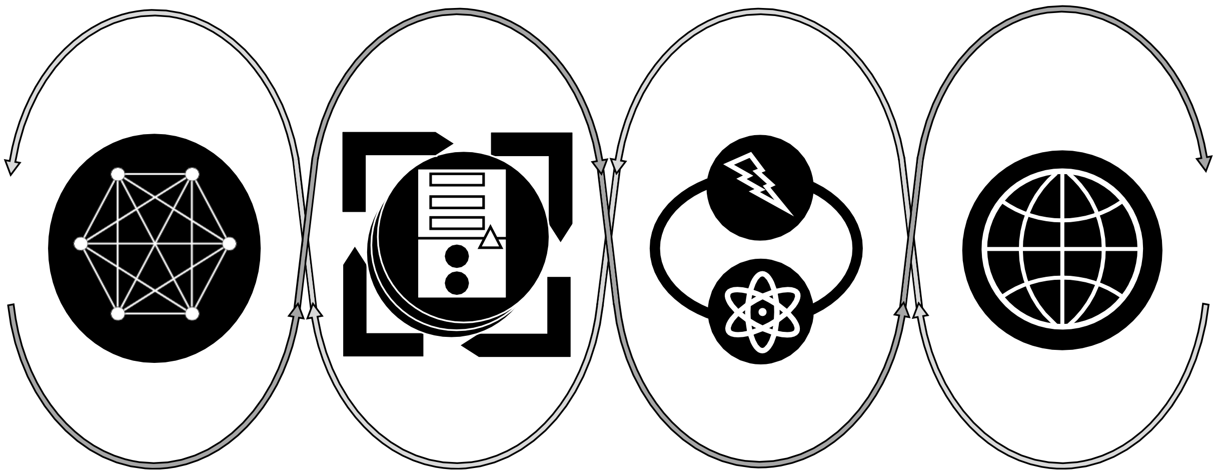
Viable communication systems

Knowledge management and text mining
for reflecting communication patterns
in municipal climate action and
research on sustainable energy



Manuel W. Bickel, 2021

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For achieving a consistent numbering of headlines, figures, and tables, the respective numbering of the journal articles presented in Chapters 5, 6, and 7 is changed in this dissertation in contrast to the formatting used in the published versions. Apart from these formal changes, no content-related changes were applied.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTE ON CITATION STYLES

The chapters of this thesis that form the framework paper (all but Chapter 5, 6, and 7) use the citation style proposed by the American Psychological Association (APA), 7th edition. Chapters 5, 6, and 7, which present the journal articles submitted for this cumulative dissertation, use the citation styles required by the individual journals.

In-text-citations include page numbers when they refer to a book or report with a larger number of pages. They do not include page numbers if they refer to journal articles, conference papers, or short reports.

SUMMARY

Since the middle of the 20th century, human society experiences a "Great Acceleration" manifesting in historically remarkable growth rates that create severe sustainability problems. The globally exploding potentials of information and knowledge exchange have been and are vital drivers for this acceleration. Society has now come to the point that it requires a "Great Transformation" towards sustainability to ensure the viability of the planet for a vital society. The energy transition plays a central role for this transformation. In this context, human society has developed a comparably good understanding of the necessary infrastructural changes of this transition. For transforming the patterns of energy production and use in an energy transition as part of the "Great Transformation", this process of change now needs to strengthen its focus on information, communication, and knowledge systems. Human society needs to establish a knowledge system that has the potential to create usable knowledge for sustainability solutions. This requires organizing a communication system that is sufficiently complex, interconnected, and, at the same time, efficient for integrating reflexive, open-ended, inter- and transdisciplinary learning, evaluation, and knowledge co-production processes across multiple levels. This challenge opens a wide field of research.

This cumulative dissertation contributes to research in this direction by applying a systemic sustainability perspective on the content and organization of communication in the field of research on sustainable energy and the operational level of municipal climate action as part of the energy transition. Regarding sustainability, this thesis uses strong sustainability and its principles as a frame for evaluating the content of communication. Regarding the systemic perspective, the thesis particularly relies on the following theories: (i) the human-environment system model by R. Scholz as an overarching framework regarding interactions between humans and nature, (ii) social systems theory by N. Luhmann to reflect the complexity of society, (iii) knowledge management to consider the human character of knowledge and a practice-oriented perspective, and (iv) management cybernetics, in particular, the Viable System Model by S. Beer as a framework to analyze and assess organizational structures. Furthermore, the thesis leverages the potential of text mining as a method to identify and visualize patterns in texts that reflect prevalent paradigms in communication.

The thesis applies the above conceptual and methodological basis in three case studies. Case Study 1 investigates the measures proposed in 16 municipal climate action plans of regional centers in Lower Saxony, Germany. It uses a text mining approach in the form of an interpretation network analysis. It analyzes how different societal subsystems are connected at the semantic level and to what extent sustainability principles can be recognized. Case Study 2 analyzes and reflects paradigms and discursive network structures in international scientific publications on sustainable energy. The study investigates 26533 abstracts published from 1990 to 2016 using a text mining approach, in particular topic modeling via latent Dirichlet allocation. Case Study 3 turns again to the cases of municipal climate action in Lower Saxony examined in Case Study 1. It examines the involvement of climate action managers of these cities in multilevel knowledge processes. Using design principles for knowledge systems, it evaluates to what extent knowledge is managed in this field across levels for supporting the energy transition and to what extent local innovation potential is leveraged or supported.

The three case studies show that international research on sustainable energy and municipal climate action in Germany provide promising contributions to achieve a transformation towards sustainability but do not fully reflect the complexity of society and still support a growth paradigm, in contrast to a holistic sustainability paradigm. Further, the case studies show that research and local action are actively engaging with the diversity of energy technologies but are lagging in dealing with the socio-epistemic (communication) system, especially with regard to achieving cohesion. Using the example of German municipalities, Case Studies 1 and 3 highlight the challenges of achieving coherent local action for sustainability and bottom-up organizational learning due to incomplete or uncoordinated multilevel knowledge exchange. At the same time, the studies also point out opportunities for supporting the required coherent multilevel learning processes based on local knowledge. This can be achieved, for instance, by strengthening the coordinating role of intermediary organizational units or establishing closer interactions between the local operational units and the national level.

The thesis interprets and synthesizes the results of the three case studies from its systemic sustainability perspective. On this basis, it provides several generalized recommendations that should be followed for establishing viable communication systems, especially but not exclusively in policy-making:

- Systemic holism: Consider matter, energy, and information flows as an integrated triplet in the context of scales, structures, and time in the various subsystems.
- Knowledge society: Focus on the socio-epistemic (communication) system, e.g., using the perspective of knowledge systems and associated design principles considering, for

instance, working environments across horizontal and vertical levels, knowledge forms and types, and knowledge processes.

- Sufficiency communication: Emphasize sufficiency approaches, make it attractive, and find differentiated ways for communicating them.
- Multilevel cohesion and innovation: Achieve cohesion between the local and higher levels and leverage local innovations while avoiding isolated local action.
- Organizational interface design: Define the role of organizational units by the interactions they create at the interfaces with and between societal subsystems.
- Local transdisciplinarity: Support local transdisciplinary approaches integrating various subsystems, especially industry, while coordinating these approaches from a higher level for leveraging local innovation.
- Digital public system: Exploit existing digital technologies or infrastructures in the public system and recognize the value of data in the public sphere for achieving cohesion.

Beyond the above recommendations, this thesis suggests that potential for further research lies in:

- Advancing nature-inspired systemic frameworks.
- Understanding the structure and creation of human knowledge.
- Developing text mining methodologies towards solution-oriented approaches.

ZUSAMMENFASSUNG

Die menschliche Gesellschaft erlebt seit der Mitte des 20. Jahrhunderts eine „Große Beschleunigung“, die sich in historisch außergewöhnlichen Wachstumsraten manifestiert, welche schwerwiegende Nachhaltigkeitsprobleme verursachen. Die weltweit explodierenden Möglichkeiten des Informations- und Wissensaustausches waren und sind ein wesentlicher Treiber für diese Beschleunigung. Die Gesellschaft ist nun an dem Punkt angelangt, an dem sie eine „Große Transformation“ hin zur Nachhaltigkeit benötigt, um die Lebensfähigkeit des Planeten für eine ebenso lebensfähige Gesellschaft zu sichern. Für diese Transformation spielt die Energiewende eine zentrale Rolle. In diesem Zusammenhang hat die menschliche Gesellschaft ein vergleichsweise gutes Verständnis über die notwendigen infrastrukturellen Veränderungen entwickeln können. Um aber Produktions- und Nutzungsmuster in der Energiewende als Teil der "Großen Transformation" zu verändern, muss dieser Änderungsprozess sich nun verstärkt auf Informations-, Kommunikations- und Wissenssysteme konzentrieren. Die menschliche Gesellschaft muss ein Wissenssystem aufbauen, welches das Potenzial hat, nutzbares Wissen für Nachhaltigkeitslösungen zu schaffen. Dies erfordert es, ein Kommunikationssystem zu organisieren, das ausreichend komplex, vernetzt und gleichzeitig effizient ist, um reflexive, offene, inter- und transdisziplinäre Lern-, Evaluierungs- und Wissenskoproduktionsprozesse auf mehreren Ebenen zu integrieren. Aus dieser Herausforderung ergibt sich ein weites Forschungsfeld.

Diese kumulative Dissertation leistet einen Beitrag zu dieser Forschungsrichtung, indem sie eine systemische Nachhaltigkeitsperspektive auf die Inhalte und Organisation von Kommunikation im Forschungsfeld zu nachhaltiger Energie sowie auf die operative Ebene des kommunalen Klimaschutzes als Teil der Energiewende anwendet. Im Hinblick auf Nachhaltigkeit stützt sich diese Arbeit auf die starke Nachhaltigkeit und ihre Prinzipien als Rahmen für die Bewertung der Inhalte von Kommunikation. Hinsichtlich der systemischen Perspektive liegen der Arbeit insbesondere folgende Theorien zugrunde: (i) das Mensch-Umwelt Systemmodell von R. Scholz als übergreifender Rahmen zur Beschreibung der Wechselwirkungen zwischen Mensch und Natur, (ii) die Theorie der sozialen Systeme von N. Luhmann, um die Komplexität der Gesellschaft abzubilden, (iii) Wissensmanagement, um den menschlichen Charakter von Wissen und eine praxisorientierte Perspektive zu berücksichtigen, sowie (iv) Management-Kybernetik, insbesondere das Viable System Model von S. Beer, um Organisationsstrukturen zu analysieren und zu bewerten

Darüber hinaus nutzt die Dissertation die Methode des Text-Mining mit ihrem Potential, Muster in Texten zu identifizieren und zu visualisieren, welche vorherrschende Paradigmen in der Kommunikation widerspiegeln.

Diese Arbeit wendet die oben genannten konzeptionellen und methodischen Grundlagen in drei Fallstudien an. Fallstudie 1 untersucht die in kommunalen Klimaschutzplänen vorgeschlagenen Maßnahmen. Hierzu werden die Klimaschutzpläne von 16 Oberzentren aus Niedersachsen, Deutschland herangezogen. Methodisch nutzt die Studie einen Text-Mining-Ansatz in Form einer Interpretationsnetzwerkanalyse. Die Studie analysiert, wie verschiedene gesellschaftliche Teilsysteme auf semantischer Ebene miteinander verbunden sind und inwieweit Nachhaltigkeitsprinzipien vertreten sind. Fallstudie 2 analysiert und reflektiert Paradigmen und diskursive Netzwerkstrukturen in internationalen wissenschaftlichen Publikationen zu nachhaltiger Energie. Hierfür werden 26533 Abstracts untersucht, die zwischen 1990 und 2016 veröffentlicht wurden. Auch hier findet die Methode des Text-Mining Anwendung, insbesondere der Ansatz der Themenmodellierung mittels „latent Dirichlet allocation“. Fallstudie 3 wendet sich wieder dem kommunalen Klimaschutz und den bereits in Fallstudie 1 betrachteten Städten in Niedersachsen zu. Die Studie untersucht, inwieweit die Klimaschutzmanager der Oberzentren in Mehrebenen-Wissensprozesse eingebunden sind. Anhand von Gestaltungsprinzipien für Wissenssysteme wird evaluiert, inwieweit Wissen über mehrere Ebenen hinweg verwaltet und koordiniert wird, um die Energiewende zu unterstützen, und in welchem Umfang lokale Innovationspotenziale genutzt beziehungsweise unterstützt werden.

Die drei Fallstudien zeigen, dass die internationale Forschung zu nachhaltiger Energie und der kommunale Klimaschutz in Deutschland vielversprechende Beiträge zur Transformation in Richtung Nachhaltigkeit leisten, allerdings die Komplexität der Gesellschaft nicht vollständig widerspiegeln und nach wie vor einem Wachstumsparadigma folgen, im Gegensatz zu einem holistischen Nachhaltigkeitsparadigma. Ferner zeigen die Studien, dass sich Forschung und lokales Handeln aktiv mit den vielfältigen Energietechnologien beschäftigen, aber bei der Auseinandersetzung mit dem sozio-epistemischen (Kommunikations-)System, insbesondere im Hinblick auf die Erreichung von Kohäsion (auch Zusammenhalt bzw. Kohärenz), zurückliegen. Am Beispiel der deutschen Kommunen zeigen die Studien 1 und 3 Herausforderungen sowohl für die Erreichung von Kohäsion des lokalen Handelns im Sinne der Nachhaltigkeit als auch für das organisationale Lernen in einem von unten nach oben verlaufenden Prozess („bottom up“) auf, die entstehen, wenn der Wissensaustausch über mehrere Ebenen unvollständig oder unkoordiniert verläuft. Gleichzeitig zeigen die Studien auch Möglichkeiten auf, die erforderlichen kohärenten Mehrebenen-Lernprozesse auf der Basis lokalen Wissens zu unterstützen. Dies kann zum Beispiel durch die Stärkung der koordinierenden Rolle von intermediären Organisationseinheiten oder durch engere Interaktionen zwischen lokalen operativen Einheiten und der nationalen Ebene erreicht werden.

In dieser Arbeit werden die Ergebnisse der drei Fallstudien unter Anwendung der systemischen Nachhaltigkeitsperspektive interpretiert und synthetisiert. Auf dieser Basis werden mehrere verallgemeinerte Empfehlungen für die Etablierung tragfähiger Kommunikationssysteme abgeleitet, die insbesondere, aber nicht ausschließlich, in der Politik befolgt werden sollten:

- Systemischer Holismus: Betrachtung von Materie-, Energie- und Informationsflüssen als ein integriertes Triplett im Kontext von Skalen, Strukturen und Zeit in verschiedenen Teilsystemen.
- Wissensgesellschaft: Fokus auf das sozio-epistemische (Kommunikations-)System, z.B. unter Verwendung der Perspektive von Wissenssystemen und damit verbundenen Gestaltungsprinzipien, dabei beispielsweise unter Berücksichtigung von Arbeitsumgebungen über horizontale und vertikale Ebenen, Wissensformen und -typen sowie Wissensprozessen.
- Suffizienz-Kommunikation: Hervorhebung von Suffizienz-Ansätzen, deren attraktive Gestaltung sowie differenzierte Wege ihrer Kommunikation.
- Mehrebenen-Kohäsion und Innovation: Erreichen des Zusammenhalts zwischen lokalen und höheren Ebenen und wirksame Nutzung lokaler Innovationen bei gleichzeitiger Vermeidung isolierten lokalen Handelns.
- Organisationales Schnittstellendesign: Definition der Rolle von Organisationseinheiten anhand der Interaktionen, die sie an den Schnittstellen mit und zwischen gesellschaftlichen Teilsystemen schaffen.
- Lokale Transdisziplinarität: Unterstützung lokaler transdisziplinärer Ansätze, die verschiedene Teilsysteme, insbesondere die Industrie, integrieren, bei gleichzeitiger Koordination dieser Ansätze von einer höheren Ebene aus, um lokale Innovationen zu befördern.

- Digitales öffentliches System: Nutzung vorhandener digitaler Technologien oder Infrastrukturen im öffentlichen System und Erkennen des Wertes von Daten im öffentlichen Bereich für die Erreichung von Kohäsion.

Über die obigen Empfehlungen hinaus werden Potenziale für weitere Forschung in folgenden Bereichen gesehen:

- Weiterentwicklung naturinspirierter systemischer Rahmenwerke.
- Verstehen der Struktur und der Schaffung von menschlichem Wissen.
- Entwicklung von Text-Mining-Methoden in Richtung lösungsorientierter Ansätze.

CHAPTER 1

INTRODUCTION: THE NEED FOR VIABLE COMMUNICATION SYSTEMS

1. INTRODUCTION: THE NEED FOR VIABLE COMMUNICATION SYSTEMS

1.1. THE GREAT ACCELERATION AND THE GREAT TRANSFORMATION

Since the middle of the 20th century, human society experiences a "Great Acceleration" manifesting in historically remarkable growth rates regarding, e.g., population, economy, infrastructure and product systems, resource consumption, or emissions to the environment (Costanza et al., 2007; Steffen et al., 2007). The globally exploding connectivity and potentials of information and knowledge exchange have been vital drivers for this acceleration that creates severe sustainability problems (Steffen et al., 2007; WBGU, 2019, pp. 48–59). However, these potentials can also support establishing solution-oriented information and knowledge systems (Clark et al., 2016; Cornell et al., 2013; Watson et al., 2010; WBGU, 2019, pp. 331–349), which might turn this acceleration into the direction of a "Great Transformation" towards sustainability (Haberl et al., 2011; WBGU, 2011, pp. 81–107). This thesis seeks to contribute to this transformation using an information and knowledge system approach and associated methods and frameworks.

In the course of history, humans have used the growing capacities of information exchange and advanced knowledge creation mainly for developing new technologies with increasing complexity and resource demand. During the Neolithic Revolution that started about 12,000 years ago, humans transitioned out of hunter-gatherer societies into agrarian societies. In terms of the interaction of humans with nature, the emerging communities were, for the first time, capable of actively managing local ecosystems for increasing human well-being (Sieferle, 1997, pp. 53–65; Weisz et al., 2001). This shift was possible by knowledge creation that enabled advancing technology, infrastructure, or labor organization (Haberl et al., 2011; Krausmann et al., 2008; Weisz et al., 2001).

Since agrarian societies depend on the biomass return per area, knowledge about local ecological limits had to be created and integrated into decision-making for achieving viability. Technological efficiency measures may increase biomass return. However, constraints for the yield are the availability of resources, especially water and fertilizer, and the geographically fixed solar energy input (Haberl et al., 2011; Sieferle, 1997, 65; 81-82). An example where overstressing the environment was one crucial factor for a collapse is the society of the Lowland Maya. It collapsed in the 9th century after the ancestors had prospered in this area for around 2,000 years (Tainter, 1995; Turner & Sabloff, 2012). Also, other societies could maintain stable ecological states for certain periods. One of them was the Central European commons system from around 1350 to 1800, which integrated early forms of environmental protection laws (Marquardt, 2005).

The impact of human actions did not endanger the ecological carrying capacity at the global level in agrarian societies (Haberl et al., 2004). However, the security, social, working, or health conditions were miserable, and ecosystems were often overexploited locally or regionally (Weisz et al., 2001). These conditions created pressure (Haan & Rotmans, 2011) and triggered technological research and innovations to increase human well-being.

The discovery of coal as an energy source with high energy-density and technological research enabled the ongoing industrial transition that is based on a high-performance but not a sustainable energy system (Haberl et al., 2011; B. K. Sovacool, 2016). In this regard, essential breakthroughs in the 18th and 19th century were the steam engine or the internal combustion engine (B. K. Sovacool, 2016). Industrialization supports human well-being in many places. However, global population growth, resource-intensive lifestyles, and further technological innovations such as digitalization are propelling the matter and energy consumption of human society, especially since the “Great Acceleration” (Costanza et al., 2007; Steffen et al., 2007) started in the middle of the 20th century (Rosol et al., 2018; WBGU, 2019, pp. 49–58). Human society has not yet achieved to decouple energy and material consumption from increasing human well-being. The global energy and material consumption are still growing in total and per capita (IEA, 2019; UN DESA, 2019).

Further, the current energy system has not been designed as a long-term solution and is in the state of a “carbon lock-in” (Unruh, 2000). An energy transition is needed urgently to mitigate the negative effects of anthropogenic climate change and to avoid the various other detrimental effects (GEA, 2012, pp. 3–30; Schlör et al., 2015; Unruh, 2000, 2002; van Vuuren et al., 2012; WBGU, 2011, pp. 2–4). The impact of human actions makes the global environment leave a state that has been stable for the past 10,000 years during the Holocene (Petit et al., 1999; Rockström et al., 2009; Steffen et al., 2015). Climate change is one of the “Planetary Boundaries” that we have crossed already and might further become the principal direct driver for the loss of biodiversity (Millennium Ecosystem Assessment, 2005, pp. 14–17). Biodiversity is a boundary that we have already crossed even further than climate change (Rockström et al., 2009; Steffen et al., 2015). The current human generation already experiences adverse effects, e.g., regarding crop yields (IPCC, 2015). The impacts and risks for future generations will even increase regarding, e.g., water and food security, security against extreme environmental events, well-being in urban areas, or social and political tensions resulting from an increase in migration (IPCC, 2015).

Society has reached a status that urges for a "Great Transformation" (Haberl et al., 2011; WBGU, 2011, pp. 81–107) towards sustainability to ensure the viability of the planet for a vital society. Based on a long history of societal learning and transitions, the principle of sustainability is now globally recognized as a guiding principle. Chapter 2 discusses this principle in more detail. Most prominently, the United Nations (UN) provide a central knowledge platform for sustainable development (UN DSDG, 2015). The platform distributes knowledge on, e.g., the Agenda 2030 action plan ratified in 2015 by the General Assembly to fulfill the Sustainable Development Goals (SDGs) (UN, 2015). Further, the High-Level Political Forum (HLPF) is going to monitor the implementation of the SDGs and is going to advance the agenda. Following the arguments given above, the UN put a special focus on climate change mitigation. Climate protection shall be achieved, in particular, by establishing a clean energy system and changing production and consumption patterns (UN, 2019).

Advancing information, communication, and knowledge systems will be crucial for transforming the patterns of energy production and use in an energy transition as part of the Great Transformation. The human society has particularly been advancing its understanding of the matter and energy metabolism generating the key interactions between human society and nature. It has developed a general understanding of the necessary infrastructural and technological changes, e.g., in the energy system. These changes require reflexive preparatory and accompanying knowledge exchange processes to ensure a coordinated implementation and responsible use of technology. However, society has not developed yet a sufficient understanding of its information metabolism and societal communication processes in terms of, e.g., institutions, decision-making, attitudes, sense-making, or ethics (Jasanoff, 2010; B. K. Sovacool et al., 2015). For avoiding collapse and, instead, further developing the achievements regarding human well-being, these processes, which determine and finally lead to action, need to be better understood. In this regard, the thoughts of various authors, which are further elaborated in the conceptual Chapter 2, may be condensed to the following research claim that is central to this dissertation (Cash et al., 2003; Cash et al., 2006; Castells, 2004; Cornell et al., 2013; Fischer-Kowalski & Rotmans, 2009; Frantzeskaki et al., 2012; Godemann & Michelsen, 2011, pp. 3–12; Jasanoff, 2010; R. W. Kates, 2001; Loorbach, 2010; Luhmann, 1986, pp. 218–226; Meadows, 1998; Meadows & Wright, 2008, pp. 145–165; Ostrom, 2010; Ostrom & Cox, 2010; Pahl-Wostl et al., 2013; Rotmans et al., 2001; Servaes & Malikhao, 2007; Tainter et al., 2006).

CLAIM

Human society must find ways to organize a communication system embedded in a global sustainability context that has the potential to produce useful knowledge for developing and implementing sustainable solutions within ecological limits. This communication system needs to be sufficiently complex, interconnected, and, at the same time, efficient for integrating reflexive, open ended, multilevel, inter- and transdisciplinary learning, evaluation, and knowledge co-production processes. This way human society can develop and incorporate a sustainability-orientated paradigm or mindset as the basis for its viability.

1.2. GENERAL RESEARCH APPROACH OF THIS THESIS

Several of the core questions of sustainability science are related to the above claim. This thesis focuses on three of these questions that are connected to evaluating the content of communication and organizing the processes of communication in an energy transition context. Due to the urgency to address climate change, advanced scholarly and societal discourses, learning activities, and organizational structures have been established in this context. Therefore, the intention of this thesis is to learn from the advanced energy transition for supporting transitions in general. The questions guiding this thesis are presented at a general level below and substantiated further in the Research Design Chapter 4.

- How can the major trends that define the society be assessed and monitored for supporting a transformation towards sustainability (R. W. Kates, 2001; R. W. Kates, 2011; Luederitz et al., 2017)? Although various assessment frameworks for material and energy flows exist, it remains unclear how to perform structured, easily repeatable sustainability assessments of societal communication.
- What can we learn from asking second-order questions by applying a systemic perspective (Fazey et al., 2018)? In specific, for the context of energy transitions and

climate change research, this thesis asks: How sustainable is sustainable energy? Considering that sustainability is a holistic multi-faceted concept, it is unclear what kind of sustainability the discourses that labels themselves as sustainable actually support for contributing to a transformation towards sustainability.

- How can integrated knowledge systems, which are based on networks of societal subsystems, be established that are capable of solving complex problems efficiently in action-oriented transition processes (Forrest & Wiek, 2014; R. W. Kates, 2001; R. W. Kates, 2011; Luederitz et al., 2017)? Although various governance frameworks or network initiatives exist, it remains unclear if they enable the required communication processes for supporting a transformation towards sustainability and how they might have to be altered to fulfill this requirement.

By approaching these questions, this thesis supports options for pre-decisional learning or, at least, options for ad-hoc learning during decision processes for steering a transformation towards sustainability. The human-environment system framework, which Section 2.2 introduces in more detail, proposes that human society typically applies “post-decisional learning” (Bossel, 1999; Scholz, 2011, pp. 407–462) as a reaction to environmental feedbacks. This thesis improves the understanding of the content and organization of communication processes as the basis for pre-decisional or ad-hoc reflections that may improve decision-making processes.

It does so by providing an aggregated view on communication patterns and corresponding assessment tools. For example, the thesis highlights how selected fields of society focus on specific technologies and how they refer to sustainability in their communication processes. For this purpose, parts of this thesis leverage the potential of text mining, i.e., computer-aided text analysis. Thereby, the thesis provides reproducible assessment schemes as a basis for establishing sustainability indicators for communication.

Further, the case studies conducted for this cumulative dissertation span the arc between the future and the present and the arc between science and practice. They deal with (i) municipal climate action as a local action context targeting the short-term and maybe medium-term future and relate these insights to (ii) the international academic discourse on sustainable energy as a prospective knowledge context that tends to consider the medium-term to long-term future.

Analyzing these contexts, this thesis is further concerned with polycentric communication. It investigates communication processes that involve many dispersed actors that cannot equally be heard or directly be involved in decision processes. By providing an aggregated view, the thesis can support understanding and evaluating polycentric communication for organizing viable communication systems.

In the following seven chapters, this thesis approaches the above questions by applying a systemic sustainability perspective. Figure 1-1 provides an overview of the structure and content of this thesis. As the basis for sustainability assessments of communication, Section 2.1 discusses the normative guiding principle of sustainability. Section 2.2 sets out the systemic analytical framework and presents the various concepts used in this thesis. Chapter 3 applies the theory of Chapter 2 to recent developments in the practical context of the energy transition. At a general level, it highlights challenges and opportunities for a transition towards a sustainable energy system that motivate various research questions. Chapter 4 explains the research design and introduces the three case studies conducted for this cumulative dissertation. It further introduces text mining as a key methodology for advancing the quantitative toolset of sustainability science. Chapter 5 and 6 present two studies that leverage this methodology. Chapter 5 presents Case Study 1 that investigates the content of municipal climate action plans in the context of the German energy transition using semantic network analysis. Chapter 6 presents Case Study 2 that analyzes the content of communication in international scientific publications on sustainable energy via topic modeling. From this global perspective on science, Case Study 3 turns again to the local implementation and examines knowledge processes in municipal climate action in Germany based on personal interviews with climate action managers. Using the systemic perspective introduced in Chapter 2, the final Chapter 8 interprets and synthesizes the results of the three case studies. On this basis, it provides general conclusions and recommendations for policy and science.

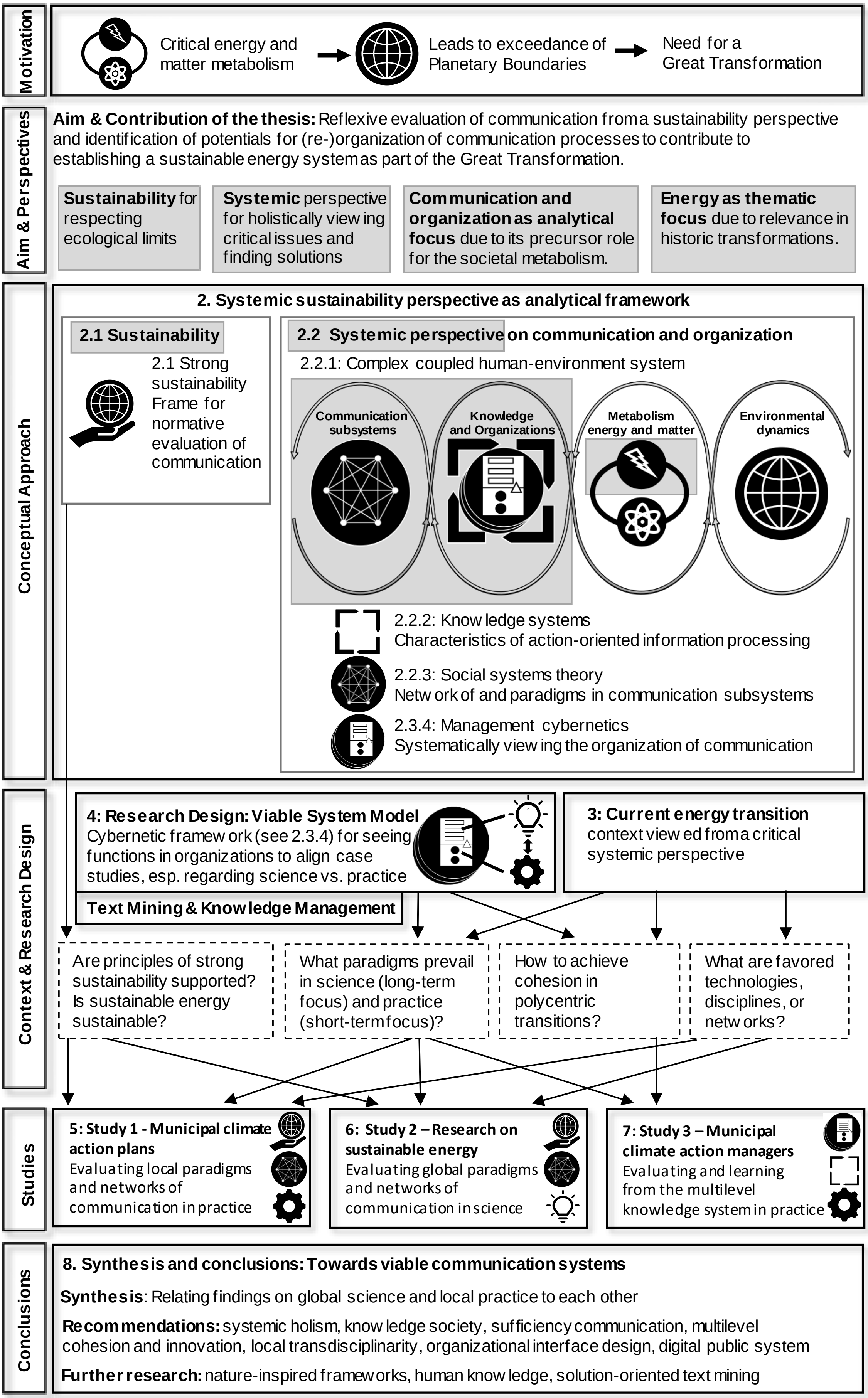

Figure 1-1: Overview of the structure and content of this thesis

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CHAPTER 2

A SYSTEMIC SUSTAINABILITY PERSPECTIVE AS ANALYTICAL FRAMEWORK

2. A SYSTEMIC SUSTAINABILITY PERSPECTIVE AS ANALYTICAL FRAMEWORK

This chapter introduces the applied systemic sustainability perspective and highlights why this kind of perspective is essential for achieving sustainability. Section 2.1 deals with the normative concept of sustainability that motivates sustainability science. In particular, this thesis uses

- Strong sustainability and its principles for evaluating the content of communication.

Section 2.2 introduces the systemic analytical framework for societal communication applied here. The thesis adopts a holistic systemic perspective and makes use of theories and concepts proposed in the field of cybernetics, the science of analyzing information flows for managing organizations. In particular, this thesis relies on four selected systemic perspectives for investigating communication and organization in human society, which are explained in detail in the following sections:

- Coupled human-environment systems for describing the basic interactions of humans with nature.
- Knowledge systems for considering the specific characteristics of information processing by humans.
- Social systems theory for analyzing the communicative interactions of coupled subsystems of the human society.
- Management cybernetics for analyzing and improving the organization of communication systems.

2.1. SUSTAINABILITY

Various local or regional societies have temporarily adopted certain forms of sustainability principles throughout history (Carlowitz, 1713, p. 105; Heinrichs et al., 2016; Marquardt, 2005; Mebratu, 1998). However, it was not until the Brundtland Commission Report (WCED, 1987) that a more comprehensive conceptualization of sustainability has achieved broad societal dissemination globally. An early precursor for this achievement was that the United Nations recognized the threats to human society by various sustainability problems (UN Secretary General - U Thant, 1969). Further, science provided evidence for global limits in the “Limits to Growth” report (Meadows, 1972). The report served as a rational argumentation basis against a development pathway following business as usual. Advancements after the Brundtland Commission Report include the Millennium Development Goals (MDGs) and, most recently, the 17 Sustainable Development Goals (SDGs). They may be viewed as a network of relationships between different development fields and, thus, have the potential to support the policy coherence required for the "Great Transformation" (WBGU, 2011). However, many of these relationships still have to be better understood (Le Blanc, 2015; Nilsson et al., 2016).

Regarding the scientific discourse, sustainability science is increasingly reaching consensus that answering questions regarding the "dynamic interactions between nature and society" (Clark & Dickson, 2003) lies at the heart of sustainability (Clark & Dickson, 2003; Haberl et al., 2004; R. W. Kates, 2001; Scholz, 2011, pp. 407–410). Understanding this relation supports answering the questions in what state human society passes the world to future generations and how it should distribute resources among the present generation. Research in this direction is not trivial. The various interactions that are relevant for sustainability involve not only scientists but stakeholders from all fields of society and are, thus, inherently dynamic and complex (R. W. Kates, 2001; Komiyama & Takeuchi, 2006; Scholz, 2011, pp. 339–404),

Due to this complexity sustainability is a contested multi-faceted normative concept without a uniform definition (Bell & Morse, 2008; Bosshard, 2000; Connelly, 2007; Gibson & Hassan, 2005, pp. 206–216; Grunwald & Kopfmüller, 2012, pp. 53–75; Kuhlman & Farrington, 2010; Luederitz et al., 2016; Tremmel, 2003). This vagueness is weakness and strength at the same time. It can lead to the misuse of sustainability as a catchphrase for relabeling or greenwashing the business as usual without significant operational changes (Ott et al., 2011; Schaltegger & Burritt, 2010). However, the vagueness also is a prerequisite for a broad societal distribution of the concept (Bosshard, 2000) and potentially allows to motivate various actors to get involved in sustainability transitions using different suitable narratives (Luederitz et al., 2016).

The Brundtland Commission Report already leaves certain vagueness regarding the definition of sustainability. It proposes principles but no explicit instruction on how to operationalize them. However, the report still lays the ground for posing the right questions in decision-making. The Brundtland Commission Report highlights several principles, in particular, (i) the two core principles of intergenerational and intragenerational equity, which are lastly principles of justice, and (ii) the necessity to respect the carrying capacity of the environment to comply with these principles (WCED, 1987, p. 41). The vagueness of the concept of sustainability becomes clear, e.g., by recognizing that the Brundtland report also supports economic growth at the same time. For several sustainability scientists, this is an unsatisfactory compromise.

They see uncontrolled economic growth as one of the drivers for unsustainable development pathways (Drews & van den Bergh, 2017; Ott et al., 2011).

The dynamics of the societal discourse and the complexity of the relevant nature-society interactions underline that a transformation towards sustainability comprises a continuous process of inquiry and learning. Applying principles of sustainability in decision-making is similar to putting decision-makers in the hypothetical "original position" and applying the "veil of ignorance" (Rawls, 1971, pp. 11–22). This means that, during decision-making, the decision-maker assumes that she does not know which person she would be in the imaginary world resulting from her decision (Rawls, 1971, pp. 11–22). This way, she can make a fair decision. For reaching sustainable decisions, it is crucial in decision-making to apply a sufficiently wide "horizon of attention" regarding various dimensions such as time and space, or the variety of functional subsystems of the society and the environment (Bossel, 1999, pp. 65–68).

The sharpest distinction between different conceptualizations of sustainability is probably the one between weak and strong sustainability. The two approaches take different standpoints regarding the extent to which humans should make use of nature (Neumayer, 2003; Pelenc et al., 2015). Weak sustainability (Hartwick, 1977; R. M. Solow, 1974; Robert Solow, 1993) assumes almost infinite interchangeability between natural capital and human-made capital. In contrast, strong sustainability highlights that these two types of capital are largely complementary and have to be maintained and further developed independently from each other (Daly, 1990b; Grunwald & Kopfmüller, 2012, pp. 65–68; Ott, 2003; Ott & Döring, 2004).

The theory of strong sustainability departs from the core idea of intra- and intergenerational justice. Three of the core principles that the theory proposes for entering sustainable pathways of societal development are: (i) sufficiency addressing the fulfillment of basic human capabilities (Nussbaum, 2011, pp. 33–34) while demanding a reduction in resource extraction from the environment by adopting resource-light lifestyles, (ii) efficiency requiring the generation of the maximum service from resources extracted, and (iii) resilience or consistency[1] demanding the use of renewable resources, the respect for environmental regeneration rates,

[1] The term originally used was resilience (Ott, 2003). In the German discourse the term "Konsistenz" (consistency) has evolved to name this core guideline of strong sustainability.

and the conservation of natural capital (Daly, 1990a, 1990b; Ott, 2003; Ott & Döring, 2004, pp. 162–164). Figure 2-1 pictures the main principles of strong sustainability.

Strong sustainability does not promote the extreme interpretation that would require humans not to use any non-renewable natural capital (Grunwald & Kopfmüller, 2012, p. 67; Ott & Döring, 2004, p. 146). It demands to (i) respect the ecological carrying capacity and regeneration rates by adhering to the constant natural capital rule and safe minimum standards, (ii) use natural capital sparingly, (iii) provide for substitutions, and (iv) apply precaution in situations of uncertainty (Grunwald & Kopfmüller, 2012, p. 67; Ott, 2006; Ott & Döring, 2004, pp. 143–147). One of the key points regarding the use of non-renewable resources is to maintain the freedom of choice for future generations, whether and how to use these resources (Döring et al., 2007). In practice, this leads inevitably to trade-offs that stakeholders need to resolve (Gibson, 2006).

This thesis uses strong sustainability as a frame for reflecting communication processes (Ott et al., 2011) to support a sustainable energy transition. Considering what the reports on the "Limits of Growth" (Meadows, 1972) and the "Planetary Boundaries" (Rockström et al., 2009; Steffen et al., 2015) have made apparent, it seems imperative to adopt a sustainability principle based on limits. This thesis does not directly deal with the physical limits in numbers that might be affected by the human energy system. However, it investigates to what extent communication processes in the context of energy systems include principles of strong sustainability.

Figure 2-1: Principles of strong sustainability for respecting planetary boundaries

2.2. SYSTEMIC PERSPECTIVE ON COMMUNICATION AND ORGANIZATION

For detecting and solving sustainability problems, large parts of the modern discourse of sustainability science are rooted in system theory or systemic thinking (R. W. Kates, 2001; Tainter, 2011). The introduction and the previous section have already made use of this kind of thinking. This chapter introduces systemic thinking in more detail from a conceptual perspective. The systemic perspective presented in the following serves as an overarching analytical framework. It further helps to explain the empirical contribution of and the relation between the three case studies conducted for this thesis (see Research Design, Chapter 4).

System theory provides a framework for generalizing knowledge and enables interdisciplinary mutual learning. It facilitates communication between different disciplines without seeking to replace the specific valuable models, knowledge, and meaning generated in the individual disciplines (Boulding, 1956; van Bertalanffy, 1968, pp. 30–53). Considering the various roots of this kind of thinking, see, e.g., in (Baecker, 2005; Hammond, 2002), one of the primary references is the “General System Theory” (van Bertalanffy, 1968). Ludwig van Bertalanffy published it in the 1930s in its earliest form and later revised it (van Bertalanffy, 1968, pp. 11–14).

Many scholars built on and further developed systemic thinking into advanced theories and models for different purposes and contexts, to name a few: (i) the “Living Systems” theory with a focus on concrete open living systems in contrast to closed systems (James G. Miller, 1965; James Grier Miller, 1978), (ii) the field of cybernetics investigating control systems and organization based on information flows (Ashby, 1956; Beer, 1981; Deutsch, 1966; Wiener, 1948), (iii) the soft systems methodology focusing on problem-solving processes in organizations (Checkland, 1981, 2000), (iv) system dynamics for modeling dynamics of socio-economic systems, e.g., local urban systems (Forrester, 1969) or the global system (Bossel, 2004; Bossel & Strobel, 1978; Meadows, 1972; Meadows & Wright, 2008), or (v) sociological system theories about societal structure and communication (Luhmann, 1984; Parsons, 1951).

Systemic thinking may serve to reduce the perceived complexity of systems to a level that allows the human mind to better understand these systems (Simon, 1962). Systems may be understood as “organized complexity” (van Bertalanffy, 1968, p. 34). The complexity of systems results from their numerous individual elements and the existing and possible connections between the individual parts (Simon, 1962; van Bertalanffy, 1968, p. 93). System boundaries are a central concept in system theory that allows to structure and thereby reduce complexity. As a method, drawing system boundaries allows analyzing the input and output of certain flows over time across system units or hierarchical scales. Flows are matter, energy, or information. Analyzing flows further shows to what extent parts of them are stored within the system boundaries or converted into different types of flows.

A key idea of system theory is the existence of universal principles valid in all types of complex systems independent of the disciplinary context. Such principles help to understand how systems organize complexity dynamically and interact with their environment. The human society has been increasing its complexity over time as one of the possible strategies to solve problems (Tainter, 2000; van Bertalanffy, 1968, vii, 30). Thus, problem-solving in human society requires a particular focus on questions of organization (van Bertalanffy, 1968, p. 34).

As highlighted in the introduction of this chapter, this thesis relies on four selected systemic perspectives for investigating communication and organization in human society: (i) complex coupled human-environment systems, (ii) knowledge systems, (iii) social systems theory, and (iv) management cybernetics. The following sections explain these perspectives in detail. Section 2.2.1. aligns the different concepts using the human-environment system framework (Scholz, 2011, pp. 407–462) and visualizes them in Figure 2-2.

2.2.1. Complex coupled human-environment system – leverage points in the communication system

As indicated in the previous section, an influential approach in sustainability science, which was motivated by systemic thinking, focuses on interactions in the coupled human-environment system. This scientific field puts particular emphasis on analyzing and influencing how the human system organizes its responses to internal change or external change in the environment (Bossel, 1998, p. 88, 1999; Clark & Dickson, 2003; Haberl et al., 2004; R. W. Kates, 2001; Ostrom, 2009; Scholz, 2011, pp. 407–462). The cited authors use various conceptualizations of the human-environment system. These show similarities at a general level but differences in the details due to the specific contexts or purposes they address. Readers interested in the details regarding such differences are kindly referred to the literature (Scholz, 2011, pp. 509–521).

As a starting point, this thesis uses the conceptualization of the human-environment system framework that divides the human system into a socio-epistemic and a material-biophysical system (Scholz, 2011, pp. 407–462). In other words, these systems may be described as a communication and an infrastructural system. The human system interacts with the environment through the material-biophysical system by the extraction of resources and output of emissions. This interaction creates physical environmental responses or feedbacks (Bossel, 1999; Scholz, 2011, pp. 407–462). Sooner or later the human system senses these feedbacks as feedback loops that enter the knowledge system of society. Influenced by its organizational set-up, society filters, processes, and organizes the dissemination of this information. This may or may not create resonance in the individual communication subsystems and, coupled to the organizational context, initiate "post-decisional learning" about the impacts of specific decisions and actions. The resulting lessons learned inform the goal formation and decision-making processes that include the preparation and selection of strategies or plans. These involve, e.g., technical, organizational, or legal measures, which may also include the adaption of goals. Finally, the implementation of the selected strategies leads to the (re-)action of the human system starting the cycle of impact, feedback, and response again. Figure 2-2 visualizes these cyclic processes.

Human society has developed a comparably decent understanding of the material-biophysical and the environment system. However, further research is required to understand the more complex socio-epistemic system (Scholz, 2011, pp. 528–529). There are valuable approaches for analyzing physical flows and detecting critical hot spots in the energy and matter processing infrastructure and in the environment system. Examples may be found in earth system science (Costanza et al., 2007; Hans-Joachim Schellnhuber, 1999; H. J. Schellnhuber et al., 2005), models of system dynamics (Bossel, 1998; Forrester, 1969; Meadows, 1972), or material and energy flow analysis at different scales (Haberl et al., 2004; Kennedy et al., 2011; Wackernagel et al., 2006). However, more research on analyzing societal communication processes is needed for a balanced, comprehensive understanding of the human-environment system (Scholz, 2011, pp. 528–529). This kind of research is crucial for transformational sustainability research. As the basis of decisions, the paradigms in society, the organization of knowledge systems and information flows, and the resulting goals are among the most effective "leverage points" for inducing change in a system, in contrast to points of lower order, e.g., flows and stocks of resources (Meadows, 1999; Meadows & Wright, 2008, p. 194).

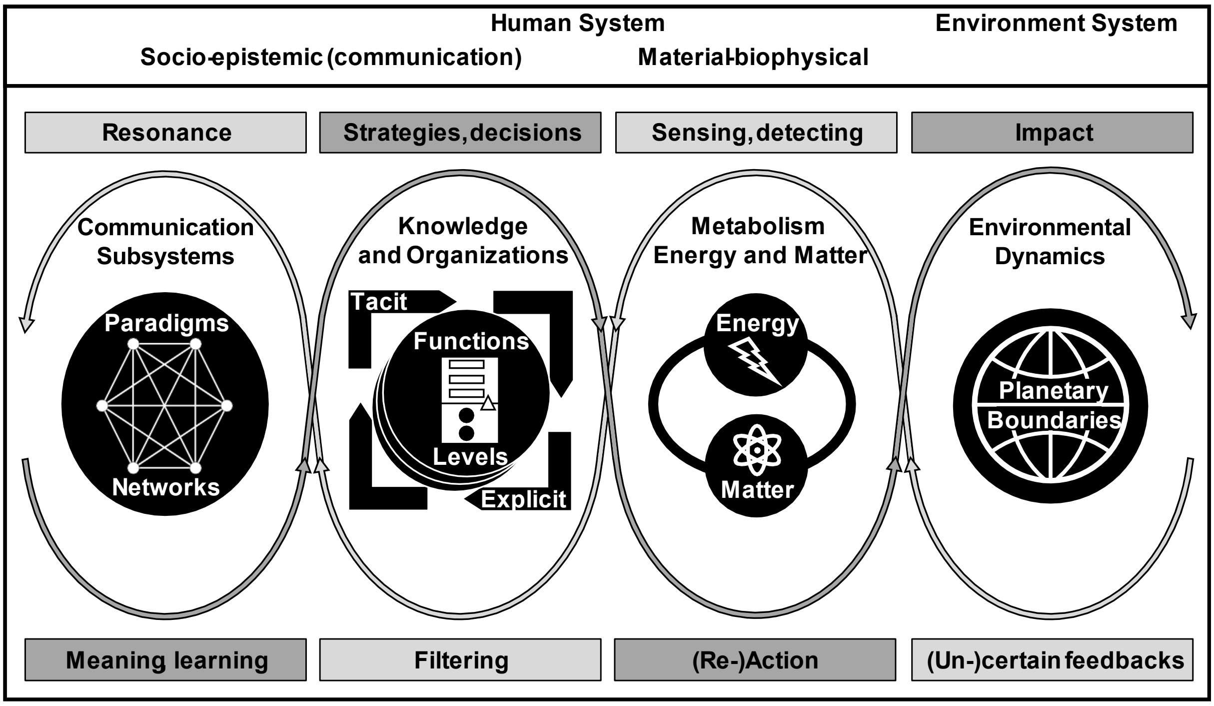

Figure 2-2: Concepts used in the thesis aligned within the human-environment system framework; the illustration is based on ideas and schemes in (Scholz, 2011); Note: The purpose of the figure is to arrange the key concepts used in the thesis. Therefore, it does not capture the complete theoretical background, relevant elements, or interactions that are necessary for understanding human-environment systems. For instance, the dimensions of time and space have not been included explicitly.

In short, the order of “leverage points” (Meadows, 1999; Meadows & Wright, 2008, p. 194), from the highest point 1 to the lowest point 12, results from the following considerations. Paradigms or mindsets, which involve values, shared ideas, or beliefs, govern knowledge (Meadows, 1999; Nonaka, 1994). Knowledge, which involves experience, strategies, or skills for solving problems, governs how organizations are formed (Nonaka, 1994; Probst et al., 2012, p. 24). Finally, these produce action that manifests, e.g., in material structures.

Following these lines of thought, this thesis investigates the leverage points of higher order. Thereby, it contributes to the research claim posed in the introduction regarding the need for viable communication systems. It analyzes the content and the organization of communication in an energy system context.

Since “we measure what we care about […and] we care about what we measure” (Meadows, 1998) the thesis provides a reflexive analysis and evaluation of the content of communication in an energy transition context. The resulting insights provide starting points to alter communication patterns. Patterns changed through reflection might finally lead to more sustainable actions. Using the leverage points terminology, the thesis empirically investigates the “structure of information flows” (Meadows, 1999) and lays the basis to change “mindset[s] or paradigm[s]” (Meadows, 1999).

Motivated by the idea that living systems can advance through learning processes that integrate diverse knowledge bases in open experimental approaches (Meadows, 1999), the thesis further provides insights into the communicative interconnection and organization of societal fields and levels. By providing insights on the structure and dynamics of organizational knowledge processes, it sheds light on ways of how to better “self organize the system structure” (Meadows, 1999)

2.2.2. Knowledge systems – human communication and organization

This thesis analyses societal communication processes to support establishing knowledge systems that enable reflexivity, learning, and strategy adaption for a transformation towards sustainability. Knowledge systems comprise individuals in organizations and their belief systems in the socio-epistemic system. The latter influence routines or practices that finally lead to action in the material-biophysical system. Therefore, knowledge systems are vital for generating useful knowledge that can lead to sustainability (Cash et al., 2003; Cornell et al., 2013; Tàbara & Chabay, 2013; van Kerkhoff & Szlezák, 2016). Major components of knowledge systems are communication and organization. The theoretical lenses introduced above, i.e., societal differentiation and viable organizations, can describe these components. Using these lenses contributes to understanding what kind of knowledge human society generates, i.e., which communication codes or subsystems prevail, and how it generates knowledge, i.e., which organizational elements govern the process of knowledge generation.

Introducing the term knowledge is important since it highlights the human character of communication. Information flows can restructure the knowledge of an individual. However, various factors influence if this kind of restructuring occurs and in which way it takes place. Two crucial factors are the individual’s experience and the context in which it receives information (Davenport & Prusak, 1998; Dretske, 1981; Krogh et al., 2000; Machlup, 1983;

Nonaka, 1994; Venzin et al., 1998). Hence, human knowledge is different from information. It is subject to interpretation, carries meaning, and, thus, is normative and connected to beliefs (Nonaka, 1994). Analyzing and reflecting the character of knowledge that human society creates or uses allows to engage with the paradigms determining human knowledge systems. This kind of reflection is the basis for potential adaptations in these systems.

This thesis makes use of concepts, in particular, from the field of knowledge management for analyzing the structure and dynamics of the multilevel knowledge system in the context of sustainable energy. In short, it investigates (i) what types of knowledge are circulated, e.g., regarding the content or domains favored in communication, (ii) what forms of knowledge prevail, especially regarding explicit and tacit knowledge, and (iii) how knowledge systems perform regarding key knowledge processes such as input or acquisition, conversion or creation, storage, and output or dissemination. Figure 2-3 provides a basic overview of knowledge processes. Chapter 7 provides further details on knowledge systems.

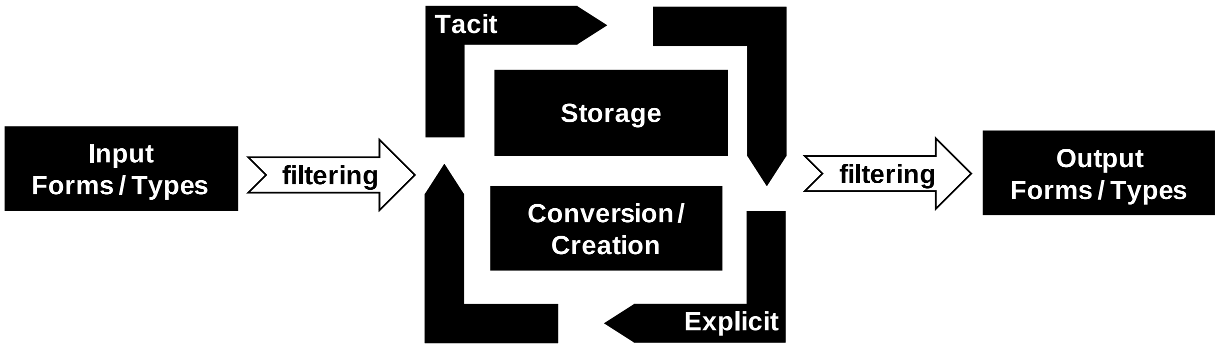

Figure 2-3: Basic overview of knowledge processes handling different forms and types of knowledge

2.2.3. Social system theory – functionally differentiated society of networked subsystems

This thesis uses the lens of a functionally differentiated society (Luhmann, 1984) for embracing the complexity of the socio-epistemic system and opening the field for a broad analytical perspective. The socio-epistemic system is increasingly complex. Society is dynamically differentiating into various functional (communication) subsystems, which each communicates in a unique code, e.g., politics, law, economy, science, education, or religion (Luhmann, 1984, 1986). At specific points of their communication, the subsystems interact, e.g., through mutual observation or articulations, and, together, produce the society as a whole (Luhmann, 1984, pp. 551–592). Figure 2-4 provides a simplified visualization of these interactions.

Understanding the interaction of networked subsystems increases the capability of the human society to reflect the paradigms and processes shaping the strategies or implementation plans that it turns into action (Loorbach, 2010; Luhmann, 1986, 227–236, 249-258; Rotmans & Loorbach, 2009). An interaction perspective is increasingly relevant, considering that, through digitalization, human society is becoming more and more a "network society" (Castells, 2004).

The three studies of this cumulative dissertation all use a network perspective to reveal interactions between different societal subsystems and levels. The thesis also investigates the differentiation of discourses into networked communication subsystems. The identified mixture of favored paradigms, disciplines, or ideas serve as an indicator for possible future configurations of society and the associated metabolism of matter and energy.

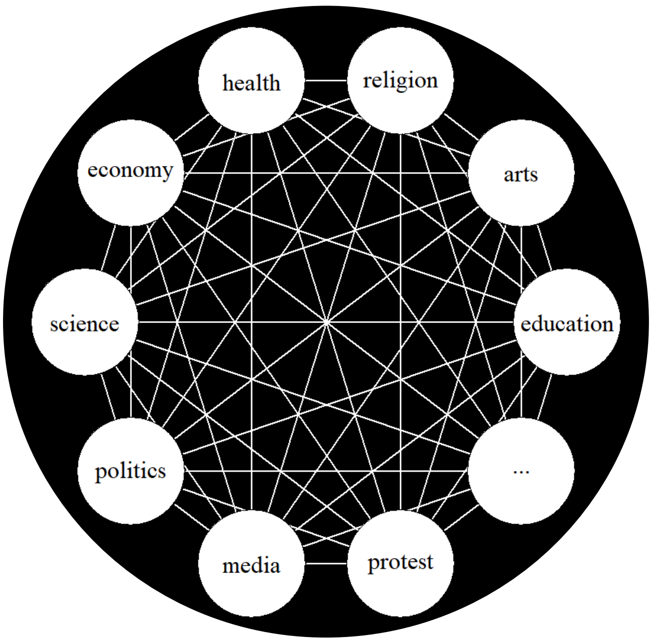

Figure 2-4: Simplified visualization of interacting differentiated societal subsystems according to social systems theory (Luhmann, 1984)

2.2.4. Management cybernetics – the Viable System Model for viewing functions in organizational communication

For complementing the complex differentiation lens, this thesis further uses the lens of management cybernetics, which offers approaches to better organize complexity by "seeing organizations" (Espejo, 2012). In particular, the thesis uses the Viable System Model (VSM) (Beer, 1979, 1981, 1984). This model proposes functional requirements for viable organizations (Beer, 1981, 1984). The VSM might be classified as nature-inspired model since it builds on the human physiology (Beer, 1981, pp. 89–102). The human body is viable only when its brain, nervous system, senses, and organs are functioning and mutually supporting each other. Using this notion, the VSM defines principles for viable organizations. An organization may be an enterprise but also a state. Figure 2-5 sketches the VSM. It assumes that viable organizations require recursively interconnected levels. For instance, in the public system recursion levels would be, e.g., the world, continents, countries, or regions. The same five generic communicative functions need to operate at each recursion level properly.

The five functions of the VSM are summarized in the following based on the literature (Beer, 1979, 1981, 1984; Espejo, 2004; Espejo & Reyes A., 2011, pp. 91–112): (i) The *implementation* function represents the production of meaning or main actions that define the purpose or identity of an organization. This function is concerned with the operational environment of the organization. (ii) The *coordination* function is needed to organize and balance the operational activities of the multiple implementation units. These two functions, which make up the primary operational activities of an organization focusing on the "here and now," are linked to the supporting or enabling management or regulatory activities focusing on the "outside and then" (Beer, 1979; Espejo & Reyes A., 2011, p. 95) via (iii) the *cohesion* function. The cohesion function balances the current operational activities with the organization's policies and long-term perspective. (iv) The *intelligence* function is concerned with the problematic environment of the organization and applies foresight. The cohesion and the intelligence function inform (v) the *policy* function that formulates the rules and normative guidelines for the organization. In the first step, the individual functions should not be interpreted as departments of an organization. The functions may coincide with departmental boundaries if reasonable, but not necessarily. Anyone can, in principle, contribute to each function (Espejo, 2015).

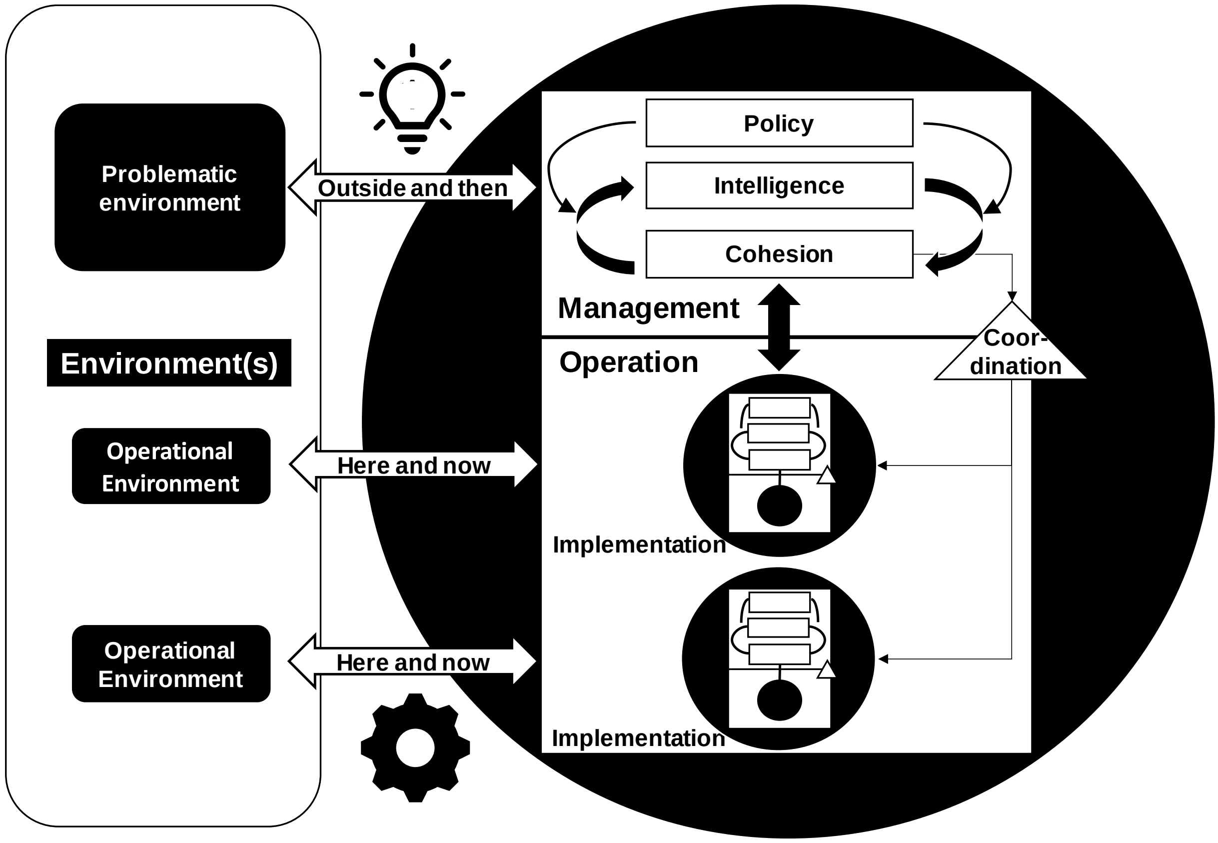

Figure 2-5: Simplified visualization of the recursive Viable System Model (Beer, 1979, 1981, 1984); the figure shows the upper recursion level in detail (when viewing a state as an organization, this level would be interpreted as the national level); the small circles indicate the lower recursion levels); adapted from (Espejo, 2015)

The principles of the VSM can be used to diagnose, improve, or re-organize knowledge systems and policy-processes for sustainability transitions (Achterbergh & Vriens, 2002; Beer, 1985; Espejo, 2015; Schwaninger, 2015). For this purpose, a particular focus on the relation between the "inside and now (cohesion function)" and the "outside and then (intelligence function)" is recommended (Achterbergh & Vriens, 2010, pp. 198–200; Beer, 1985, pp. 19–35; Espejo, 2015). These two functions are essential sensors of a system since they incorporate highly relevant information on the future and on the current system into the whole system. They form an arch of information around the whole system. Focusing on the "inside and now" reveals the actual complexity and "identity-in-use" of a system (Espejo, 2015). There will always be "complexity asymmetries" between the design of solutions or regulations and the complexity of society (Espejo, 2015). Being aware of these asymmetries is crucial to find suitable ways for designing coherent solutions that are sufficiently but not overly complex (Espejo, 2015). For this purpose, the intelligence function can increase the system's "self-reference and reflexivity" by comparing the “identity-in-use” with the “desired identity” (Espejo, 2015). Knowledge about the internal differences of these identities in different organizational units is essential for bridging them and establishing or maintaining a viable system.

This thesis uses the VSM as an overarching framework for organizing the case studies and insights. As explained in detail in the Research Design, Chapter 4, the thesis follows the above recommendation and investigates the intelligence and the cohesion functions in organizational communication in the context of sustainable energy systems. Chapter 8 synthesizes the findings regarding these functions.

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CHAPTER 3

A SYSTEMIC VIEW ON THE CURRENT CONTEXT: TRANSITION TOWARDS A COMPLEX SUSTAINABLE ENERGY SYSTEM

3. A SYSTEMIC VIEW ON THE CURRENT CONTEXT: TRANSITION TOWARDS A COMPLEX SUSTAINABLE ENERGY SYSTEM

The systemic sustainability perspective introduced in Chapter 2 at a theoretical level is used in the following for providing an initial reflection of recent developments in the practical context of energy transitions. Highlighting critical issues in practice from a systemic perspective here leads to the research questions and needs addressed in the Research Design in Chapter 4. The following paragraphs highlight particularly the complexity of sustainable energy systems in the material-biophysical and the socio-epistemic system of the human system. They point out the need to organize this complexity by advancing knowledge systems.

3.1. THE COMPLEXITY OF SUSTAINABLE ENERGY

Establishing a decarbonized sustainable energy system plays a crucial role in the current societal transformation towards sustainability. The introductory Chapter 1 highlights that the energy system is a critical system mediating the interaction between human society and nature. Therefore, a transition of the energy system towards sustainable production and consumption of energy is required, which may be understood as a long-term change process as part of the Great Transformation involving all subsystems of the human system (Patwardhan et al., 2012). This process includes all stages of the energy system in the material-biophysical system, i.e., material and energy resource extraction, conversion in power plants or refineries, distribution networks, and end-use via energy technologies for providing the desired energy services (Grubler, Johansson et al., 2012; Nakicenovic et al., 1996; Rogner, 1994). Further, this kind of transition involves the socio-epistemic system including, e.g., institutions, policies and politics, markets, culture, behavior patterns, and belief systems (Geels et al., 2017; Patwardhan et al., 2012; Scholz, 2011, pp. 525–529; B. K. Sovacool, 2014).

For changing the energy system infrastructure, human society introduces several elements that increase the complexity of the system and require advancing information and knowledge exchange (Cherp et al., 2011; GEA, 2012, 27-30, 60-63; Tainter et al., 2006). Beyond the cited literature, Case Study 2 of this thesis in Chapter 6, which investigates the scientific discourse on sustainable energy, also highlights the complexity of the energy system empirically. In the course of history, the increase of complexity and energy consumption has been an intertwined upward spiral. Increasing the complexity of a system is a typical problem-solving strategy (Tainter, 2000). It has been argued that increasing complexity might work as a solution for decarbonizing the energy system (Tainter et al., 2006; Tainter, 2011). However, this requires society to establish efficient information exchange processes (Cherp et al., 2011; Tainter et al., 2006; Tainter, 2011). These processes need to connect the parts of the system suitably, including technology and people, for achieving synergistic integrated approaches (Cherp et al., 2011; Tainter et al., 2006; Tainter, 2011).

3.2. MATERIAL-BIOPHYSICAL ELEMENTS OF THE ENERGY SYSTEM

Concerning energy generation, the energy system is developing to higher complexity through increasing shares of renewable energy and higher interconnectedness (Cherp et al., 2011; IEA, 2016). Renewables have lower energy density in comparison to fossil fuels and will, thus, require an increasingly decentralized infrastructure for harvesting energy in different regions. It should be noted that a renewable energy system does not necessarily require a higher overall land-use when considering the whole power plant life cycle (Fthenakis & Kim, 2009). However, site-specific assessments of landscape changes need to be considered, e.g., regarding habitat fragmentation (Jones et al., 2015; Trainor et al., 2016). Beyond these general technical and environmental aspects, several relevant socio-economic effects may be identified in the case of developing countries. The potential of installing decentralized renewable power plants or connecting rural areas to electricity grids may increase the geographical coverage of energy access to advanced energy technologies. This may contribute to decreasing energy poverty and health problems (Deichmann et al., 2011; Pachauri et al., 2012; Palit & Chaurey, 2011). In summary, supporting renewable energies alleviates various sustainability problems, but increases the complexity of the energy system. This increase is due to adding technologies, plants, or remote consumers to the system and by establishing advanced electricity grids with various storage and security components (Cherp et al., 2011; Tainter et al., 2006).

The various technical efficiency measures that increase the diversity of materials and the number of parts further add to the complexity of the energy system. This increase calls for more sophisticated management systems regarding materials and energy system components. We can observe a trend towards more complex or composite materials for the various renewable energy or efficiency technologies (Chu et al., 2016; Serrano et al., 2009). Examples in the field of solar cells are the beginnings of using multi-junction instead of single-junction cells (Green & Bremner, 2016) or using nanotechnology to improve material properties (Baxter et al., 2009; Serrano et al., 2009). Further, from a more general perspective, rising demand for and diversity of metals can be identified for the various efficiency and renewable energy technologies (Held

& Reller, 2016; Zepf et al., 2014). Issues of availability, recyclability, or social and environmental conditions along their life cycle create various sustainability challenges (Altvater, 2016; Held & Reller, 2016). Turning from the scale of materials to the scale of technological equipment, advanced integrated heat systems are an example of increasing complexity in the industrial energy end-use sector. These systems interconnect or optimize various processes by introducing additional plant components (Banerjee et al., 2012, pp. 522–545). In the private end-use sector, smart buildings are another example. For increasing energy efficiency, these buildings use self-learning digital management systems that couple technology with user behavior. Thereby, they may optimize supply and demand (Zhou et al., 2016). At an even larger scale, the proposal to establish smart energy systems by interconnecting various sectors and using digital optimization and management technologies might lead to higher energy efficiency (Lund et al., 2017).

It should also be noted that centralized solutions for decarbonization offered by nuclear energy would not necessarily mean a reduction of complexity. Increasing shares of nuclear power would require high efforts for establishing secure infrastructure systems and would lead to highly interdependent political systems (Cherp et al., 2011; B. K. Sovacool & Saunders, 2014). This expected increase of complexity is due to the experience of past accidents with this complex technology and the still fragmentary integration of the concept of sustainability in this field (Gralla et al., 2016),

3.3. SOCIO-EPISTEMIC ELEMENTS OF THE ENERGY SYSTEM

The transformation of the energy system will also require changes in the socio-epistemic system. Human society needs to establish suitable information systems, policies, markets, and other soft elements as solutions for making the complex energy infrastructure work efficiently. These solutions will increase in complexity for reflecting appropriately our multi-faceted urban world. Urbanization is on the rise (UN DESA, 2014, 2018) and cities are major contributors to climate change (IEA, 2008; Marcotullio et al., 2013). Urban areas and the associated urban energy systems, which are embedded in the global context, will be a major focal point for tackling climate change effectively and supporting a sustainable energy transformation (Seitzinger et al., 2012; Shah & Keirstead, 2013; WBGU, 2016, pp. 387–409). This will require participatory management of the transformation process to establish coherent approaches considering a broad spectrum of societal subsystems and stakeholder networks instead of fragmented approaches (Bulkeley & Betsill, 2013; Grubler, Bai et al., 2012; Kemp et al., 2007; Loorbach et al., 2008).

Various authors promote polycentric or multilevel governance approaches (Betsill & Bulkeley, 2006; Ostrom, 2010; Seitzinger et al., 2012; WBGU, 2016, pp. 387–394). These approaches are not considered per se as the solution to all problems since, e.g., inconsistent policies and leakage effects are potential caveats. However, for approaching complex problems such as climate change, it seems reasonable to respond with solutions that reflect the complexity of society (Ostrom, 2010).

On the one hand, widening the area of responsibility for local decision-making would reduce complexity by simplification. Providing cities with a higher self-organization capability might enable such simplification (Tainter, 2000). This could support effective, evolutionary innovative solutions at the local level (Flanagan & Uyarra, 2016). On the other hand, this may complicate coherent multilevel approaches. The complexity of communication processes for integrating and aggregating local perspectives at higher levels may increase with higher local autonomy (Bulkeley & Betsill, 2013; Bulkeley & Schroeder, 2012). This is due to the multi-faceted characteristics and contexts of different cities and the complexity of urban life (UN-Habitat, 2011, pp. 9–16; WBGU, 2016, pp. 56–65). The difficulties to achieve cohesion have been investigated and highlighted particularly in the context of local climate action (Bulkeley, 2010; Bulkeley & Betsill, 2005; Bulkeley & Betsill, 2013; Bulkeley & Schroeder, 2012; Castán Broto & Bulkeley, 2013; Ohlhorst, 2015; Schreurs, 2008; Wheeler, 2008).

Above considerations indicate that for successfully navigating the energy transformation it is crucial to establish suitable information and knowledge systems for structuring, aggregating, assessing, and integrating knowledge. The potential of public sector knowledge management to contribute, e.g., to the improved multilevel alignment of energy or climate action policies, still needs to be leveraged. Despite the low attention to bottom-up public knowledge management approaches in research, individual studies and political developments indicate the potential of a knowledge perspective as a success factor.

The advantages of knowledge-based societies for developing human well-being have been discussed, e.g., concerning the potential role of "knowledge cities" (Ergazakis et al., 2006). The prominent concept of smart cities enqueues therein. The latter highlights that organizing and generating knowledge efficiently in collaborations of government, industry, and universities leads to valuable innovations (Leydesdorff & Deakin, 2011). In this kind of setting, studying the knowledge activities of various stakeholders may reveal various potentials for public administrations. Such approaches may lead to improving public services, managing local networks strategically, leveraging local innovation potential, or establishing a collaborative communication arena for preparing policies (Heinelt & Lamping, 2015; Lenhart et al., 2014; Wiig, 2002). Looking at the example of the EU, this kind of opportunity has motivated the increasing valuation of knowledge approaches for developing policies based on local or regional knowledge (European Commission, 2003), or establishing municipal innovation partnerships (European Commission, 2012). Further, several European cities have started to use a knowledge perspective explicitly and are developing a "knowledge-identity" (van Winden, 2010).

The above considerations emphasize the importance of knowledge systems in the context of increasing complexity regarding the energy transition and efforts for climate change mitigation. Increasingly, human society values knowledge explicitly as a public resource, especially from a local perspective. However, the frameworks for analyzing communication or organizational constellations for achieving a coherent knowledge system still need to be improved.

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CHAPTER 4

RESEARCH DESIGN: EVALUATING COMMUNICATION THROUGH THE LENS OF THE VIABLE SYSTEM MODEL

4. RESEARCH DESIGN: EVALUATING COMMUNICATION THROUGH THE LENS OF THE VIABLE SYSTEM MODEL

The research design of this thesis is motivated by the general questions of sustainability science posed in the introductory Chapter 1, the research needs stemming from the conceptual considerations in Chapter 2, and the problems in the practice of energy transitions highlighted in Chapter 3. From an overarching perspective, these questions, needs, and problems relate to challenges of organizing the complexity of the current and the future energy system. Figure 4-1 provides an overview of how this thesis translates the general research gaps into concrete questions, which it addresses in the three case studies presented in the Chapters 5 to 7. The present chapter outlines the rationale of the three studies and provides a brief introduction into interviews and text mining as key methodologies.

In brief, the three case studies are: (i) Case Study 1, which assesses municipal climate action plans of German cities in Lower Saxony using text mining, (ii) Case Study 2, which examines scientific trends in international research on sustainable energy, also via text mining, and (iii) Case Study 3, which investigates the involvement of the climate action managers based in the cities of Case Study 1 in multilevel knowledge processes. Tables 4-1 to 4-3 at the end of this chapter summarize the case studies with respect to research gaps and motivation, scope, approach, and contributions.

The three studies contribute to evaluating and organizing communication in the socio-epistemic system for fostering sustainability transitions. The following section explains how this thesis uses the Viable System Model (VSM), introduced in Section 2.2.4, as an overarching framework for relating the case studies to each other and placing them into a broader context. The individual studies make use of various other concepts discussed in Chapter 2. Due to the different purposes of the studies, each of them uses different combinations of these concepts as shown in the summarizing tables at the end of this chapter. The final concluding Chapter 8 relies again on the VSM for synthesizing and interpreting the findings from an overarching systemic perspective.

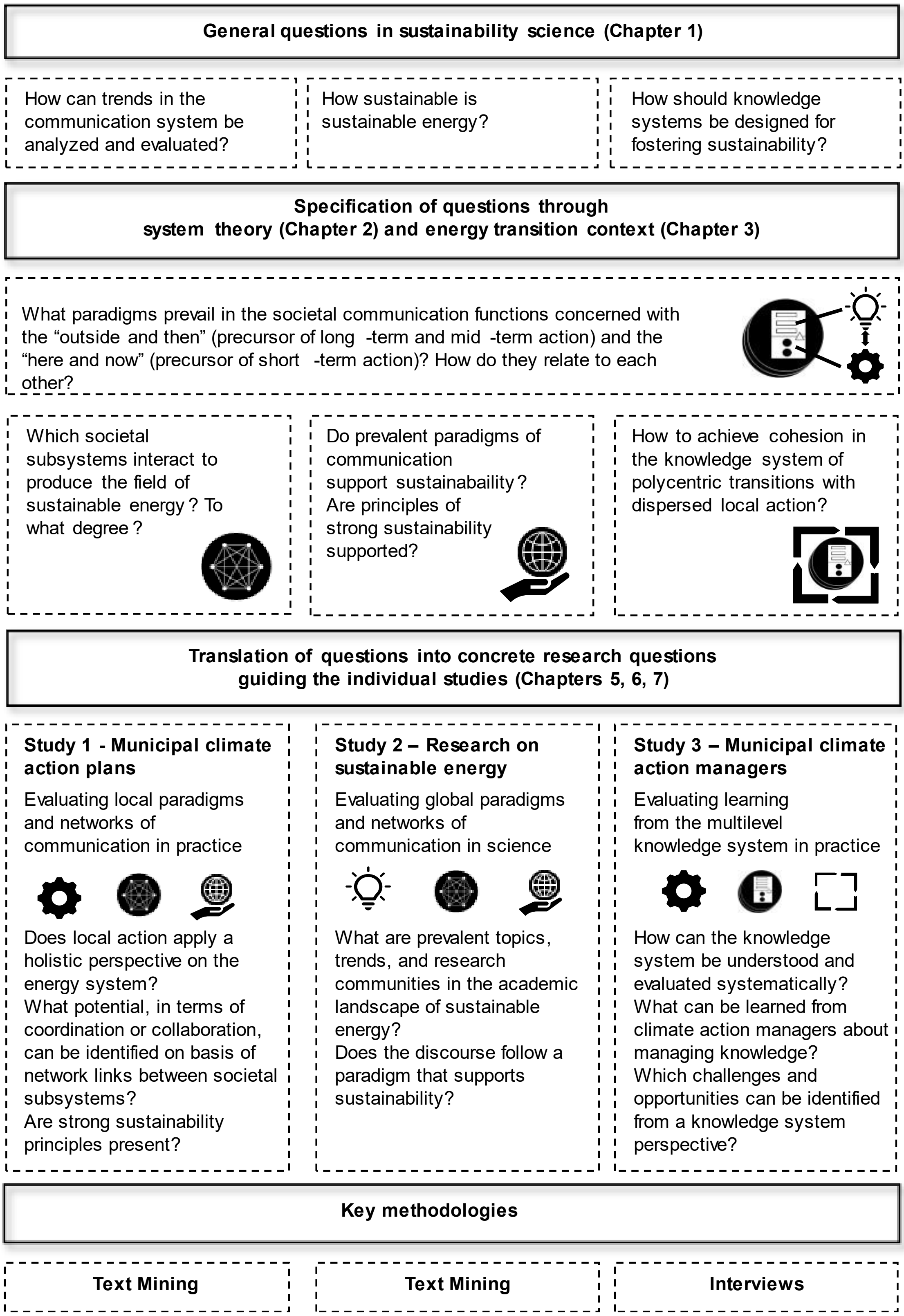


Figure 4-1: Overview of general and specific research questions guiding the three case studies

4.1. CASE SELECTION FOR ANALYZING COMMUNICATION ON THE "HERE AND NOW" AND THE "OUTSIDE AND THEN"

This thesis uses the VSM for diagnosing the organization and management of the energy system from a multilevel perspective. The relation between the intelligence function focusing on the future and the cohesion function focusing on the present is key for organizing the complexity of a system, e.g., through re-organizing knowledge systems or policy-processes (see Section 2.2.4). The practical context of energy transitions (see Chapter 3) suggests that understanding the relation between higher and lower levels, especially the global and the local level, is crucial for transitioning towards a sustainable energy system. This thesis examines international science as a proxy for the global intelligence function in Case Study 2, and municipal climate action as a proxy for the local implementation function in Case Studies 1 and 3. In addressing the concrete research questions listed in Figure 4-1, the case studies contribute to understanding the paradigms and societal networks that shape these functions. They further suggest ways for improving the self-organization of the system with a particular focus on the effectiveness of the local implementation function.

Figure 4-2 provides an overview of the organization of the energy system through the lens of the VSM. It shows where Case Studies 1 to 3 are located in this organization and how they relate to each other. The underlying rationale of this perspective is explained in the following paragraphs. At the bottom, the figure shows an individual department in local administration as the lowest recursion level. It further shows the higher recursion levels, i.e., the municipal, regional, national, supranational, and, finally, the global level. At each level, it shows the five functions defined in the VSM: implementation, coordination, cohesion, intelligence, and policy.

Following the above considerations, Case Study 2 examines the global intelligence function of the energy system that is concerned with the "outside and then" (Beer, 1979) at the highest recursion level. It uses the international scientific discourse on sustainable energy as a proxy for this function. The study analyzes the prevalent paradigms in this discourse and shows (i) to what extent this field dedicated to sustainability actually supports a transformation towards sustainability, and (ii) to what extent the intelligence function is capable of reflecting the complexity of the human (energy) system. These insights are critical for understanding the discourses regarding the future of the energy system that might influence policy or strategy processes. Further, they highlight which adaptations or additional ideas might be required to address potential blind spots.

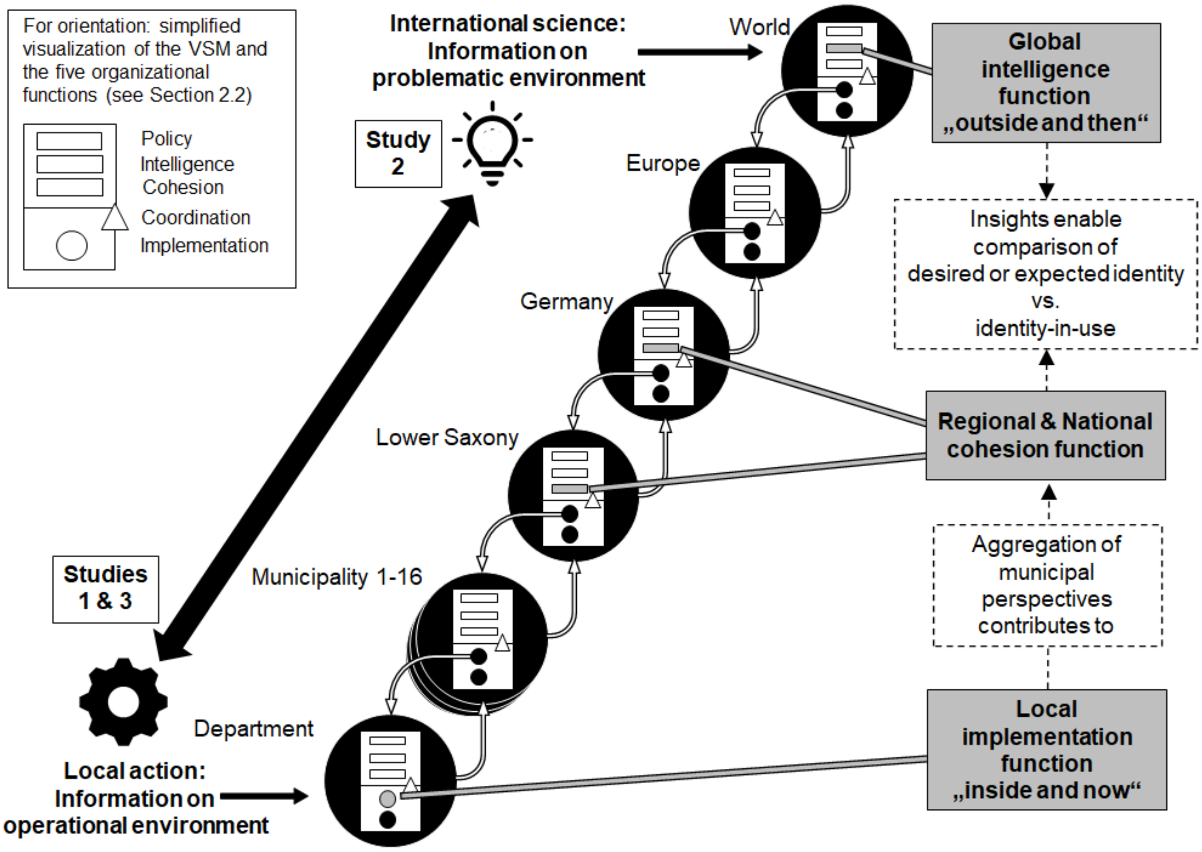


Figure 4-2: The organization of the energy system and elements investigated in this thesis from the perspective of the Viable System Model; visualization inspired by (Schwaninger, 2015)

Case Studies 1 and 3 examine multiple entities of the implementation function at the lowest recursion level. Through aggregating and reflecting these insights from a multilevel perspective, the thesis also provides insights on the cohesion function focusing on the "here and now" (Beer, 1979). The thesis uses the case of municipal climate action in Germany, which may also be referred to as sustainable energy action (Covenant of Mayors, 2010, 2016), as a proxy for the implementation function. Based on the considerations in Chapter 3, urban areas are currently the main places that produce the primary activities and meaning of society. A crucial strategy in the research design is to create an aggregated perspective on multiple municipalities. Analyzing a single municipality would only provide insights into the implementation but not the cohesion function, which is vital for understanding the "identity-in-use" (Espejo, 2015).

Case Study 1 analyzes municipal climate action plans that represent a codification of local paradigms and highlights (i) which subsystems of the energy system favor what kind of sustainability principles and, also, (ii) how individual subsystems are interconnected. These insights may serve as the basis for drafting subsystem-specific or actor-specific communication strategies for better integration of sustainability principles in local networks.

Case Study 3 investigates the involvement of climate action managers in information and knowledge processes and shows how the administrative system manages climate action knowledge, i.e., knowledge to support transitions. It identifies various challenges and opportunities regarding multilevel communication and deficiencies regarding the smooth interaction of systemic functions with the implementation function. These insights can be used to better leverage local transformational knowledge.

Regarding the representativeness of the case selection, it should be noted that the empirical basis for Case Studies 1 and 3 is the context of the German Energy Transition. This transition is a pioneering process and receives great global attention. Germany represents an energy system of a developed country that is shifting away from conventional to renewable power generation. Considering the desired global development towards higher levels of prosperity, the features of the German Energy Transition might be precursors for future energy systems to evolve in other countries. Not all features are transferable since they may depend on, e.g., the geographical, economic, or cultural conditions. Still, the German system may provide lessons learned about promising but also misleading approaches in general.

4.2. TEXT MINING AND INTERVIEWS FOR ANALYZING COMMUNICATION

This section briefly explains the methodological rationale for analyzing communication patterns and prevalent paradigms in the energy context. In general, observing and expressing paradigms involve all human senses. This is relevant in specific communication situations or events that may involve, e.g., varying intonations, body language, or physical contact. This thesis is interested in more overarching patterns regarding communication between organizational units or societal subsystems. Therefore, it focuses on communication via language. Words, which are codifications of meaning, are the primary medium of how humans exchange information and create knowledge (Luhmann, 1984, pp. 42–43; Maturana, 1988; Nonaka, 1994). This thesis uses text mining, i.e., computer aided-text analysis, and interviews to analyze communication patterns. It deals with the context of individuals and large-scale patterns.

To start with the classical methods, Case Study 3 uses interviews for analyzing the integration of climate action managers into the national knowledge system. Understanding the operational context of individuals, which represents the implementation function, requires “human-centred” (B. K. Sovacool, 2014) methods. Interviews are one of the key methods in knowledge management or knowledge audits for mapping and analyzing knowledge processes. They provide deep insights into the practices of an organization and are the basis for developing efficient knowledge systems.

Case Studies 1 and 2 use text mining as a central approach for evaluating communication processes. Text mining, which comprises a family of methods, can analyze large amounts of unstructured text data in a structured way via exploratory or confirmatory approaches (Bickel, 2017; Blake, 2011; Carley & Palmquist, 1992). Exploratory approaches provide an overview of the content of a collection of documents. Confirmatory approaches evaluate texts regarding the presence of pre-defined terms. The resulting patterns can serve as indicators for the content of communication, such as prevalent paradigms.

This thesis exemplifies the potential of exploratory and confirmatory text mining. Case Study 2 uses latent Dirichlet allocation (LDA) as an exploratory method that can identify latent topics in texts (Blei et al., 2003; Blei, 2012). This machine learning method investigates the differentiation of texts into sub-units, i.e., topics. LDA can provide indications on communication codes, subsystems, or societal structures that might not have been reflected in theory yet. Case Study 1 applies a semantic network analysis in a confirmatory manner to analyze organizational structures and to assess the presence of sustainability principles. By definition, this approach can resolve the differentiation of subsystems or sustainability principles on a semantic level by using pre-defined categorization schemes. Motivated by social systems theory that proposes to focus on interactions between societal subsystems (see Section 2.2), both studies also make use of network analysis methods. Network analyses re-combine the various elements that have been separated during individual analytical steps. They indicate, e.g., the strength of the interaction between subsystems and, thus, can help to understand the structure of their organization.

Beyond its empirical or theoretical contributions, this thesis offers a methodological contribution to the toolset of sustainability science. It demonstrates how text mining methods can support sustainability assessments or related studies. Two online open source repositories (Bickel, 2019a, 2019b) make available the complete code and the individual functions created for Case Studies 1 and 2 in the R programming language (R Core Team, 2019). The most recent repository, “textility” (Bickel, 2019b), represents a consolidation of the code and is under steady development. Beyond this thesis, the repository has already been used in an advisory study to the German Science Platform Sustainability 2030 (Domröse et al., 2019).

- Bickel, Manuel W. (2019). *textility - An R package for applied text mining with an example of topic modeling in the field of research on sustainable energy* https://zenodo.org/record/2550719; https://github.com/manuelbickel/textility. Zenodo. DOI: http://doi.org/10.5281/zenodo.2550719.

4.3. SUMMARY OF THE THREE CASE STUDIES CONDUCTED

The following Tables 4-1 to 4-3 provide the bibliographic information and publication status of the three case studies conducted for this thesis. They further summarize the motivation, scope, methodological approach and contribution of the studies. Chapters 5 to 7 present the individual studies in detail.

Table 4-1: Overview of Case Study 1

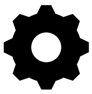
Title	**A new approach to semantic sustainability assessment. Text mining via network analysis revealing transition patterns in German municipal climate action plans**
Author	Bickel, Manuel W.
Publication status	**Published** 17 July 2017 in Energy, Sustainability, and Society 7 (1) DOI: 10.1186/s13705-017-0125-0
Research gap & Motivation	There is no comprehensive study that maps networks of local climate action in a quantitative way using a repeatable method. Further, it is unclear to what extent municipal climate action actually supports sustainability.
Scope	<u>Thematic:</u> 16 municipal climate action plans of regional centers in Lower Saxony, Germany, more specifically the measures proposed therein. <u>Systemic:</u> Investigation of the local implementation function as well as the paradigms and communication network of subsystems constituting this function.
Approach	- Semantic interpretation network analysis. - Qualitative categorization of words for establishing a semantic model of subsystems and strong sustainability principles. - Frequency analysis and network analysis of the semantic categories applied to the measures proposed in the 16 plans.
Contribution   	<u>Thematic</u>: Insights into the roles attributed to individual sectors and their interconnectedness that allow targeted climate action interventions in local networks. <u>Systemic</u>: The study reveals the interaction between different subsystems (reference to *social systems theory*, Section 2.2.3). By providing an aggregated perspective on the local implementation function, it can inform or even represent a part of the cohesion function (reference to *Viable System Model*, Section 2.2.4). <u>Methodological</u>: Development of a mixed qualitative and quantitative method to assess semantic adherence to sustainability principles and to analyze the coupling of subsystems. <u>Sustainability science</u>: Explicit evaluation to what extent strong sustainability principles are present in the plans (reference to *sustainability*, Section 2.1).

Table 4-2: Overview of Case Study 2

Title	**Reflecting trends in the academic landscape of sustainable energy using probabilistic topic modeling**
Author	Bickel, Manuel W.
Publication status	**Published** 20 December 2019 in Energy, Sustainability, and Society 9 (1) DOI: 10.1186/s13705-019-0226-z
Research gap & Motivation	There is no overarching comprehensive picture of the academic landscape of research on sustainable energy. It is unclear to what extent this hybrid field between energy research and sustainability science actually supports sustainability.
Scope	Thematic: Trends, topics, networks in international research on sustainable energy, 26533 abstracts published from 1990 to 2016. Systemic: Investigation of the global intelligence function as well as the paradigms and communication network constituting this function.
Approach	- Qualitative screening of published reviews as reference background for the analysis. - Topic model of the scientific discourse via latent Dirichlet allocation. - Further analyses using linear regression, multidimensional scaling, cluster analysis, and network analysis.
Contribution   	Thematic: Evidence for prevalent paradigms and blind spots in the academic landscape without selection bias regarding publications to be analyzed. Systemic: Assessment to what extent the global intelligence function is capable of providing comprehensive information to support self-reference and reflexivity to advance the energy system and organize its complexity (reference to *Viable System Model*, Section 2.2.4). The network analysis provides insights into the structure of subsystems shaping this function (reference to *social systems theory*, Section 2.2.3). Methodological: Development and application of an advanced analytical text mining pipeline, i.e., an integrated combination of suitable processing sequences and methods. The code is available in an Open Access online repository. Sustainability science: Monitoring of trends in science on sustainable energy over time and evaluation to what extent they support strong sustainability (reference to *sustainability*, Section 2.1).

Table 4-3: Overview of Case Study 3

Title	**Multilevel knowledge management for municipal climate action: Lessons from evaluating the operational situation of climate action managers in the German Federal State of Lower Saxony**
Authors	Bickel, Manuel W.; Caniglia, Guido; Weiser, Annika; Lang, Daniel; Schomerus, Thomas
Publication status	**Published** 17 August 2020 in The Journal of Cleaner Production 277 DOI: 10.1016/j.jclepro.2020.123628
Research gap & Motivation	It is unclear to what extent the valuable local knowledge created in municipal climate action is integrated into national planning or knowledge systems. More research is needed to achieve a higher degree of knowledge integration and cohesion considering the polycentric nature of transition activities.
Scope	Thematic: Interviews with 14 municipal climate action managers of regional centers in Lower Saxony, Germany. Systemic: Investigation of the connectedness of the local implementation function to other functions at higher levels.
Approach	- Literature review on design principles for knowledge systems. - Personal interviews with 14 climate action managers in their offices. - Qualitative coding and frequency analysis of interview transcripts. - Assessment of results regarding the adherence of the public climate action system to the design principles.
Contribution	Thematic: The study highlights challenges and opportunities for municipal climate action as a field of local experimentation to better leverage its potential through structured and synchronized multilevel knowledge processes. Systemic: It shows the degree of integration and effectiveness of the implementation function (reference to *Viable System Model*, Section 2.2.4) within the national knowledge system (reference to *knowledge systems*, Section 2.2.2) and proposes ways to improve the interaction with other functions for increasing cohesion. Methodological: Structured compilation of principles for designing effective multilevel knowledge systems. Sustainability science: Knowledge management approach for supporting multilevel governance of sustainability transitions and for leveraging sustainability innovations emerging in local transition contexts.

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CHAPTER 5

CASE STUDY 1 - A NEW APPROACH TO SEMANTIC SUSTAINABILITY ASSESSMENT: TEXT MINING VIA NETWORK ANALYSIS REVEALING TRANSITION PATTERNS IN GERMAN MUNICIPAL CLIMATE ACTION PLANS

5. CASE STUDY 1 - A NEW APPROACH TO SEMANTIC SUSTAINABILITY ASSESSMENT: TEXT MINING VIA NETWORK ANALYSIS REVEALING TRANSITION PATTERNS IN GERMAN MUNICIPAL CLIMATE ACTION PLANS

BIBLIOGRAPHIC DATA

Bickel, M.W. A new approach to semantic sustainability assessment: text mining via network analysis revealing transition patterns in German municipal climate action plans. *Energ Sustain Soc* **7,** 22 (2017).
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ABSTRACT

Background: Various monitoring approaches have shown that urban areas and their energy systems are major contributors to climate change. Corresponding observations have mostly been based on physical data. However, text data is an untapped source of information that can be analyzed by text mining methods. Taking the example of the German Energy Transition, an interpretation network analysis was used to assess local transition patterns in 16 municipal climate action plans of regional centers in the State of Lower Saxony. Based on the holistic concept of social-ecological systems, three analytical perspectives were introduced, the social system, the energy system, and the three principles of strong sustainability, which inspired three questions: What is the “horizon of attention” regarding the stages of the energy system? What potential, in terms of coordination or collaboration, can be identified on basis of network links between societal sub-systems and the energy system? Are strong sustainability principles adequately linked to the energy system to support a transition towards sustainability?
Methods: A computer-aided interpretation network analysis was used. The (co-)occurrence of indicative words representing pre-defined categories was checked in the measures proposed in the plans to analyze the importance and connectedness of these categories. For this purpose, three thesauri were created as fixed literature-based categorization schemes.
Results: Municipalities had a nuanced understanding of climate protection focusing on energy conversion and end-use. Public administrations were closely connected role models, economic stakeholders seemed only partly interlinked. The plans referred to all three sustainability

principles. However, their implementation might not fully acknowledge the ecological carrying capacity, because, e.g., the strategy of setting limits could not be clearly identified.

Conclusions: To advance municipal climate protection, current cross-sectoral multilevel governance approaches should be improved with emphasis on capacity of local administrations, electricity grids, or renewables in the sectors heat and mobility. Also, more emphasis on sustainability communication and education based on all three sustainability principles will be crucial for a transition towards sustainability. From a methodological viewpoint, the text mining approach could confirm and complement recent studies. Considering its limitations and prospects, it can be advanced to useful tool sets for semantic sustainability assessments.

ABBREVIATIONS

A#	Appendix
ANCO	Average normalized co-occurrence
ANCOM	Average normalized co-occurrence matrix
ANO	Average normalized occurrence
CoM	Covenant of Mayors
Difu	Deutsches Institut für Urbanistik (German institute of urban affairs)
ds-c-m	document-section-category-matrix
ds-t-m	document-section-term-matrix
d-t-m	document-term-matrix
F#	Numbered finding
ICLEI	International Council for Local Environmental Initiatives
L#	Strength of link between two categories (scaling option one)
MCAP	Municipal climate action plan
NKI	Nationale Klimaschutzinitiative (National climate protection initiative)
S#	Representation of a sustainability category relative to another (scaling option two)

5.1. BACKGROUND

One of the key questions in sustainability science is how environmental and social conditions can be monitored and how the information generated by monitoring systems can contribute to a transition towards sustainability [1]. This question is particularly important when it comes to urban areas, which are the “key context” for current and future sustainable challenges [2]. The rapid growth of urban populations [3] will lead to increased resource consumption, waste outputs, or emissions from urban activities, which already exceed the ecological carrying capacity [4, 5, 6]. Regarding global energy-related CO2 emissions from urban areas, the fifth assessment report of the Intergovernmental Panel on Climate Change provided recent estimates [7]. If one considers the estimates generated with the help of the three main accounting approaches, an average of 71% may be stated for the first decade of the new millennium [8, 9, 10]. This number clearly shows that urban areas are significant contributors to climate change, one of the main global sustainability challenges of humankind in the twenty-first century [1, 11]. While urban energy systems have already received considerable scholarly attention [8, 12, 13], some dimension of these drivers of global climate change need to be examined to an even greater extent. More specifically, “effort to improve measurement and monitoring […] is urgently needed” to contribute to “learning, transfer of knowledge, and sharing experiences and information” [8].

This study complements current monitoring approaches by introducing standardized semantic sustainability assessment as a method based on computer-aided text mining for analyzing urban transition patterns. Reviews of monitoring and assessment tools [14, 15, 16] or exemplary frameworks [17, 18, 19] show that sustainability monitoring has so far mainly been based on physical data such as mass, energy, or emission balances and socio-economic indicators. This kind of data describes impacts of human action caused, e.g., by the implementation of policies [20]. To identify improved ways of action before policies become manifest in physical indicators, approaches are needed to monitor their content. Established qualitative methods are valuable for this purpose, see, e.g., Jane and Spencer [21]. However, their time-efficiency is limited for large case numbers and their results often lack structure for coupling them with quantitative methods. Text mining, a mixed qualitative and quantitative approach, could be used to bridge this gap by presenting the content of documents in a quantitative way. As laid out in the following, this study, as first of its kind, uses a text mining approach to analyze energy transitions in the context of municipal climate action by applying a new holistic perspective.[2]

For providing comprehensive bottom-up insights in the nexus of urban energy systems and climate protection, text mining allows handling large numbers of cases and amounts of text. This could provide answers to the following questions: How are responses to the global challenge of climate change shaped at the local level and what “forms of intervention or transition […do] they aim to produce” [22]? To what extent do these responses support a transition towards sustainability? Answers to these questions may contribute to “mapping practices of design and implementation of urban low carbon energy transition policy” [2]. Thereby, the multilevel coordination and integration of policies that is necessary for successful transitions [2, 23, 24] may be supported. Integrating local insights in this process requires a broader empirical basis [2, 25]; however, studies on municipal climate action have focused on limited case numbers and qualitative research designs [25]. As a first step to close this gap, Castán Broto and Bulkeley mapped 100 municipal climate action experiments by applying quantitative content analysis that required manual screening and coding of text data [26]. To advance this direction of research by overcoming limitations of manual approaches, this study proposes a structured computer-aided approach.

Addressing above questions concerning transition patterns and their degree of sustainability, text mining was applied to municipal climate action plans (MCAPs), which are governance instruments in the context of the German Energy Transition. To explore the potential of text mining, this study focuses on this prominent example [24, 27] to show how such approach might complement existing ones. Sixteen regional centers of the State of Lower Saxony served as an initial set of cases. Before providing details on the methodological approach, the context of MCAPs is summarized.

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[2] Text mining is a fairly recent approach in sustainability science. Original articles are available from around the 1970s. In sustainability science, the first relevant article was published in 2007 by Kajikawa. Regarding the particular sub-field of sustainable energy, there are only eight journal articles referring to text mining approaches that examine an individual technology or sector in isolation. The availability of articles was checked via the Scopus and Web of Science databases. The search term for original and review articles was TITLE-ABS-KEY((“text mining” OR “natural language processing”) AND (sustainab* OR “climate action” OR “climate protection” OR “climate change mitigation”) AND energy). The search was performed on the 22 May 2017.

MCAPs have become standardized to a certain extent. At the international level, MCAPs have been promoted, e.g., by the International Council for Local Environmental Initiatives (ICLEI) [28] or the Covenant of Mayors (CoM) [29]. Both have issued guidelines [30, 31]. Since MCAPs are usually voluntary [25, 32], it is not clear to what extent they have been implemented. However, it was noted for USA cases that they can still provide a "framework for action" [33]. A study focusing on California found, e.g., that MCAPs "codify […] outcomes that would have happened anyway" and, thus, reveal "local preferences" [32, 34] that are crucial for understanding energy transition patterns [2]. This characteristic could, as shown in this study, serve as a basis for monitoring such patterns. While MCAPs provide information on the visions and specific steps to be taken, monitoring reports that track the implementation of MCAPs may also shed light on implementation patterns. However, only a few of these reports are available [33, 35, 36]. Therefore, they might only be subject of future studies.

In Germany, climate protection is a voluntary task of municipalities [37, 38]. However, a national framework offers incentives such as partial funding and thereby has moved MCAPs one step closer to implementation. Since 2008, MCAPs have been embedded in the National Climate Protection Initiative (Nationale Klimaschutzinitiative - NKI), which is a key government instrument to reduce Germany's greenhouse gas emissions. It supports planning, communication, and capital-intensive measures in four sectors: municipalities, the economy, consumers, and education [39].

The financial support scheme of the NKI for municipalities is laid out in the so-called municipal legal guideline (Kommunalrichtlinie) [40] that is the basis for partial funding of the three standard implementation steps: (i) preparation of MCAPs, (ii) 3-year management of implementation, and (iii) capital-intensive implementation measures [39, 40, 41]. The capital is provided out of the Energy and Climate Fund (Gesetz zur Errichtung eines Sondervermögens 'Energie- und Klimafonds' - EKFG), which is financed by federal budget funds and national revenues from emission trading [42, 43]. For operational support, a practical guide for drawing up MCAPs [44, 45], similar to the ones provided by ICLEI or CoM, was published by the German Institute of Urban Affairs (Deutsches Institut für Urbanistik - Difu), which assigned the role of the national service center for municipal climate protection [46]. It should be noted that individual municipalities have prepared MCAPs before the NKI was launched. However, their activities have largely been aligned with the NKI, which functions as the framework for the majority of German MCAPs.

From the variety of text mining methods, this study applied an interpretation network analysis [47, 48] to examine MCAPs in order to contribute to a nuanced meta-network perspective on cities that has so far been missing according to, e.g., Bulkeley [25]. This and other methodological limitations can be illustrated by the following examples of studies on municipal climate action that have focused on the USA and Europe and that have considered the content and impact of MCAPs, or governance [25, 33, 49, 50, 51, 52]. In the following, the focus is on methodological aspects of these studies. Details on their results are treated in the discussion section.

Several studies have provided valuable quantitative insights into municipal climate action, however, without quantifying the weighting of topics in individual municipalities or highlighting the local interactions. The quality of MCAPs in US cities was examined, e.g., by Wheeler or Brody [33, 51]. At a general level, their studies included an analysis of the spectrum of sectors and implementation strategies considered in the plans [33, 51]. A similar approach was followed by Castán Broto and Bulkeley in their comprehensive survey of climate action experiments, which looked beyond MCAPs, e.g., by also screening websites [26]. Basically, this kind of studies reported the number of municipalities that refer to selected aspects.

By applying qualitative research designs, several studies have provided meaningful insights into local interactions and governance. However, they have been limited to selected cases and actor constellations. Furthermore, comparing their results is not trivial due to qualitative reporting. Yalçın and Lefèvre studied the “the climate plan process” in French pioneer cities and considered, e.g., the potential of actor networks as resources [52]. Rutland applied actor network theory and the framework of governmentality to the developments in Portland, Oregon, to track the interest of actors, especially government, citizens, and companies, and their influence on the “energy reform” [53]. Similarly, Fuchs and Hinderer applied field theory to examine four German cases regarding conflicts between electricity grid operators and municipalities concerning decentralization of the energy system [54]. Focusing on the perspective of three local governments in Germany, Bulkeley and Kern examined their modes of “governing of climate change” and identified the potential for success in different fields of implementation [38, 55]. This kind of studies provides valuable insights into social dynamics, however, on basis of small empirical samples and a low degree of standardization.

Adopting a computer-aided mixed qualitative and quantitative network analysis approach, this study seeks to complement above approaches to document the roles assigned to actors and the relative importance of topics as codified in MCAPs in a structured quantitative way. This can be used, e.g., to identify gaps in the local collaboration or actor constellations that require additional attention in terms of coordination. Furthermore, applying a computer-aided approach, which is based on counting the occurrence and co-occurrence of categorized terms [56], allows for repeatability and facilitates comparability. Details on the method are provided in the following section. The remainder of the introduction discusses the theoretical considerations that underlie the selection of analytical categories for this study.

Since a “systemic perspective” is essential for transitioning towards sustainability [24], this study adopts a tripartite social-ecological system perspective. This conceptualization has not been adopted before in studies on municipal climate action. This study extends this discourse by incorporating the perspective of Weisz and Fischer-Kowalski [57, 58] that was concisely defined by Haberl as follows: “Social-ecological systems can be defined […] as comprising a ‘natural’ or ‘biophysical’ sphere of causation governed by natural laws, and a ‘cultural’ or ‘symbolic’ sphere of causation reproduced by symbolic communication. These two spheres overlap, constituting what is here termed ‘biophysical structures of society.’ […] (Un)sustainability refers to the interaction process between nature and culture which can only proceed indirectly, via the biophysical structures of society” [59]. The energy system represents the core of these intermediary structures of social-ecological systems and the “most basic constraint for […their] differentiation” [60]. Due to the finite nature of “energy stocks,” the current “fossil energy system is a future-closed system” [61]. To allow “future-openness” for the social system, shifting to a “post-fossil energy system” is necessary [61]. Such “radical reorganization” will require humanity to adequately consider “the manifold interconnections between the energy system and society” [62].

On basis of above considerations, the categorization scheme for the interpretation network analysis was operationalized by creating thesauri covering three analytical perspectives: (1) the social system, (2) the energy system, and (3) strong sustainability. By adopting the notion of the differentiation of the social system into subsystems [24, 63, 64], it was possible to create categories to describe them. These subsystems can be seen as collective institutions for a specific function in society such as the economy, education, or religion. They can be further differentiated internally into sub-units. Accordingly, the differentiation of the energy system, the biophysical sphere of society, was specified by considering its stages from resources to consumption [65, 66]. This specification takes into account that municipalities are embedded in a multilevel system and that “an urban energy system comprises all components related to the use and provision of energy services associated with a functional urban system, irrespective where the associated energy use and conversion are located in space” [8]. Hence, municipalities have a far-reaching “horizon of responsibility” [67] to be considered for sustainable climate action. The first two analytical perspectives were used in this study to evaluate if MCAPs considered a “horizon of attention” for the energy system stages [67] that matches the responsibilities and if emerging actor constellations were adequate to meet them.

The third analytical perspective adopts the operational normative principles of strong sustainability that have been introduced by Daly [68] and elaborated by Ott and Döring [69]: sufficiency, efficiency, and consistency[3]. In contrast to weak sustainability [70], strong sustainability acknowledges the critical limits of resource extraction and ecological carrying capacity, which have been pointed out in various studies [71, 72, 73]. It proposes three complementary principles [68, 69]: First, sufficiency requires a decrease of resource extraction from the environment “to limit the human scale to a level which, if not optimal, is at least within carrying capacity and therefore sustainable” [68]. Second, efficiency implies generating “more service per unit of resource” [68]. Third, consistency stipulates that renewable resources have to be used and that “harvesting rates should not exceed regeneration rates” [68]. Hence, all three principles need to be incorporated in the energy system to allow for an interaction with nature that leads to a sustainable state. The degree of representation of these principles in MCAPs was used to indicate their potential to contribute to a transition towards sustainability.

The analytical perspectives served to create a word categorization scheme used to examine MCAPs by means of the following three questions:

[3] The original term used by Ott was resilience instead of consistency. For a clear demarcation to the discourse that deals with the concept of resilience, which is used, e.g., by the Stockholm Resilience Center, the term consistency was used in this study. This term has evolved in the German discourse with reference to consistent resource cycles.

- Q1: What is the "horizon of attention" regarding the various stages of the energy system?
- Q2: What potential, in terms of coordination or collaboration, can be identified for municipal climate action on basis of network links between societal sub-systems and stages of the energy system?
- Q3: Are strong sustainability principles adequately linked to the stages of the energy system to support a transition towards sustainability?

Summing up, this study advances existing sustainability assessment approaches by contributing to the gap between qualitative and quantitative methods. It exemplifies the use of a text mining approach, in particular, a computer-aided semantic interpretation network analysis, in the context of municipal climate action. It extends this discourse by adopting a social-ecological system perspective and incorporating a holistic network perspective and the normative viewpoint of strong sustainability. By an exemplary study of MCAPs, it provides a new quantitative approach to identify predominant or missing topics, gaps, or collaboration potential in local networks, and the degree of adherence to sustainability principles. It thereby lays the ground for a standardized quantitative monitoring of policies that may be applied to large case numbers for mapping and investigating transition patterns.

5.2. METHODS

This section provides a detailed discussion of the interpretation network analysis, which can be used to generate macroscopic network data for an automatic semantic sustainability assessment. First, text mining is introduced as a general methodological framework. Then, details on the selected cases in Lower Saxony and the characteristics of their MCAPs are provided. This is followed by an overview of the network analysis used to examine the occurrence and co-occurrence of categories. Furthermore, the literature-based categorization scheme is described, i.e., the thesauri that served as the knowledge base. Finally, details on the generation of network data and the subsequent analysis are provided. Limitations concerning aspects such as data structure, negations, or syntax parsing will be addressed in the discussion section.

5.2.1. General introduction to text mining

Text mining serves to “identify […] patterns from a collection of texts” [74]. By using computers and natural language processing methods, it is possible to handle large amounts of unstructured text data. Examples of text mining applications are “information extraction, topic tracking, summarization, categorization, clustering, concept linkage, information visualization, or question answering” [75].

Text mining generally comprises the following six methodological steps: “selection, pre-processing, transformation, data mining, interpretation, and evaluation” [76]. After the first step, selection of a sample (i), the text data require “pre-processing” to remove “noise” (ii) [74, 76], e.g., by “stemming” words or deleting irrelevant “stopwords” such as articles or prepositions [74, 75]. Then, “features to represent the data” are selected [76], and a “dimensionality reduction” is performed to increase information density (iii) [74, 76]. The most common text representation with a reasonable performance is splitting text into a vector of terms [74, 77]. This results in a document-term-matrix (d-t-m). Each row represents a document and each column the frequency of each term per document. A term may be a single word or a phrase. Further options of representation include text parsing to consider additional information on terms such as word type or syntax [77]. Depending on the chosen representation, various methods for dimensionality reduction may be applied. In case of a d-t-m, this may include “pruning terms based on their frequency,” “principal component analysis,” or mapping synonymous terms “onto a higher order representation” [74]. After data structuring, data analysis is performed (iv). This involves data mining methods such as “classification,” “clustering,” or network analysis to identify “patterns of interest” [75, 76, 77]. In the final steps, the resulting patterns are interpreted, which may be aided by “visualization” (v), in order to summarize and evaluate the data (vi) [75, 76]. In practice, the six steps described here are often not strictly separated and may involve “significant iteration” or mixed approaches [76].

Whether previous knowledge is considered in the steps of text representation and analysis makes a major difference: A pure machine learning approach relies on probabilistic models, whereas a knowledge-based approach involves “existing knowledge resources” such as pre-defined ontologies or training data [74]. In this study, the latter approach was followed.

Before providing details on the data and methodological approach, the software used for this study is briefly described. The open source software R was chosen here [78]. As high-level programming language, it provides interfaces to other software solutions. It offers a growing set of extension packages for various purposes including text mining [79]. R was combined with the following software solutions for converting pdf documents into plain text: pdftotext [80] for extracting text layers and Tesseract [81] for optical character recognition (OCR). Furthermore, the following R packages were used: text2vec [82] for setting up document-term-matrices, SnowballC [83] for stemming, plyr [84] and reshape2 [85] for handling data, and gridExtra [86], gtable [87], and ggplot2 [88] for visualization. To honor R’s open source ideal, the data and code of this study may be accessed via the section “Availability of data and materials.”

5.2.2. Data selection - municipal climate action plans of regional centers in Lower Saxony

Due to the important role of MCAPs in the German Energy Transition, their sections on proposed measures to be implemented were used to reveal planned local transition patterns. Since many municipalities have used the guide issued by the Difu to prepare MCAPs, these plans are fairly similar in terms of structure and content. They basically include four key sections: (i) vision and goals, (ii) status quo report, (iii) descriptions of process and conditions of plan preparation, and (iv) a catalogue of measures containing descriptions of various measures that are proposed for implementation. Since contextual or strategic aspects are primarily addressed in sections (i) to (iii), the catalogue of measures contains rather straightforward statements, which do not require “reading between the lines.” Hence, it represents a suitable basis for automated analyses.

The catalogues of measures in MCAPs provide insights concerning local transition patterns because they state who is expected to act and what could be done. They include information on a wide range of sectors, issues, and measures such as solar installations on school roofs, city bike projects, or energy efficiency roundtables involving local factories. The guide issued by the Difu proposes various participatory methods for developing measures to allow for input by stakeholders such as administrative bodies, citizens, or companies [44, 45]. Thus, the catalogues potentially represent a broad spectrum of stakeholders. These catalogues include form sheets for each measure. Table 5-1 shows an exemplary sheet.

Table 5-1: Exemplary form sheet to report climate action measures in MCAPs (short version)

Generic heading	Description (exemplary)
ID of measure:	M-01
Title of measure:	PV power plants on school roofs
Stakeholder(s):	building department of municipality, municipal schools, PV contracting company
Short description:	installation of plants in all schools of the city
Milestones / goals:	three plants per year and project completion within five years
Economic viability:	given when using contracting solution and national funding programs

In this study, the catalogues of measures included in MCAPs of 16 regional centers in the State of Lower Saxony were analyzed. By considering these centers, which are subject to the same national and state laws, as a group, it is possible to discern urban developments in this state. In other words, rather than comparing individual cities, this study aims to describe average regional patterns.

The Regional Development Plan of Lower Saxony defines 17 cities as regional centers. At the time of writing, 16 of them had released an MCAP. They were issued between the years 2010 and 2014 and, on average, contained 86 measures. Ordered by population size, the 16 centers studied are Hannover, Braunschweig, Oldenburg, Osnabrück, Wolfsburg, Göttingen, Hildesheim, Salzgitter, Wilhelmshaven, Delmenhorst, Lüneburg, Celle, Hameln, Nordhorn, Langenhagen, and Emden. Lüneburg had a climate action activity report instead of an MCAP. As its content resembled that of MCAPs, it was included in this study. Details on the characteristics of the individual cities and their MCAPs are provided in A1.

5.2.3. Text representation

A vector space model was used to represent the individual measures of the catalogues of measures and to create document-section-term-matrices (ds-t-m) for each measure. Each catalogue was split into individual measures using a semi-automated approach. The generic headings repeated at the top of each measure sheet (see Table 5-1), e.g., Title of measure, were identified manually and used to automatically split the texts into sections. These were then split into terms.

5.2.4. Pre-processing

The words of the extracted measures were then harmonized. Encoding errors of characters were corrected, and special characters were replaced with basic letters, e.g., *ä* was replaced by *ae*. Words were then shortened to their grammatical stems using Porter's stemming algorithm [89, 90], e.g., the word forms *Einsparungsziele*, *Einsparungszieles*, and *Einsparungszielen* were transformed to *Einsparungsziel* (*saving target*). In addition, stopwords were deleted. Finally, only unique terms were kept in each ds-t-m. As a matter of course, this kind of harmonization had also been applied to the thesauri after their creation. The latter is discussed below.

5.2.5. Interpretation network analysis as a text mining application

Given the data structure described above and the aim to reveal links between network nodes and their connectedness to sustainability aspects, an interpretation network analysis was conducted [47, 48]. The following section describes how individual network nodes and links were defined.

To represent network nodes, hyperonyms, i.e., higher ontological categories, were used that represent several closely related terms. Hence, each ds-t-m was transformed to a document-section-category-matrix (ds-c-m). This reduction of dimensionality was achieved by involving knowledge resources to assign categories to terms that are synonymous at higher ontological levels and could thus be aggregated [47, 74]. The terms *photovoltaics* or *wind power plant* could, e.g., be subsumed under the category renewable energy conversion.

Practical and theoretical literature on energy, society, and sustainability was used as knowledge resource to create a fixed semantic categorization scheme. It contained groups of synonymous terms, which were tagged with categories already found in the literature. In addition, the literature provided lists of terms for the categories that were then extended in this study. More specific information on the knowledge resources, definitions of categories, and the creation of lists of terms are provided in the following sections.

Regarding the definition of links for the network analysis, the occurrence and co-occurrence of categories in individual measures were counted [56]. The co-occurrence in a single measure was defined as a link. These undirected links provide information on potential connections between societal subsystems or sustainability aspects. Addressing the questions guiding this study, this approach provides information on the relative importance of categories in the catalogues of measures and also reveals connections between categories [56].

5.2.6. Knowledge base - categorized terms in three thesauri

To store lists of terms in pre-defined categories, one thesaurus was created for each analytical perspective: (i) the social system, (ii) the energy system, and (iii) strong sustainability principles. Although all three thesauri were created in German, selected terms and categories are included here in English. The following sub-sections describe the general structure of the thesauri with reference to some of the most relevant terms and categories. They also explain the process of creating categorized lists of terms based on the knowledge resources used to aggregate each ds-t-m.

5.2.6.1. General structure of the thesauri and naming of categories

The three thesauri were numbered and named <1><SOC>, <2><ENG>, and <3><SUS>. Their first level consisted of meta-categories, which included more specific individual categories at lower levels. In the thesaurus <2><ENG>, the meta-category <Conversion> included, e.g., the categories <renewable> and <fossil>. Terms such as *photovoltaic power plant*, *solar heat*, or *wood chip heating system* were tagged with the first of these categories, whereas terms such as *coal power plant*, *peak load boiler*, or *oil-fired heating* were tagged with the second. As an example, the full notation for the second category was <2><ENG><Conversion><fossil>.

There were also categories referred to as <general_reference> which were assigned to terms that qualified for a general meta-category but not exclusively for a specific category. Terms such as *economy*, *company*, or *business location* were tagged, e.g., with the category <1><SOC><Economy><general_reference> that represents a general thematic reference to economic topics at a high ontological level. Similarly, the terms *energy conversion*, *power plant*, or *energy supply* were tagged with the category <2><ENG><Conversion><general_reference>. The lists of terms of this kind of categories did not overlap with lists of more specific categories under the same meta-category. The category <2><ENG><Conversion><general_reference> had, e.g., no overlap with the category <2><ENG><Conversion><fossil>.

5.2.6.2. Exploratory and confirmatory approach for knowledge-based creation of lists of terms

Knowledge-based text mining may follow two different approaches concerning the compilation of terms for individual categories, a confirmatory or an exploratory approach [47]. An exploratory approach asks “What does the text contain?” and “the words are drawn from the texts themselves.” This approach is followed when it is “impossible to anticipate” which terms are used within the text and whether they fit into individual categories [47]. A confirmatory approach asks, “Does the text contain what I expect it to contain?” and “the words [to represent individual categories] are defined independent of and prior to any textual coding” [47]. This kind of pre-definition is possible if the content of categories can be anticipated based on theoretical or normative considerations. Such “a priori design” [91] is related to quantitative content analysis, which is a commonly used method in the social sciences [92].

The thesauri <1><SOC> and <2><ENG> were compiled in an exploratory approach in order to comprehensively cover the content of the documents as a basis for answering the three research questions. It was not feasible to anticipate the majority of terms in the catalogues of measures. Therefore, terms were extracted from the catalogues of measures and tagged with categories.

For these two thesauri, tagging of terms was limited to nouns. This word class tends to refer to elements such as objects, places, persons, or events. The descriptions of measures in the MCAPs were primarily composed of such elements. Therefore, it was assumed that by focusing on nouns, the basic patterns of meaning in terms of societal subsystems could be described. Since nouns start with an uppercase letter in German, they could automatically be identified. The meaning of abbreviations that were identified on this basis was looked up in the documents or the Internet in order to assign categories to various abbreviations such as *RROP (Regionales Raumordnungsprogramm; regional spatial planning program)*, *SWE (Stadtwerke Emden; public utilities of Emden)*, or *LED (light emitting diode)*.

In contrast to the exploratory approach, <3><SUS> was compiled using a confirmatory approach. Due to the normative nature of strong sustainability, it was deemed reasonable to pre-define lists of synonymous terms for representing sustainability categories and to check whether the documents contained these terms or categories. Since the meaning of the three principles of strong sustainability is quite straightforward, it was assumed that the corresponding synonyms could be anticipated to a satisfactory degree at a linguistic level.

The third thesaurus was not limited to any specific word type. No restrictions were made because characteristics of sustainability require consideration of dynamic word types related to action in addition to the rather static aspects represented by nouns.

For each municipality, the average number of words and tagged nouns per measure are reported in Appendix A7.

5.2.6.3. Categorization of terms - <1><SOC> AND <2><ENG> - exploratory approach

To create categorized term lists for <1><SOC> and <2><ENG>, the nouns contained in the MCAPs were tagged in two steps. First, existing knowledge resources were used to initialize the categorization scheme with categories and lists of terms. Using literature-based lists reduced the effort required for the second step, i.e., the manual tagging of nouns not matched during the first step. When appropriate, more than one category was assigned to individual nouns, in particular compounds, which are frequently used in German. A brief overview of the literature used to tag nouns is provided in the following. The complete list is included in Appendix A2.

The categories of <1><SOC> addressing the social system were mainly based on subsystems suggested in the theoretical discourse of structural functionalism [63, 64, 93, 75], the field of sustainability related system dynamics [94, 95], and the guide issued by the Difu [45]. This set of literature provides a systematic perspective on the social system. It proposes or uses relevant conceptual categories to describe, model, analyze, or, in case of the Difu guide, implement projects in the context of municipal climate action. Combining established conceptual categories was deemed reasonable for initializing the scheme for this study.

The categories of <2><ENG> were based on the sequence of energy system stages proposed by Rogner or Nakicenovic [65, 66]. Their scheme of meta-categories was refined in a way that allowed for a distinction between the conventional and the renewable energy sector in particular. In addition, some categories from <1><SOC> were integrated to represent various energy end-use sectors that are typically addressed in energy balances such as the German national balance [96] and stakeholders that are especially relevant at the municipal level.

In the first semi-automated step, term lists with known categorization were extracted from the literature to tag nouns in the documents. Schemes and thesauri of, e.g., public institutions such as statistical offices or the Publications Office of the European Union European were used. They include thematically ordered lists, e.g., for professions of craftsmen or university staff, and contained several nouns that were likely to appear in the MCAPs. Thematic book chapters from professional literature, e.g., on wind energy, were also used to prepare these lists. Automated extraction of nouns from single chapters of these sources resulted in several lists of terms, which were categorized based on their chapter headings. These lists were then screened and cleaned.

5.2.6.4. Categorization of terms - <3><SUS> - confirmatory approach

The meta-categories of <3><SUS> were based on the three guiding principles of strong sustainability [68, 69]. The thesaurus was created by compiling synonyms that are related to these principles at the linguistic level from a language database. The resulting lists of synonyms were clustered into categories representing sub-aspects of the sustainability principles. In addition, some categories of <2><ENG> were integrated that referred to sustainable technologies or options for action.

To compile terms, the German language database Deutscher Wortschatz [97] was used, which is one of the most comprehensive digital resources on the German language. It provides large sets of synonyms collected from selected publicly available sources and also includes the compilations of the classical philologist Dornseiff [98].

An iterative search in the database led to lists of nouns, adjectives, verbs, and participles related to the sustainability principles and their sub-aspects. Terms such as *save* for sufficiency, *renew* for consistency, or *optimize* for efficiency served as initial search words. The resulting synonyms were iteratively used to search for additional ones until no new relevant terms were found.

In a last step, special terms that emerged from the text exploration for the other two thesauri were added to the term lists of sustainability categories. This step considered, e.g., anglicisms such as *least cost planning (LCP)*, which were not contained in the database as synonyms, or relevant abbreviations such as *LCP* or *EnEV (Energieeinsparverordnung; energy savings ordinance)*. Furthermore, several terms such as *photovoltaics, wind power*, or *bioenergy* were included into the list of terms of the category regeneration that also included the term *renew*. These terms are not synonyms of the term *renew* in a narrower sense. However, they were important representatives of the aspect of regeneration in the given context.

5.2.6.5. Categories of <1><SOC>

In summary, the first thesaurus contained 26 meta-categories and 86 categories. The meta-categories covered <Agriculture>, <Art>, <Climate_Protection>, <Communication>, <Consumption>, <Economy>, <Education>, <Environment>, <Finance>, <Food>, <Health>, <Infrastructure>, <Institution>, <IT>, <Law>, <Leisure>, <Mobility_Sector>, <Planning>, <Politics>, <Psyche>, <Religion>, <Residents>, <Resources>, <Security>, <Spatial_Scale>, and <Technology>. Selected meta-categories, categories, and exemplary terms in <1><SOC> are listed in Table 5-2. A list of all meta-categories and categories is provided in A3.

5.2.6.6. Categories of <2><ENG>

In summary, the second thesaurus contained 13 meta-categories and 56 categories. The meta-categories concerning rather technical aspects are <Resources>, <Conversion>, <Distribution>, <Sales_Contracts>, <Technology_Options>, <Energy_Form>, and <End_Use>. The selected meta-categories concerning social subsystems include <Institution>, <Mobility_Sector>, <Infrastructure>, <Residents>, <Food>, and <Economy>. The meta-categories, categories, and exemplary terms in <2><ENG> are listed in Table 5-3.

5.2.6.7. Categories of <3><SUS>

In summary, the third thesaurus contained the three meta-categories <Sufficiency>, <Efficiency>, and <Consistency> and 14 categories. Categories representing aspects of sustainability include, e.g., <avoidance>, <prohibition>, or <limit_sufficiency> for sufficiency; <control>, <optimization_efficiency>, or <progress> for efficiency; and <life_cycle>, <maintenance_reanimation>, or <regeneration> for consistency. The meta-categories, categories, and exemplary terms in <3><SUS> are listed in Table 5-4.

Table 5-2: Selected meta-categories, categories and exemplary terms in <1><SOC>

Meta-category	Category	Exemplary terms
<Communication>	<publicity_campaigns_PR>	campaign days, image campaign, leaflet, poster, flyer, public relations, flagship project, demonstration projects, publicity
<Consumption>	<consumption_in_general >	consumer advice center, shopping mall, consumer, quantity buyer, private consumption
<Economy>	<commerce><com_trade_procurement>	supply and demand, proposal, trade, procurement, commercialization, service company, client satisfaction, fair trade
<Economy>	<industry><heavy_industry>	heavy industry, Volkswagen AG, large-scale industry, factory
<Economy>	<industry><intermediate_products>	manufacturing process, production volume, compressed air supply, paint center, works manager
<Economy>	<industry><general_reference>	industry and commerce, producing companies, industry association
<Economy>	<service><consulting>	consulting, consulting service, advice center, initial advice, advisory program
<Economy>	<general_reference>	economy, company, enterprise, business location, business area, limited company, SME, business start-up
<Finance>	<funding_financing_banks>	contracting, funding, credits, accounting, profit-sharing schemes, investment, bank
<Food>	<processing_consumption>	food, deep-freeze facility, super market, kitchen
<Infrastructure>	<construction_craft_sector>	building, new construction, property developer, civil engineering, architect, crafts business, janitor
<Institution>	<local_administration_bodies>	municipal administration, town hall, public property, office for construction, office for environment, citizens' office, energy agency
<Infrastructure>	<waste_sector>	waste, waste disposal, waste management, landfill, composting facility
<Infrastructure>	<wastewater_sector>	wastewater, wastewater treatment plant, sewage, toilet
<Infrastructure>	<water_supply_and_consumption>	water supply, ground water, water utilities

Meta-category	**Category**	**Exemplary terms**
<Mobility_Sector>	<general_reference>	mobility concept, traffic area, parking space, commuter, main route, fleet
<Psyche>	<psyche_consciousness_motivation>	acceptance, motivation, success, life style, consciousness, behavior, role model
<Residents>	<population_in_general>	population, people, citizens
<Residents>	<residential_area>	residents, inhabitants, living area, garden, single-family home, apartments, neighborhood
<Spatial_Scale>	<municipality_city_districts>	downtown, city district, urban district, local authority district, municipal area, metropolitan region, county, affiliated town

Table 5-3: Meta-categories, categories and exemplary terms in <2><ENG>

Meta-category	**Category**	**Exemplary terms**
<Resources>	<general_reference>	energy resources, energy source, combustible, fuel
<Resources>	<fossil>	fossil energy carrier, peat coal, hard coal, crude oil, gas field, shale gas, coal imports
<Resources>	<nuclear>	uranium mining, thorium ore, yellow cake, fuel assembly
<Resources>	<remains_waste>	bio waste, waste wood, sewer gas, substitute fuel
<Resources>	<renewable>	solar cadaster, biomass, ground heat, wind power potential, wood chips
<Conversion>	<general_reference>	energy production, energy conversion, energy supply, power plant fleet
<Conversion>	<combined_heat_power>	combined heat and power plant, CHP plant, organic rankine cycle
<Conversion>	<fossil>	fossil power plant, coal power plant, peak load boiler, gas fired condensing boiler
<Conversion>	<nuclear>	nuclear power plant, atomic energy, nuclear waste disposal site
<Conversion>	<renewable>	renewable energy, photovoltaics, solar energy plant, biogas power plant, geothermal power plant, wind power plant
<Distribution>	<general_reference>	energy distribution, grid operator, grid territory
<Distribution>	<electricity>	electricity grid, grid overload, transmission losses
<Distribution>	<gas_oil>	gas grid, biogas feed-in, gas expansion facility
<Distribution>	<heat>	district heating, heating network, local heating
<Sales_Contracts>	<general_reference>	energy mix, energy service provider, energy supply contracts, energy customer

Meta-category	Category	Exemplary terms
<Sales_Contracts>	<coal_oil>	crude oil price, oil market, coal market, spot trading of coal for power plants
<Sales_Contracts>	<electricity>	electricity mix, electricity supply contract, electricity product, electricity tariff
<Sales_Contracts>	<gas>	gas supply contract, gas tariff, gas supplier
<Sales_Contracts>	<heat>	heat supply contract, heating costs, heat sales
<Sales_Contracts>	<renewable>	green electricity, renewable energy certificate, wood energy center, biogas product
<Technology_Option>	<fuel_cell_and_hydrogen>	fuel cell, hydrogen, hydrogen storage, polymer electrolyte membrane
<Technology_Option>	<storage>	electricity storage, energy storage, heat storage, storage concept, battery
<Energy_Form>	<electricity>	electric, current, electricity, voltage
<Energy_Form>	<heat_cold>	heat, warm, cold, heating, cooling
<End_Use>	<consumption><general_reference>	energy consumption, gas consumption, energy use, energy management, energy consumer
<End_Use>	<mobility><bike_pedestrian>	bike, bicycle lane, city bike, pedestrian, pedestrian zone
<End_Use>	<mobility><biofuels>	biofuels, biodiesel, bioethanol, blending
<End_Use>	<mobility><car_incl_hybrid>	car, national highway, fuel station, natural gas vehicle, hybrid car
<End_Use>	<mobility><car_sharing>	car sharing, city car, car sharing station
<End_Use>	<mobility><electric_mobility>	charging station, electric vehicle, e-bike, electric drive
<End_Use>	<mobility><hydrogen>	hydrogen car, hydrogen filling station, fuel cell bus, hydrogen bus
<End_Use>	<mobility><air_travel>	plane, short distance flight, airport, air traffic
<End_Use>	<mobility><public_transport>	train, bus, public transport, bus stop, train station

Meta-category	**Category**	**Exemplary terms**
<End_Use>	<mobility><freight_transport>	logistic sector, harbor, truck, distribution of goods
<End_Use>	<building><general_reference>	building, house, building stock, facility management, real estate, property rental
<End_Use>	<building><heat_pump>	heat pump, air-to-water heat pump, coaxial heat probe, ground heat collector
<End_Use>	<building><insulation>	building refurbishment, building insulation, building thermography,
<End_Use>	<building><standards>	passive house, plus energy house, building energy certificate, building standards
<End_Use>	<building><climatisation_heat_cold>	heating system, air ventilation system, heating circulation pump, condensing boiler
<End_Use>	<electric_application><household_office>	illumination, lamps, fridge, dry cleaner, standby, printer, laptop
<End_Use>	<electric_application> <public_illumination>	street lighting, city lighting, sodium vapor lamp, lighting cadaster

The following (meta-)categories were included in <2><ENG> from <1><SOC> to represent specific aspects or stakeholders of the end-use sector. Please refer to Table 5-2 for exemplary terms: <Institution><local_administration_bodies>; <Mobility_Sector><general_reference>; <Infrastructure><construction_craft_sector>, <Infrastructure><waste_sector>, <Infrastructure><wastewater_sector>, <Infrastructure><water_supply_and_consumption>; <Residents><population_in_general>, <Residents><residential_area>; <Food><processing_consumption>; <Economy><general_reference>, <Economy><service><consulting>, <Economy><commerce><com_trade_procurement>, <Economy><industry><heavy_industry>, <Economy><industry><intermediate_products>, <Economy><industry><general_reference>

Table 5-4: Meta-categories, categories and exemplary terms in <3><SUS>

Meta-category	Category	Exemplary terms
<Sufficiency>	<avoidance>	avoid, fasting, renounce, non-use
<Sufficiency>	<decrease_rational_use>	reduce, lower, decrease
<Sufficiency>	<limit_sufficiency>	limit, restrict, threshold value
<Sufficiency>	<prohibition>	prohibit, interdict, forbid
<Sufficiency>	<saving>	Save
<Sufficiency>	<switch_off>	turn off, switch off, overnight shutdown
<Efficiency>	<control>	control, monitor, manage
<Efficiency>	<optimization_efficiency>	optimization, optimize, efficiency, improve
<Efficiency>	<progress>	modernize, progress, further develop
<Efficiency>	<storage>	store, accumulate, aggregate
<Consistency>	<life_cycle>	circulation system, life cycle
<Consistency>	<maintenance_reanimation>	maintain, rehabilitate, replace, repair
<Consistency>	<recycling>	recycling, reuse, composting
<Consistency>	<regeneration>	renew, regenerate, recover, solar power, wind power, photovoltaics, bioenergy

5.2.7. Network analysis

Using the categorized term lists in the thesauri, the networks of categories within the catalogues of measures were analyzed for each municipality. The results are presented as graphs showing average patterns of main topics (Q1) and network links (Q2 and Q3). Two options of scaling were applied to these graphs. Focusing on Q2, the first increased the visibility of the most relevant links between categories referring to the energy and the social system. With reference to Q3, the second highlighted to what relative extent sustainability principles were linked with other categories. The analysis of the catalogues of measures involved four steps: counting occurrences and co-occurrences, normalizing and averaging, scaling, and grouping of scaled values.

5.2.7.1. Occurrence and co-occurrence of categories

For each possible pair of categories from all three thesauri, it was automatically counted, on basis of the categorized term lists and each ds-c-m, in how many measures two categories co-occurred. The results were stored in a symmetric co-occurrence matrix for individual municipalities. The diagonal of the matrix showed the number of measures in which categories co-occurred with themselves. Hence, the co-occurrence matrix included information on the occurrence of individual categories and showed the co-occurrence of pairs of different categories.

To establish the co-occurrence matrix, the occurrence of harmonized categorized terms in individual measures was counted by applying two search modes. These searches were applied on the terms in each d-t-m. Following this procedure, each d-t-m could be converted into a ds-c-m. A restrictive mode that respected word boundaries of the searched term was used for the harmonized terms of <1><SOC> and <2><ENG> to avoid false matches. *Schul (school)* would, e.g., not match *Schuld (debt)*. A non-restrictive mode was used for the harmonized terms of <3><SUS> to allow for more potential hits and fulfilling the confirmatory purpose. The term *effizien (efficient)* would, e.g., match *Energieeffizien (energy efficiency)*. Due to the limited number of terms in <3><SUS>, a manual quality check of samples of matches justified this approach.

5.2.7.2. Normalizing and averaging

To present the average for Lower Saxony, the co-occurrence matrices had to be normalized due to their differing numbers of measures. Each value of the co-occurrence matrices was divided by the total number of measures of the individual municipality to present the share of measures in which specific categories (co-)occurred. On this basis, the overall average normalized co-occurrence matrix (ANCOM) was calculated by summing up the matrices and dividing the result by the total number of municipalities. Its diagonal contained values of average normalized occurrence (ANO). The other entries showed values of average normalized co-occurrence (ANCO).

Parts of an exemplary ANCOM are shown in Table 5-6. It contains the value of 0.15 for the ANCO of two artificial categories, <1><SOC><cat1> and <2><ENG><cat1>. The calculation of this value is exemplified in Table 5-5.

Table 5-5: Exemplary calculation of average normalized co-occurrence (ANCO) considering three artificial municipalities and two artificial categories

	municipality 1	**municipality 2**	**municipality 3**
total number of measures in MCAP of individual municipality	70	50	100
number of measures in which two categories c_x and c_y co-occur	14	9	10
normalized co-occurrence	=0.2	=0.15	=0.1
average normalized co-occurrence (ANCO):		(0.2+0.15+0.10)/3=0.15	

5.2.7.3. Scaling

Two options of scaling the ANCOM served to emphasize, on the one hand, the most relevant links among the categories and, on the other hand, the representation of sustainability principles. Expressed in terms of network metrics, these scaling options are a variation of the degree centrality as a measure for the importance of network nodes. Considering two nodes (categories) that are linked via various edges (measures), the two maximum numbers of possible edges (ANO values in diagonal) may be used as reference values for scaling. From two nodes with two different ANO values two options of scaling arise.

The first scaling option focused on the strength of the link between two categories and allowed highlighting pairs of categories with the most relevant links from <1><SOC> to <2><ENG>. It showed to what extent the maximum ANCO potential between two categories was realized. This potential was limited by the respective minimum ANO value of the individual categories of a pair.

As an example, in Table 5-6, the maximum possible ANCO of <SOC><cat1> and <ENG><cat1> is min(0.5;0.2) = 0.2. Applying the first scaling option, their ANCO of 0.15 is divided by this value resulting in a scaled value of 0.75. Hence, on average, 75% of the measures containing the category with the lower ANO, i.e., <ENG><cat1>, also contain the category with the higher ANO, i.e., <SOC><cat1>. Table 5-7 shows the scaled entries of the exemplary ANCOM.

Table 5-6: Exemplary average normalized co-occurrence matrix with artificial categories <cat1> to <catX> of <1><SOC>, <2><ENG>, and <3><SUS> (for better readability, leading numbers were omitted in the table)

	<SOC> <cat1>	**<SOC> <cat2>**	**…**	**<ENG> <cat1>**	**<ENG> <cat2>**	**…**	**<SUS> <cat1>**	**<SUS> <cat2>**	**…**
<SOC> <cat1>	0.5	…		0.15	0.1	…	…	…	…
<SOC> <cat2>	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
<ENG> <cat1>	0.15	…	…	0.2	…	…	0.2	0.05	…
<ENG> <cat2>	0.1	…	…	…	0.6	…	0.15	0.3	…
…	…	…	…	…	…	…	…	…	…
<SUS> <cat1>	…	…	…	0.2	0.15	…	0.4	…	…
<SUS> <cat2>	…	…	…	0.05	0.3	…	…	0.3	…
…	…	…	…	…	…	…	…	…	…

entries not being relevant for the purpose of demonstration are shown as dots

Table 5-7: Part of an exemplary average normalized co-occurrence matrix after applying scaling option one

	<SOC> <cat1>	**<SOC> <cat2>**	**…**	**<ENG> <cat1>**	**<ENG> <cat2>**	**…**
<SOC> <cat1>	0.5/0.5=1	…		0.15/0.2=0.75	0.1/0.5=0.2	…
<SOC> <cat2>	…	…	…	…	…	…
…	…	…	…	…	…	…
<ENG> <cat1>	0.15/0.2=0.75	…	…	0.2/0.2=1	…	…
<ENG> <cat2>	0.1/0.5=0.2	…	…	…	0.6/0.6=1	…
…	…	…	…	…	…	…

entries not being relevant for the purpose of demonstration are shown as dots

The second scaling option indicated how far sustainability aspects were linked to the respective energy system sub-units. It was applied for checking to what relative extent individual sustainability categories of <3><SUS> were present in the set of all measures that contained a specific category of <2><ENG>. For this purpose, the entries of each row of the ANCOM referring to a specific category were divided by the respective ANO in the diagonal.

As an example, in Table 5-6, the sustainability category <SUS><cat2> co-occurs with <ENG><cat1> at a rate of 0.05 that must be divided by 0.2 when applying the second scaling option. Table 5-8 shows the scaled value of 0.25 in the exemplary scaled ANCOM indicating that <SUS><cat2> appears in 25% of the set of measures in which <ENG><cat1> occurs.

Table 5-8: Exemplary average normalized co-occurrence matrix after applying scaling option two

	<ENG> <cat1>	**<ENG> <cat2>**	**…**	**<SUS> <cat1>**	**<SUS> <cat2>**	**…**
<ENG> <cat1>	0.2/0.2=1.0	…	…	0.2/0.2=1.00	0.05/0.2=0.25	…
<ENG> <cat2>	…	0.6/0.6=1.0	…	0.15/0.6=0.25	0.3/0.6=0.5	…
…	…	…	…	…	…	…
<SUS> <cat1>	…	…	…	…	…	…
<SUS> <cat2>	…	…	…	…	…	…
…	…	…	…	…	…	…

Entries not being relevant for the purpose of demonstration are shown as dots

5.2.7.4. Grouping of scaled values

After normalizing, averaging, and scaling, the ranges of the ANCO values in the ANCOM were grouped to create a condensed graphical presentation. Four groups of equal range and a group for zero ANCO were defined (see Table 5-9). The strength of links between categories of <1><SOC> and <2><ENG> are presented in the groups L0 to L4, which are related to Q2 and the first scaling option. The degrees of representation of sustainability categories relative to categories of <2><ENG> are presented in the groups S0 to S4, which are related to Q3 and the second scaling option.

Table 5-9: Grouping intervals for co-occurrence of categories after applying scaling option one or two

Scaling option one		**Scaling option two**	
Averaged, normalized and scaled co-occurrence	Strength of link between categories	Averaged, normalized and scaled co-occurrence	Representation of a sustainability category relative to another
0%	L0	0%	S0
(0%;25%]	L1	(0%;25%]	S1
(25%;50]	L2	(25%;50]	S2
(50%;75]	L3	(50%;75]	S3
(75%;100%]	L4	(75%;100%]	S4

For a clear graphical arrangement, only significant links between categories of <1><SOC> and <2><ENG> are presented in the following "Results" section. Categories of <1><SOC> with a significant link were defined as having at least two L3s to one category of <2><ENG> and at least a mean ANCO of 20% with all categories of <2><ENG>. Categories not fulfilling these thresholds were not considered for answering Q2. These thresholds were arbitrary but were considered reasonable to highlight the most significant links with the energy system for the purpose of this article.

5.3. RESULTS

Following the generic steps of the text mining, the main results of the data analysis procedure are reported in this section showing average patterns in terms of main topics and network links that could be identified in the 16 municipal MCAPs of regional centers in Lower Saxony. First, three figures show the results in their raw visual form.

Figure 5-1 shows the ANO of categories of <2><ENG>. Based on the ANCOM, Figure 5-2 shows the most relevant network links between categories of <2><ENG> and <1><SOC>, and Figure 5-3 the representation of categories of <3><SUS> in relation to categories of <2><ENG>. The axes of these figures are numbered to be referenced for interpretations of results. It has to be noted that this numbering is not fixed for individual categories and only valid within each graph. To focus on main patterns regarding ANCO, the categories of <1><SOC> and <2><ENG> with an average normalized occurrence (ANO) lower than 1% were excluded from the ANCOM. However, independent of their ANO, all categories of

<3><SUS> were kept due to the confirmatory purpose of this thesaurus. For interested readers, boxplots of ANO of all individual categories and the complete ANCOM are documented in the Appendices A4 to A6. These might be the basis for insights beyond the chosen perspectives adopted in this article.

The visual presentation of results is followed by a summary of main results and their interpretation in three tables. Addressing the three introductory questions, Table 5-10 focuses on planned configurations of the energy system, Table 5-11 on roles of societal subsystems, and Table 5-12 on preferences in terms of sustainability principles. Each finding in these tables is based on a combination of ANO or ANCO values in the figures. Regarding ANCO values, only selected L3 and L4 or S3 and S4 representations were considered to focus on main patterns. The findings are numbered from F1 to F26 to be referenced in the discussion.

5.3.1. Visual presentation of results

5.3.1.1. Occurrence of categories of <2><ENG>

The ANO of categories of <2><ENG> referring to specific stages of the energy system are displayed in Figure 5-1. The boxplot shows common patterns among the municipalities on basis of median values that are also reported in the graph. Boxes, which represent 50% of the data, appeared mostly in limited ranges. The same accounts for the outliers. Thus, the validity of the results was deemed acceptable for the purpose of presenting common average patterns. A detailed discussion of differences between MCAPs might be carried out elsewhere. The mean of the 56 median values displayed in the graph was 9.7%. This number served as a reference to assess whether median ANO values of categories were rather low or high.

5.3.1.2. Co-occurrence of categories of <2><ENG> AND <1><SOC>

The left axis of the co-occurrence plot in Figure 5-2, which is scaled by scaling option one, displays the energy system categories. Categories with ANO values lower than 1% were excluded. Categories of <1><SOC> referring to societal subsystems with the most significant links to the energy system categories appear at the bottom. Since several categories were included from <1><SOC> into <2><ENG>, some appear at both axes. For better readability, the bottom categories referring to financing and climate protection were excluded since it is obvious that corresponding aspects are referred to in MCAPs. Also, the category referring to technical parts or tools was excluded, since it did not provide useful insights.

5.3.1.3. Co-occurrence of categories of <2><ENG> AND <3><SUS>

Figure 5-3, which is based on scaling option two, shows the degree of representation of sustainability aspects in the energy system stages and its sub-units. The energy system categories of <2><ENG> are shown at the left axis and categories of <3><SUS> at the bottom.

5.3.2. Main results and interpretations

5.3.2.1. Energy system configuration

The main results and findings concerning the energy system configuration are presented in Table 5-10.

5.3.2.2. Roles of societal subsystems

The main results and findings concerning the roles of societal subsystems are presented in Table 5-11.

5.3.2.3. Preference regarding sustainability principles

The main results and findings concerning the preferences for sustainability principles are presented in Table 5-12.

#	category	m
01	<Resources><general_reference>	0.00
02	<Resources><fossil>	0.00
03	<Resources><nuclear>	0.00
04	<Resources><remains_waste>	0.01
05	<Resources><renewable>	0.10
06	<Conversion><general_reference>	0.14
07	<Conversion><combined_heat_power>	0.06
08	<Conversion><fossil>	0.02
09	<Conversion><nuclear>	0.00
10	<Conversion><renewable>	0.24
11	<Distribution><general_reference>	0.01
12	<Distribution><electricity>	0.01
13	<Distribution><gas_oil>	0.00
14	<Distribution><heat>	0.05
15	<Sales_Contracts><general_reference>	0.02
16	<Sales_Contracts><coal_oil>	0.00
17	<Sales_Contracts><electricity>	0.03
18	<Sales_Contracts><gas>	0.00
19	<Sales_Contracts><heat>	0.00
20	<Sales_Contracts><renewable>	0.05
21	<Technology_Option><fuel_cell_and_hydrogen>	0.00
22	<Technology_Option><storage>	0.00
23	<Energy_Form><electricity>	0.21
24	<Energy_Form><heat_cold>	0.27
25	<End_Use><consumption><general_reference>	0.29
26	<End_Use><mobility><air_travel>	0.00
27	<End_Use><mobility><bike_pedestrian>	0.09
28	<End_Use><mobility><biofuels>	0.00
29	<End_Use><mobility><car_incl_hybrid>	0.08
30	<End_Use><mobility><car_sharing>	0.03
31	<End_Use><mobility><electric_mobility>	0.05
32	<End_Use><mobility><hydrogen>	0.00
33	<End_Use><mobility><public_transport>	0.13
34	<End_Use><mobility><freight_transport>	0.01
35	<End_Use><building><general_reference>	0.34
36	<End_Use><building><climatisation_heat_cold>	0.15
37	<End_Use><building><heat_pump>	0.00
38	<End_Use><building><insulation>	0.10
39	<End_Use><building><standards>	0.03
40	<End_Use><electric_application><household_office>	0.08
41	<End_Use><electric_application><public_illumination>	0.04
42	<Institution><local_administration_bodies>	0.54
43	<Mobility_Sector><general_reference>	0.35
44	<Infrastructure><construction_craft_sector>	0.40
45	<Infrastructure><waste_sector>	0.04
46	<Infrastructure><wastewater_sector>	0.02
47	<Infrastructure><water_supply_and_consumption>	0.02
48	<Residents><population_in_general>	0.15
49	<Residents><residential_area>	0.29
50	<Food><processing_consumption>	0.15
51	<Economy><general_reference>	0.33
52	<Economy><service><consulting>	0.13
53	<Economy><commerce><com_trade_procurement>	0.30
54	<Economy><industry><general_reference>	0.04
55	<Economy><industry><heavy_industry>	0.04
56	<Economy><industry><intermediate_products>	0.19

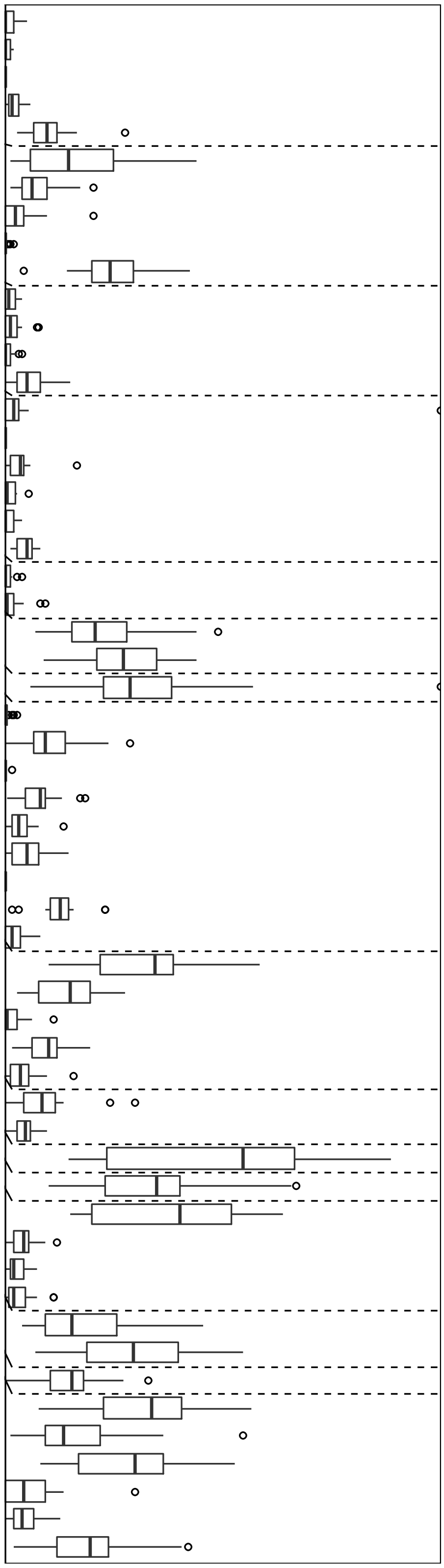

Figure 5-1: Boxplot showing average normalized occurrence of categories of <2><ENG>. Boxes represent the mid-ranges (50% of the data), lines in boxes show the median, upper and lower hinges show the first and third quartiles, and outliers are shown as circles [89]. The column m of the table on the left-hand side shows the median values in numeric format

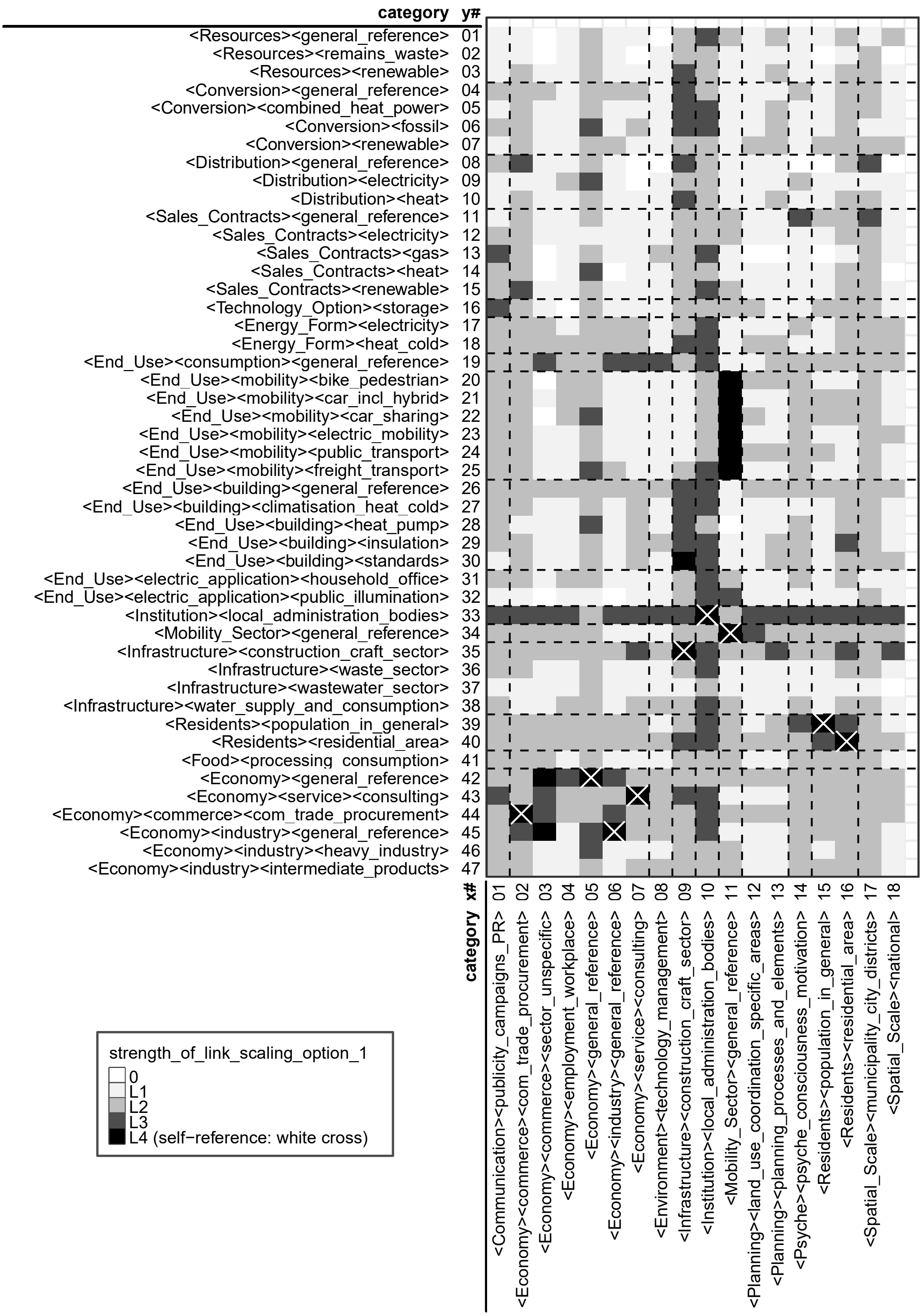

Figure 5-2: Average normalized co-occurrence scaled by the first scaling option showing the strongest links of categories of <1><SOC> with categories of <2><ENG>

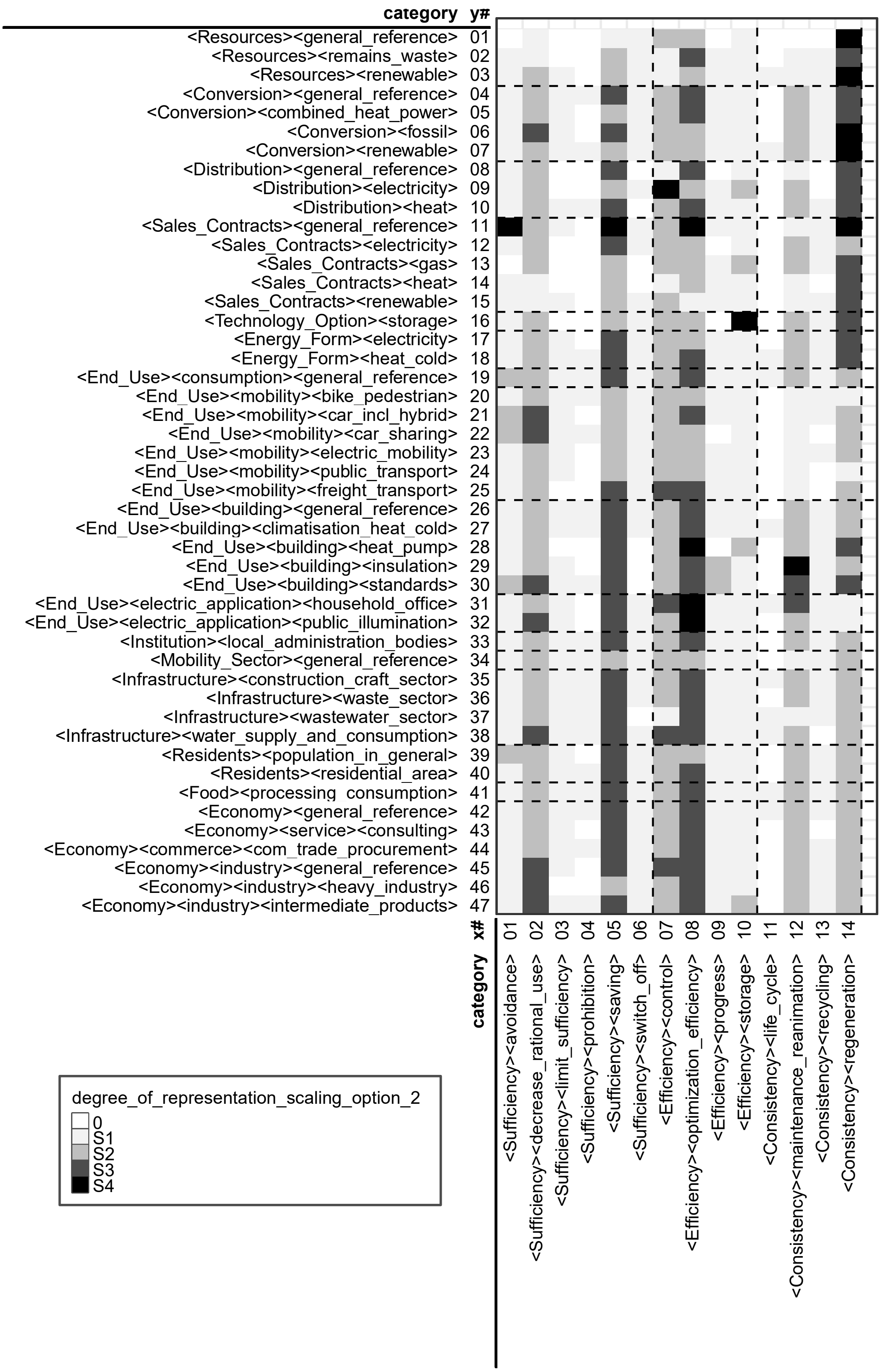

Figure 5-3: Average normalized co-occurrence scaled by the second scaling option showing representation of categories of <3><SUS> within full sets of measures containing individual categories of <2><ENG>

Table 5-10: Findings concerning the energy system configuration

No.	Results	Implications	Reference in figures
F1	Focus on the energy system stages of energy conversion and end-use; minor importance of other stages.	A nuanced understanding of climate and serious energy transition efforts in the conversion and end-use stages could be observed. Regarding energy consumption, the MCAPs referred to all relevant sectors considered in the federal energy balance, and the corresponding technologies.	Figure 5-1:6, 25; 1, 11, 15, 21, 22
F2	High relevance of renewable energy power plants.		Figure 5-1:5, 10 Figure 5-3: *x*14*y*1-18
F3	The majority of relevant end-use sectors were addressed, i.e., households, economy, mobility, and local administration. A broad range of end-use technologies were considered, e.g., cars, bikes, heating and insulation of buildings, or electric appliances.		Figure 5-1: 49, 51, 53, 43, 42; 30, 27, 36, 38, 40
F4	No local actor was clearly linked with electricity distribution except parts of the economic sector.	Electricity distribution was a missing topic, although being a prerequisite for technologies that have been addressed, i.e., renewable energies and e-mobility. Hence, additional planning steps will be required in the future.	Figure 5-1: 12; 10, 31 Figure 5-2: *x*6*y*9
F5	In the heating and cooling sector, measures often addressed the building sector in connection with households, but less often to aspects of district heating. The latter was not clearly linked to residential areas.	Transition activities in the heating sector, which appeared to be close to implementation, could clearly be identified with a focus on the residential sector. Burning natural gas in individual heating installations was the preferred heating option. There were only a few approaches of combined heat and power production tended towards centralized rather than decentralized solutions.	Figure 5-1: 36, 38; 7 Figure 5-2: *x*17*y*29; *x*16/17*y*5
F6	Stakeholder of the construction sector were already considered or involved in MCAPs for implementation of measures in the heating sector.		Figure 5-2: *x*10*y*18/27/29, 17*y*35
F7	Gas supply contracts were the most advertised type of contracts.		Figure 5-2: *x*1*y*13

No.	Results	Implications	Reference in figures
F8	Alternative urban mobility modes received higher attention than individualized motorized mobility modes, of which e-mobility received the highest attention. The fuel options hydrogen or biofuels were not addressed.	In the mobility sector, planning options to support alternative modes of mobility were considered. However, this sector was not fully integrated into local climate action and the transitions activities require more coordination and collaboration.	Figure 5-1: 27, 33, 29, 30, 31; 28, 32
F9	Common urban mobility modes were weakly linked with categories representing local actors.		Figure 5-2: *y*20-24*x*3/4/7/10/11/16/17; *x*12*y*33
F10	Several subsectors related to the local administration were weakly addressed, i.e., the education sector and the sectors concerning water supply or the disposal of waste or wastewater.	Efforts of various private but also public actors could be strengthened. The education sector could improve its multiplying function. Economy, supply, and disposal sectors might strengthen their climate action efforts.	Figure 5-1: 45, 46, 47 Figure 5-2: education not on *x* axis
F11	The industrial sector was weakly addressed.		Figure 5-1: 54, 55

Figure N x#*y*# numbered result referring to the co-occurrence of two categories at determined positions on the *x* and *y* axis of a Figure *N*

Table 5-11: Roles of societal subsystems

No.	Results	Implications	Reference in figures
F12	Local administrations were linked to upgrades of public properties, contracts for eco-electricity, or the use of efficient appliances more than other actors.	Local administrations sought to be a role model for local actors in terms of activities to reduce energy consumption.	Figure 5-1: 42 Figure 5-2: *x*11*y*15//27/29/30/31/32
F13	Like no other subsystems, local administrations were linked with almost all other local actors.	Local administrations were important mediatory nodes in stakeholder networks. They engaged particularly in campaigns to motivate private households for transition activities and employed consulting companies to support this process. In a secondary role, they were concerned with energy supply.	Figure 5-2: *x*3/4/7/8/10/16/17,*y*33
F14	Local administrations were clearly linked with communication measures and the consulting sector.		Figure 5-2: *x*1/8/15*y*33
F15	Local administrations showed connections with the conventional heating sector, including rehabilitation of buildings, and district heating.		Figure 5-2: *x*11*y*5/6/13/18/27
F16	Local administrations engaged in land-use planning processes and thereby considered building energy standards. In these processes, they considered standards of the national level.	Local administrations partly made use of their regulatory power; however, they tended to follow federal provisions or to coordinate local activities in this regard.	Figure 5-2: *x*11*y*30, *x*13/14/19*y*33
F17	Residential areas and citizens were particularly linked with insulation of buildings and aspects of motivation.	Energetic building refurbishment was the favored transition path for households. Households were the main target of campaigns to motivate transition activities.	Figure 5-2: *x*1/29*y*39/40, *x*15*y*39
F18	The economic sector was not fully linked with other sectors. Links with the local administrations could be observed at a general level; however, connectedness of the producing economic sectors was weak.	Typical for the economic sector, its main activities revolved around optimization. However, the distance to the local role model, the local administrations, indicates that these activities might have followed their own standards in contrast to the high and maybe more idealistic standards applied by local administrations.	Figure 5-2: *x*6*y*33, producing not on *x* axis; *x*6/11*y*25

No.	Results	Implications	Reference in figures
F19	The economic sector focused on efficient operation of fossil power plants and rational use of energy, optimization of logistics, contracts for external heat supply, and the use of heat pumps.		Figure 5-2: *x*6*y*6/25/14/28 Figure 5-3: *x*1*y*45-47, *x*8*y*42
F20	The economic sector was the only one to clearly consider energy distribution, or power grids in particular.	The economic sector was aware of electricity distribution, since stable power supply is crucial for economic activities and suitable grid infrastructure is a prerequisite for feasible business models, e.g., for electric mobility.	Figure 5-2: *x*6*y*9

Figure N x#y# numbered result referring to the co-occurrence of two categories at determined positions on the *x* and *y* axis of a Figure *N*

Table 5-12: Preferences regarding sustainability principles

No.	Results	Implications	Reference in figures
F21	Sustainability was mainly expressed as applying renewable energy conversion, using energy efficiently, and saving energy.	Hence, in general, all three strong sustainability principles were present.	Figure 5-3: *x*5*y*25-47, *x*8*y*25-47, *x*14*y*1-18
F22	Optimization and saving were clearly present in the end-use sectors. However, they were only partially present in the mobility sector and the other energy system stages.	The strategy of setting limits and refraining from the use of energy without the advantage of saving something for other purposes could not be clearly identified. Energy consumption habits were in the process of adaption, but aiming at a radical change could not be observed.	Figure 5-3: *x*5*y*1-24, *x*8*y*1-24; *x*2*y*6/21/22/30
F23	Regarding aspects of sufficiency aside from saving, only the consideration of rational energy use could clearly be observed in the context of using fossil fuels for power generation, energy consumption in buildings, public illumination, or individual motorized mobility.		
F24	Aspects with a potentially stronger impact in terms of sufficiency than saving such as switching off, limiting or avoiding were weakly addressed.		Almost no S3/S4 for *x*1/3/4/6
F25	Although aspects of consistency referring to regeneration that are particularly associated with renewable energies were present in MCAPs, energy supply contracts based on renewable sources were weakly addressed and not clearly linked to the majority of societal subsystems.	Saving energy for the benefit of switching to renewable energy contracts did not appear to be the preferred strategy.	Figure 5-3: *x*14*y*1-18 Figure 5-2: *x*1-20(except 3, 11)*y*15 Figure 5-1: 20
F26	Aspects of sufficiency and efficiency were considered for heating of buildings. This does not apply to aspects of consistency.	A full shift to renewable energies in the heating sector was not observed.	Figure 5-3: *x*14*y*27

Figure N x#y# numbered result referring to the co-occurrence of two categories at determined positions on the *x* and *y* axis of a Figure *N*

5.4. DISCUSSION

The first part of the discussion deals with main patterns of municipal climate action in Lower Saxony. These findings (F1–F26) were presented in the previous section. They confirm and complement the ones of other studies. Apart from thematic issues, the second part of the discussion addresses methodological limitations and prospects for semantic sustainability assessment.

5.4.1. Patterns of municipal climate protection in Lower Saxony

The nuanced understanding of climate action and the focus on energy conversion and end-use (F: 1–3) is in line with international trends examined by Castán Broto and Bulkeley [22, 26] or the promising fields of implementation identified by Schreurs such as “energy efficiency incentive programs, educational efforts, green local government procurement standards, [or] public transportation policies […]” [49]. The present study complements these findings by quantitative insights regarding the current importance of these issues to examine the “horizon of attention” of municipalities. It showed, e.g., that the attention to procurement standards is limited to one actor, the local administrations (F: 12), that activities in the mobility sector are followed in an unstructured way (F: 9), and that educational efforts are rather limited to motivation or advisory campaigns (F: 10, 14, 17). Furthermore, the energy system stages of resources, distribution, and contracts receive disproportionately low attention (F: 1). Hence, the “horizon of responsibility” is not matched by the “horizon of attention” that has been restricted to the local sphere of action. The potential to extend the municipal “horizon of attention” depends on multilevel actor constellations and framework conditions of which some are discussed in the following.

By adopting a network perspective, this study highlighted the central roles of the local administrations and the resulting coordination efforts (F: 12-16). These roles covered all the four governing modes as proposed by Kern, i.e., (i) “Planning and Regulation,” (ii) “Direct Services,” (iii) “Consumer and Role-model,” and (iv) “Facilitating and Encouraging Action” [38, 55]. Furthermore, on a broader empirical basis, this study supports the finding of Bulkeley and Kern that local administrations in Germany prefer mode (iii) and (iv) [38]. However, it showed that efficiency standards, associated with mode (i), and district heating, associated with mode (ii), played a secondary but more important role (F: 15, 16) than observed by Bulkeley and Kern in their study in 2006. This might be due to the ambitious national “Energiekonzept” released in 2010 [27] that, as a side effect, widened the scope for municipalities. In this context, the network perspective adopted here (F: 13) urges to consider the potential problem of information overload [99, 100]. Due to the variety of topics and actors, local administrations might fail to stay involved in all relevant coordination and communication processes. Hence, adequate staffing and external support will be crucial to properly coordinate efforts.

This study indicates that conflicts and issues concerning electricity grids may go unnoticed in municipal climate action planning (F: 1, 4, 20) and, thus, calls for improved cross-sectoral multilevel coordination. Several studies emphasize that a suitable grid infrastructure is a prerequisite to increase the share of renewables [101] or to engage in e-mobility projects [102]. In Germany, the issue of integrating renewable energies into the grid has, as discussed by Hake et al. [27], already received considerable attention. One of the reasons for neglecting this issue in MCAPs might be the dependence of municipalities on electricity grid operators that was identified by Fuchs and Hinderer [54]. Regarding mobility or electric mobility, Gawel et al. noted that multilevel coordination generally lacks behind in Germany [24]. The present study provides quantitative empirical evidence for the need to improve multilevel coordination in above mentioned fields (F: 1, 4, 8, 9) and to create actor networks that are capable to efficiently operate the future energy system. This would require closer cross-sectoral multilevel cooperation, e.g., between municipalities, mobility providers, local and regional grid operators, and the German Federal Network Agency.

Advancing multilevel coordination will also be required to overcome the missing overarching shift to renewable energies in the heating and mobility sector identified here on a bottom-up basis (F: 5, 7, 8, 15, 26). From a general top-down perspective, this was also noted by Gawel et al. [24]. Clear signals in national legislation would be required to establish suitable standards and to allow more business cases for renewable heating and mobility markets that are still challenging [103]. Flanking national support for municipalities to increase efficiency of air conditioning in the building sector has already been provided in form of standards, e.g., in the energy savings ordinance (EnEV). This study showed that MCAPs refer to such standards and that municipalities use these standards to strengthen their regulatory role to a certain extent (F: 16). Regarding the mobility sector, the study further showed that the integration of this sector in MCAPs is incomplete (F: 9). This might be due to the lack of a standard that would make administrations a more important reference point in the local network, especially for user of individual modes of transport. Hence, it may be concluded here that effectively steering the transition to renewables will require more consolidated legislative approaches for the energy sectors that are not bound to a grid and that have decentralized stakeholder structures.

Regarding industrial sectors, this study revealed a distance to the local role model, i.e., the administrations (F: 18) and, on this basis, indicates their non-collaborative behavior in public transition activities. Kern et al. found that municipal instruments to involve these stakeholders are largely limited to motivation campaigns [55], which is a common constellation in environmental governance [104]. This might be the reason why industrial sectors may keep distance and develop their own standards and approaches to climate action. The current legislative framework does not provide sufficient incentives for them to become involved in municipal climate action. This might be explained by the transposition of the EU Energy Efficiency Directive, which demands energy audits for larger companies [105]. It has been delayed in Germany [106], and in the case of Lower Saxony, 287 manufacturers were granted a reduced renewable energy surcharge in 2015 [107]. Several authors, e.g., Gawel et al. or Fischer et al., have criticized the numerous “exceptions for industry” [24] in terms of social justice or fair competition [24, 108]. This study illustrated that such exceptions may restrict the collaboration in public transition activities. In conclusion, the successful energy transition in economic sectors could be supported by a strong enforcement of existing regulation and by a legislative framework that strengthens the position of public administrations vis-à-vis economic stakeholders by additional governance instruments.

By adopting the concept of strong sustainability, this study raises doubts whether implementing the MCAPs examined here will reduce the current ecological footprint of the municipalities to an extent that acknowledges the ecological carrying capacity. MCAPs followed the strategies of advancing renewable energies and optimizing energy consumption (F: 21–22). Gawel et al. pointed out that these have to remain essential strategies of the German Energy Transition [24].

The concept of strong sustainability that demands equal consideration of consistency, efficiency, and sufficiency allowed this study to open up a new perspective on these strategies. It showed that it was unclear whether renewable energy produced by the cities would be consumed by their own end-users (F: 25). Fischer et al. argued that there is a competition for renewable generation rates at subnational levels [108]. In addition, this study identified an aversion to change supply contracts (F: 1, 7, 25), a phenomenon that was also observed by Fuchs and Hinderer [54]. Hence, the places of production and consumption of green energy might be decoupled to a certain extent. Hence, benefits from saving and optimizing might be used for unknown other purposes than supporting renewable energies. Furthermore, not all efficiency measures necessarily lead to an overall reduction of natural resource consumption. Buying new appliances might, e.g., be “efficiency-increasing” [68] in terms of energy but “throughput-increasing” [68] in terms of material resources. Hence, this study cannot rule out direct and especially indirect rebound effects, see, e.g., Herring and Roy [109], for the implementation of the MCAPs. Finally, this study revealed that avoiding energy use or setting absolute limits was not explicitly addressed (F: 23, 24). This shortcoming in terms of sufficiency has not been shown as clearly by other studies. Since the absolute energy demand is a significant “boundary” of the “sustainable solution space” [61], efforts in favor of sufficiency should be strengthened beside the other principles.

An improvement of the equal consideration of sustainability principles could be achieved by extending the campaigns that were identified as a key communication instrument of local administrations (F: 14) and intensifying the integration of the education sector (F: 10). This proposal is based on the argument by Luhmann that communication processes are key to trigger societal change [110] and the argument of Ott et al. that incorporating all three strong sustainability principles in these processes is crucial [111]. One option could be the involvement of the higher education sector as facilitator. Transdisciplinary learning environments, as proposed by Hagemeier-Klose et al. [112], could be a suitable set-up, which require provision of intellectual resources as principal basis. Such initial non-binding commitment might be a low barrier for actors to get involved. Diligently planned, such environments offer the chance to integrate subsystems which have been weakly interconnected according to this study such as the water supply, waste and wastewater, and industrial sectors (F: 10, 11). Communication about change does, of course, not guarantee the success of transition processes due to “value action gaps,” which have been pointed out by Blake [113]. However, it can be the starting point to reflect mindsets, a key leverage point in systems according to Meadows [114].

In the context of municipal climate action, this study opens up the question what sustainable configurations of network patterns should look like with regard to cross-sectoral multilevel collaboration and allocation of responsibility or authority The findings of this study indicate serious local transition efforts (F: 1–3, 6, 8, 12, 21, 22), while traces of the societal “carbon lock-in” highlighted by Unruh [115] could still be identified (F: 7, 17, 19, 25, 26). Of course, such lock-ins cannot be solved solely at the municipal level. For a transition towards sustainability, a well-orchestrated cross-sectoral multilevel approach is required. From a governance perspective, the "restructuring of the state" is already being discussed [25]. Bulkeley and Betsill [116] or Benz et al. have, e.g., demanded "trans-local action [that] […] opens local policymaking to the outside world" [117]. Such approach would allow for an integration of local knowledge from operational practice into national policy-making. This study proposes that unfolding the cross-sectoral multilevel interactions that result from existing policies is a prerequisite to define target network structures of collaboration as a basis to design policies for an effective implementation of sustainable climate action.

5.4.2. Prospects and limitations of semantic sustainability assessment

As shown above, the main findings resulting from the interpretation network analysis are in line with and complement those of other studies. Hence, the knowledge-based semi-automated text mining approach generated reliable results. By structuring the processing of information, the interpretation network analysis identified and visualized network patterns that would not have been readily apparent when reading MCAPs. This approach showed the importance of topics and the intensity of network links on a quantitative basis. Other studies on MCAPs have not provided such detailed quantitative insights and reported on general references to individual topics. However, based on qualitative research methods, e.g., qualitative content analysis or interviews, these studies have shed light on the dynamics behind topics and links. They have provided the context knowledge that was needed in this study to interpret results. Hence, text mining approaches for sustainability monitoring cannot be seen as standalone tools, but as standardized and repeatable approaches, they can support tracking of topics and links. The remainder of the discussion addresses prospects and limitations of the interpretation network analysis and general methodological questions concerning text mining.

The sample examined in this study consisted of 16 MCAPs in Lower Saxony. In future studies, a larger spatial area and different levels could be examined. Additional documents from other administrative departments or stakeholders could also be considered. For documents that are separated into single units of meaning, the approach applied here provides a monitoring tool that can support generating and testing hypotheses. Semantic patterns could not only be used for posterior assessments but would also support planning processes by revealing cooperation potential on basis of mutual topics or missing links. This could lead to a better alignment of activities and improve "multi-level control," which has, according to Ohlhorst [23], received insufficient attention.

Although the interpretation network analysis tested here has the potential to support the field of sustainability monitoring, the structure and content of documents pose several limitations. For approaches based on counting (co-)occurrence, the issue of negations could, as discussed by Blake [74], be a challenge. Words such as no, none, or not are often neglected in vector representations of text. This may or may not have an influence on the results. Although negations were neglected in this study, the findings were largely in line with other studies. The reason for this is the direct formulations used in MCAPs to describe measures. In this study, a shallow manual screening showed that negations mostly addressed aspects or conditions that should be considered in the future but had not been realized yet. Measures are often described in concise and incomplete simple sentences. This syntactical simplicity facilitates the analysis, especially concerning the (co-)occurrence of terms. Still, a crucial precondition for the method used in this study is the availability of comparable sections of text that allows for a structured analysis and evaluation of topics and the intensity of links.

As mentioned in the introduction, monitoring reports issued by municipalities concerning their activities might also be analyzed in future studies in terms of the frequency of topics or links. However, counting the (co-)occurrence of categories in such documents is problematic if they subsume similar aspects or mix different ones in a given paragraph. Furthermore, the degree of implementation of measures would have to be considered when analyzing monitoring reports. In addition to merely counting terms, this would require an analysis of syntax. Considering an analysis that includes all kinds of documents, not only planning or reporting documents, even more sophisticated methods would be needed. Due to different writing styles, direct comparisons between, e.g., political speeches that use metaphorical language and action plans that use straightforward technical language would not be feasible in a monitoring approach such as the one used in this study.

The knowledge-based approach applied in this study to analyze (co-)occurrence of categories is a reasonable basis for standardized and repeatable sustainability assessments. The thesauri created for this study capture theoretical aspects of systems theory and normative aspects of strong sustainability in a fixed semantic categorization scheme. In future studies, the possibility of automatically comparing lists of terms by different authors would provide the basis for transparency of assessments. Such comparisons could advance the understanding of sustainability and contribute to the creation of a controlled holistic set of sustainability vocabulary. In technical fields, the use of standardized terminologies is common. However, such unified terminologies require ongoing harmonization processes. In the case of smart grids, this was pointed out, e.g., by Arndt et al. [118]. The holistic perspective of this study might be a starting point for such harmonization process to establish the field of semantic sustainability assessment. Moreover, the thematic range of such terminology could be advanced, e.g., by modeling the material life cycle, see, e.g., Rebitzer et al. [119], in the same manner as the energy system. Additional principles of sustainability might also be covered by creating new lists of terms or integrating sustainability vocabulary proposed by other authors, e.g., Abson et al. [120].

Mapping methodological options and conducting structured sensitivity analyses would be a useful next step to advance semantic sustainability assessment. The step of text representation might be supported by text parsers, e.g., the Stanford Parser [121] or the TreeTagger [122], which provide information on syntax. This approach might address some of the limitations discussed above concerning, e.g., negations or the nature of links between terms. Of course, the performance of such algorithms again depends on the content and structure of documents. Regarding the data transformation and analysis step, there is potential for probabilistic text mining methods. Fully automated topic modeling methods such as Latent Dirichlet Allocation [123] might be used to create a sustainability vocabulary database. The semi-automated approach of this study was more time-consuming than a fully automated approach, but it allowed for testing specific perspectives informed by theory and normative considerations. A comparison of the thesauri created this way with automatically modeled thesauri would be an important task for future studies to gain experience with parametric statistical methods. Various other data analysis methods might also be considered. Different kinds of semantic network analysis and the corresponding network metrics, see, e.g., Doerfel [48], Diesner [124], or Shim et al. [125], could provide additional insights on local networks. Furthermore, clustering algorithms could be used, e.g., to identify typologies of MCAPs.

Considering the methodological prospects discussed above, it will be crucial to perform sensitivity analyses if the results of text mining approaches are to be used for monitoring purposes. As mentioned in the introduction, in the field of CO2 emission accounting, there has not yet emerged one single standardized method. Experience from different approaches was and still is important to understand the effects of parameter choices. This is also true for text mining approaches. The data processing and visualization steps of this study were adjusted to highlight specific aspects in relation to the three guiding empirical questions. A sensitivity analysis would be required to gain more experience with the corresponding parameters used, e.g., in the search algorithm to count (co-)occurrence or as thresholds for visualization. Such sensitivity analyses might be conducted in future studies for semantic monitoring approaches in general.

As a final remark, attention is turned to one question that could be answered by building up long-term experience with the proposed methodological approach: What do (graphical) patterns based on text mining look like that actually lead to a sustainable state? This study provided some indications on intended developments by analyzing the representation of sustainability principles in action plans. The extent, to which MCAPs are implemented, is unknown. However, since they are fairly specific and usually created by several stakeholders, they are more likely to be turned into reality than, e.g., mission statements or urban visions. Assessing the actual impact of the patterns identified in MCAPs requires examination of similar document types at different points in time and relating the results from semantic analyses to indicators based on physical data. Research in this direction could provide further insights on impacts concerning the interplay of governance instruments and material reality.

5.5. CONCLUSIONS

The interpretation network analysis implemented in this study provides a new approach to semantic sustainability assessment by applying text mining methods. As first of its kind in the discourse of municipal climate action, this study combined a social-ecological system perspective, a network perspective, and the viewpoint of strong sustainability to reveal major issues and network structures in 16 climate action plans by municipalities in Lower Saxony. With this bottom-up approach, the study provided evidence for the strong commitment of these regional centers to contribute to the German Energy Transition. The measures proposed in the plans represent multifaceted approaches to climate protection considering renewable energy conversion and stakeholders from all typical German end-use sectors. Strong commitment by local administrations as role models, facilitators, planners, and energy service providers was observed. This will require adequate institutional resources for municipalities to coordinate the local networks. The new approach also indicated that, to advance municipal climate protection and to overcome societal carbon lock-in, current cross-sectoral multilevel approaches should be improved. Municipalities could be supported by, e.g., national legislation favoring markets based on renewable sources in the heat or mobility sectors, and serious enforcement of audits or energy charges in all sectors of the economy. Improvement potential was also identified concerning the cross-sectoral multilevel coordination of electricity distribution. From a strong sustainability perspective, more emphasis on sustainability communication and education, which equally consider all three sustainability principles, will be crucial for a transition towards sustainability. The benefits of the optimization and saving strategy identified in the plans should be used to procure renewable energy instead of other purposes to avoid rebound effects. With regard to sufficiency, the strategy of setting limits should be reinforced.

From a methodological viewpoint, this study showed that the text mining approach could confirm and complement recent studies and can be used to analyze intended actions and networks in climate action plans. Standardized semantic sustainability assessments of large amounts of different kinds of text data may be achieved by using additional text mining or natural language processing methods, e.g., for syntax parsing or automated generation of categorization schemes. In addition to the purpose of monitoring and assessment, such approaches might also be used to support planning processes by identifying mutual topics or missing links between various stakeholders. Of course, the structure and content of documents pose several limitations that would have to be considered. Hence, mapping methodological options and conducting structured sensitivity analyses would be a useful next step. Despite the need for further research in this direction, semantic sustainability assessment is a reasonable option to complement existing monitoring systems based on physical indicators. This way, the methodological approach applied here could contribute to a deeper understanding of the nature of transition processes and the advancement of sustainability science.

5.6. NOTES

5.6.1. Acknowledgements

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5.6.2. Availability of data and materials

The dataset and the R code supporting the conclusions of this article are available in the following repository: https://github.com/manuelbickel/semantic_sustainability_assessment.

The code is platform independent. The repository is licensed under a GNU GENERAL PUBLIC LICENSE.

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APPENDICES

A1. Data summary of municipalities and climate action plans

*Table A1: Data summary of the studied municipalities in Lower Saxony and their climate action plans (*activity report instead of MCAP)*

State / City	**Population in 2014** (source: Federal Statistical Office of Lower Saxony)	**MCAP issued in**	**Number of proposed measures in MCAP***
Lower Saxony	7826739	-	-
Hanover	523642	2008	134
Braunschweig	248502	2010	106
Oldenburg	160907	2011	122
Osnabrück	156897	2014	96
Wolfsburg	123027	2009	21
Göttingen	117665	2010	217
Hildesheim	99979	2012	66
Salzgitter	98966	2014	87
Wilhelmshaven	75534	2013	70
Delmenhorst	74804	2014	55
Lüneburg**	72546	2013	51
Celle	68721	2010	104
Hameln	56310	2010	85
Nordhorn	52579	2013	39
Langenhagen	52330	2010	78
Emden	50016	2010	37

* In some MCAPs, measures were not described using the form sheet presented in the manuscript in Table 5-1 but in a comparable form, individual sub-sections or paragraphs.

** Lüneburg, had a climate action activity report instead of an MCAP. As its content resembled that of MCAPs, it was included in this study.

A2. Literature used to create the thesauri

In the following, sources are listed that supported the semi-automatic creation of the thesauri and accelerated the tagging of concepts in the MCAPs (see section 5.2.6 of the manuscript). The following sources served to compile German concept lists for specific categories.

A2.1 Professional literature

Diekmann B, Rosenthal E (2014) Energie. Physikalische Grundlagen ihrer Erzeugung, Umwandlung und Nutzung, 3., vollst. überarb. u. erw. Aufl. 2014. Springer Fachmedien Wiesbaden, Wiesbaden

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Reich G, Reppich M (2013) Regenerative Energietechnik. Überblick über ausgewählte Technologien zur nachhaltigen Energieversorgung. Springer Fachmedien Wiesbaden, Wiesbaden

Schabbach T, Wesselak V (2012) Energie. Die Zukunft wird erneuerbar. Technik im Fokus. Springer Vieweg, Berlin

Strauß K (2006) Kraftwerkstechnik. Zur Nutzung fossiler, nuklearer und regenerativer Energiequellen, 5., völlig aktualisierte und erg. Aufl. VDI-Buch. Springer, Berlin, Heidelberg, New York

Usemann KW (2005) Energieeinsparende Gebäude und Anlagentechnik. Grundlagen. VDI-Buch. Springer, Berlin

A2.2 Public institutions or public thesauri

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) Energierohstoffe 2009: Reserven, Ressourcen, Verfügbarkeit. Enthält Teil 1 bis 3. Stand: 10.11.2009, Hannover. Accessed 20 Aug 2015

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A3. <1><SOC> - meta-categories and categories

Table A3: Meta-categories and categories of the thesaurus <1><SOC> representing subsystems of the social system

#	Meta-category	category
1	<Agriculture>	<agriculture>
2	<Agriculture>	<domesticated_animal>
3	<Agriculture>	<fishery>
4	<Agriculture>	<forestry>
5	<Art>	<arts_handraft_performances>
6	<Climate_Protection>	<unspecific_action> (including strategies and plans)
7	<Communication>	<citizen_participation>
8	<Communication>	<fair_exhibition>
9	<Communication>	<material_tool>
10	<Communication>	<meetings_networks>
11	<Communication>	<press_media>
12	<Communication>	<public_contest_audit>
13	<Communication>	<publicity_campaigns_PR>
14	<Consumption>	<consumer_goods_objects>
15	<Consumption>	<general_reference>
16	<Economy>	<commerce><com_trade_procurement>
17	<Economy>	<commerce><sector_unspecific>
18	<Economy>	<commerce><tariffs_standing_orders>
19	<Economy>	<general_reference><economic_viability>
20	<Economy>	<general_reference><employment_workplace>
21	<Economy>	<industry><heavy_industry>
22	<Economy>	<industry><intermediate_products>
23	<Economy>	<industry><general_reference>
24	<Economy>	<service><consulting>
25	<Economy>	<service><personal_services_crafting>
26	<Economy>	<general_reference>
27	<Education>	<continuing_education_events_locations>
28	<Education>	<primary_secondary_apprenticeship>
29	<Education>	<tertiary_R&D_institutions>
30	<Environment>	<ecological_action>
31	<Environment>	<environment_physical>
32	<Environment>	<harmful_emission>
33	<Environment>	<technology_management>
34	<Finance>	<contracts>

#	Meta-category	category
35	<Finance>	<costs>
36	<Finance>	<funding_financing_banks>
37	<Finance>	<insurance_incl_company_names>
38	<Finance>	<investment>
39	<Finance>	<public_fees>
40	<Finance>	<taxes>
41	<Food>	<processing_consumption>
42	<Health>	<physical_health_care>
43	<Health>	<social_mental_care>
44	<Infrastructure>	<building_parts_materials>
45	<Infrastructure>	<construction_craft_sector>
46	<Infrastructure>	<disposal_unspecific>
47	<Infrastructure>	<supply_unspecific>
48	<Infrastructure>	<unspecific>
49	<Infrastructure>	<waste_sector>
50	<Infrastructure>	<wastewater_sector>
51	<Infrastructure>	<water_supply_and_consumption>
52	<Institution>	<execution_of_law_police>
53	<Institution>	<federal_national_administration_ministries>
54	<Institution>	<local_administration_bodies>
55	<Institution>	<public_utilities>
56	<IT>	<unspecific_and_software_hardware>
57	<Law>	<EU_world>
58	<Law>	<local_and_national>
59	<Leisure>	<sports_gambling>
60	<Leisure>	<tourism_travelling>
61	<Mobility_Sector>	<general_reference>
62	<Planning>	<land_use_coordination_specific_areas>
63	<Planning>	<planning_processes_and_elements>
64	<Politics>	<general_reference_and_parties>
65	<Psyche>	<psyche_consciousness_motivation>
66	<Religion>	<religion>
67	<Residents>	<population_in_general>
68	<Residents>	<rental_of_houses>
69	<Residents>	<residential_area>
70	<Residents>	<social_groups>
71	<Resources>	<extraction>
72	<Resources>	<raw_materials_anorganic>
73	<Resources>	<raw_materials_organic_non_energy>

#	Meta-category	category
74	<Security>	<military>
75	<Security>	<observation_technologies_services>
76	<Spatial_Scale>	<countries_not_Germany>
77	<Spatial_Scale>	<EU>
78	<Spatial_Scale>	<international>
79	<Spatial_Scale>	<municipality_city_districts>
80	<Spatial_Scale>	<national>
81	<Spatial_Scale>	<offshore>
82	<Spatial_Scale>	<onshore>
83	<Spatial_Scale>	<regional>
84	<Spatial_Scale>	<regional><names_of_German_areas>
85	<Technology>	<associations>
86	<Technology>	<parts_tools_objects>

A4. Occurrence of categories of <1><SOC>

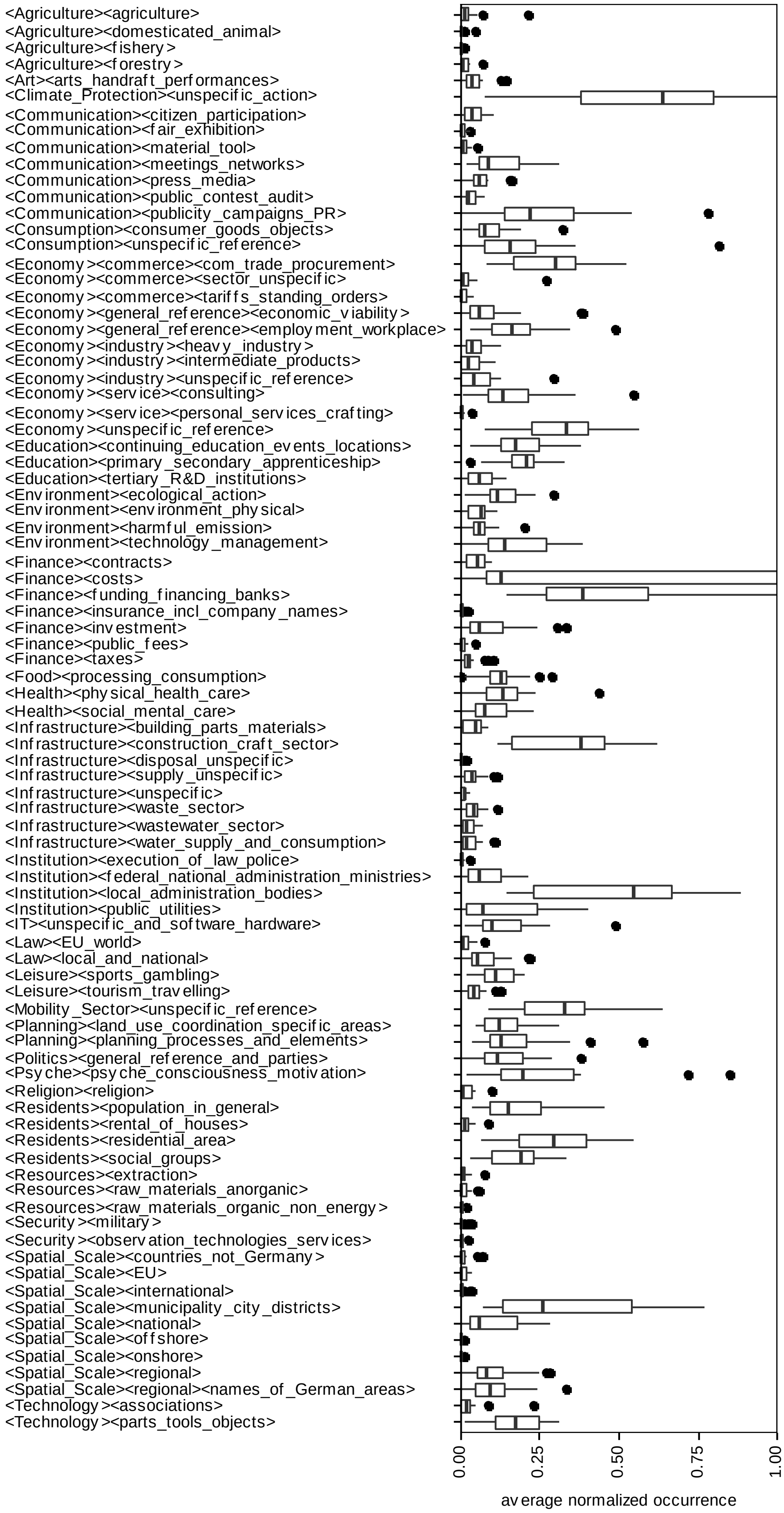


Figure A4: Boxplot of average normalized occurrence of categories of <1><SOC>

A5. Occurrence of categories of <3><SUS>

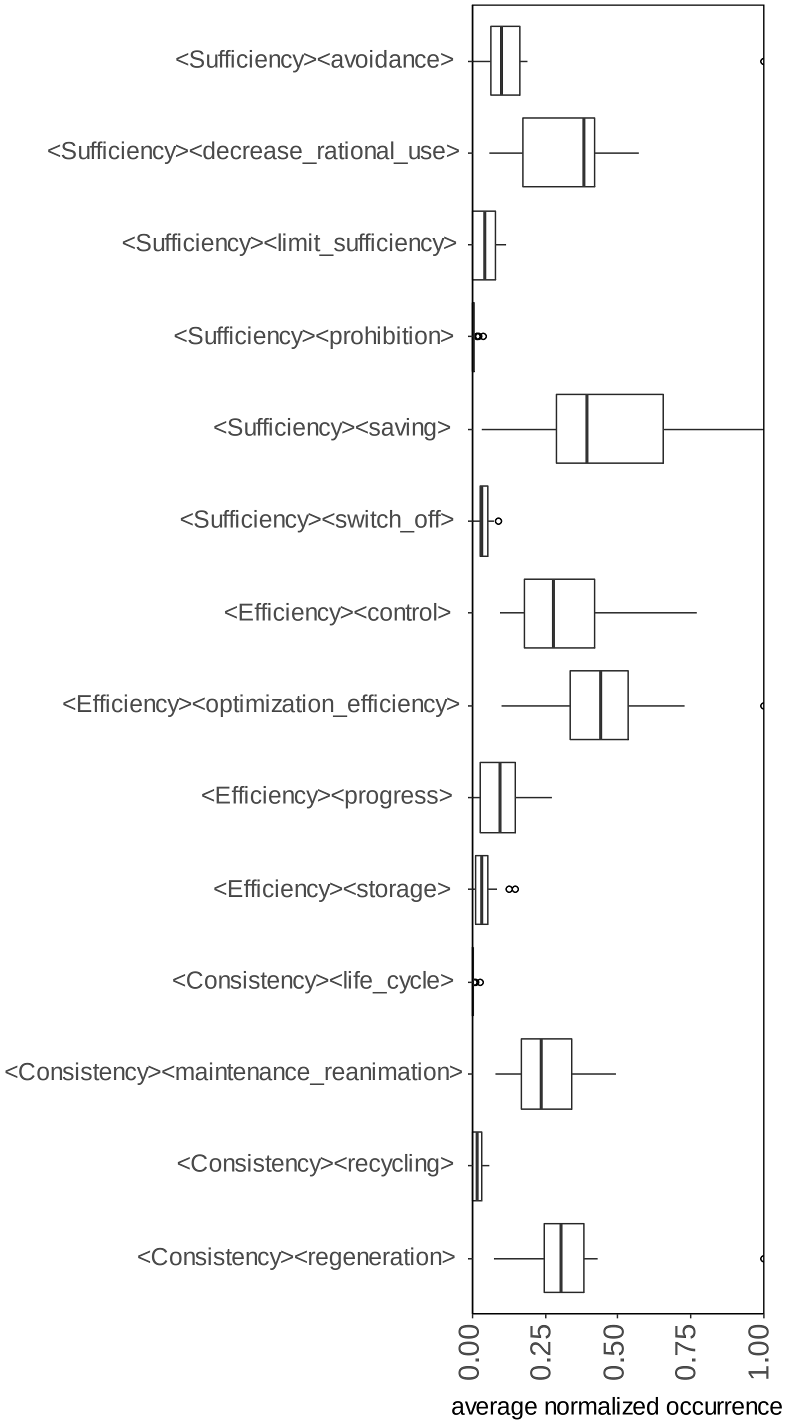


Figure A5: Boxplot of average normalized occurrence of categories of <3><SUS>

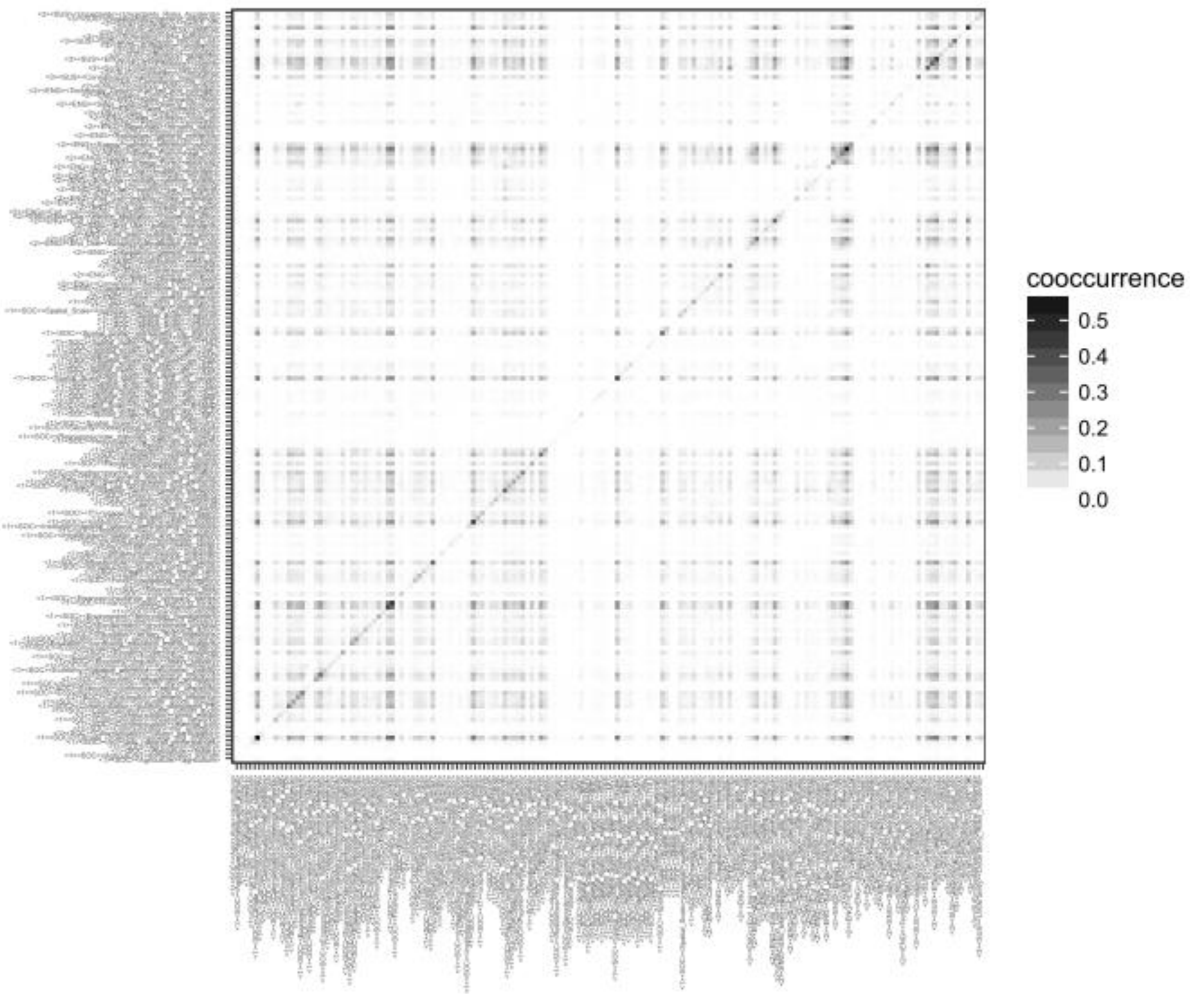
A6. Unscaled average normalized co-occurrence matrix

Please refer to the attached pdf file named:

"Appendix11_Semantic_sustainability_assessment_full_COOCM".

Note: *The dimensions of the attachment file are very large. Therefore, it is only reproduced in this print version in the context of this dissertation as a very small image that is not readable – please see below. The electronic version can be accessed via the supplementary electronic material of the online publication of the article, via the following link.*

https://static-content.springer.com/esm/art%3A10.1186%2Fs13705-017-0125-0/MediaObjects/13705_2017_125_MOESM1_ESM.zip



A7. Number of words per measures and tagged words per measure

Table A7: Number of tagged words

city	number of measures	average number of words per measures	average number of unique stemmed words per measure	average number of unique uppercase stemmed words per measure	average number of tagged unique uppercase stemmed words per measure
Hanover	134	82	80	50	25
Braunschweig	106	110	106	52	26
Oldenburg	122	169	165	89	39
Osnabrück	96	108	104	53	27
Wolfsburg	21	97	94	44	24
Göttingen	217	68	67	39	18
Hildesheim	66	127	122	69	29
Salzgitter	87	59	57	24	14
Wilhelmshaven	70	31	31	17	8
Delmenhorst	55	177	172	95	47
Lüneburg*	51	38	37	18	11
Celle	104	14	14	8	5
Hameln	85	65	64	33	20
Nordhorn	39	149	144	77	38
Langenhagen	78	66	65	32	18
Emden	37	148	144	77	40

CHAPTER 6

CASE STUDY 2 - REFLECTING TRENDS IN THE ACADEMIC LANDSCAPE OF SUSTAINABLE ENERGY USING PROBABILISTIC TOPIC MODELING

6. CASE STUDY 2 - REFLECTING TRENDS IN THE ACADEMIC LANDSCAPE OF SUSTAINABLE ENERGY USING PROBABILISTIC TOPIC MODELING

BIBLIOGRAPHIC DATA

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ABSTRACT

Background: Facing planetary boundaries, we need a sustainable energy system providing its life support function for society in the long-term within environmental limits. Since science plays an important role in decision-making, this study examines the thematic landscape of research on sustainable energy, which may contribute to a sustainability transformation. Understanding the structure of the research field allows for critical reflections and the identification of blind spots for advancing this field.

Methods: The study applies a text mining approach on 26533 Scopus-indexed abstracts published from 1990 to 2016 based on a latent Dirichlet allocation topic model. Models with up 1100 topics were created. Based on coherence scores and manual inspection, the model with 300 topics was selected. These statistical methods served for highlighting timely topic trends, differing thematic fields, and emerging communities in the topic network. The study critically reflects the quantitative results from a sustainability perspective.

Results: The study identifies a focus on establishing and optimizing the energy infrastructure towards 100% renewable energies through key modern technology areas: materials science, (biological) process engineering, and (digital) monitoring and control systems. Energy storage, photonic materials, nanomaterials, or biofuels belong to the topics with the strongest trends. The study identifies decreasing trends for general aspects regarding sustainable development and related economic, environmental, and political issues.

Conclusions: The discourse is latently adopting a technology-oriented paradigm focusing on renewable energy generation and is moving away from the multi-faceted concept of sustainability. The field has the potential to contribute to climate change mitigation by optimizing renewable energy systems. However, given the complexity of these systems, horizontal integration of the various valuable vertical research strands is required. Furthermore,

the holistic ecological perspective considering the global scale that has originally motivated research on sustainable energy might be re-strengthened, e.g., by an integrated energy and materials perspective. Beyond considering the physical dimensions of energy systems, existing links from the currently technology-oriented discourse to the social sciences might be strengthened. For establishing sustainable energy systems, future research will not only have to target the technical energy infrastructure but put a stronger focus on issues perceivable from a holistic second-order perspective.

ABBREVIATIONS

(N)PMI	(Normalized) pointwise mutual information
CCSU	Carbon capture, storage, and use
DIF	Difference (metric)
DTM	Document-term-matrix
LDA	Latent Dirichlet allocation
LFMD	Log-frequency biased mutual dependency
NLP	Natural language processing
NPMI COSIM (SET)	NPMI cosine similarity (to set)
POS	Part-of-speech
SES	Social-ecological system
STS	Socio-technical system

6.1. BACKGROUND

For a vital society, the energy system has always been a key component. Facing climate change in the context of “planetary boundaries” [1, 2], it is crucial to establish a sustainable energy system that can provide its life support function for society in the long-term within environmental limits [3,4,5]. This triggers the twofold question: What are the main elements of an energy system, and what is an optimum design of our human-made energy system, in particular, with respect to its interactions with nature [6, 7]? As a response to this question, the normative multi-faceted concept of sustainability has developed into a popular guiding principle over the past decades [8,9,10,11,12,13,14]. It is expected to lead to a socio-technical system that does not exceed the “carrying capacity” of the natural system [9, 15].

These thoughts increasingly influence guidelines, initiatives, and policies, as shown by various examples. To name a few, at global level, the Sustainable Development Goals of the United Nations promote sustainability in different sectors and, for the energy sector, propose to “ensure access to affordable, reliable, sustainable and modern energy” via Goal 7 [16]. Regarding the European continent, the European Energy Strategy aims at a “sustainable, competitive and secure energy system” [17]. At a national level, examples are China´s 13th Five-Year Plan incorporating aspects of “green development” [18, 19] or the German Energy Transition supporting a systemic shift towards renewable energies [20, 21]. Of course, these examples are not final answers and face various challenges [22,23,24,25,26]. However, they are steps within a transformation towards sustainability, of which the field of *sustainable energy* is a crucial element.

Science has been a key initiator for the attention to sustainability and is to further play an active role [6, 27,28,29]. The outputs of the research branch concerned with *sustainable energy* are, therefore, precursors of a potentially sustainable global energy system of the future. For anticipating the nature of this kind of system, this study analyzes the structure of the hybrid research field of *energy* and *sustainability*. The following background briefly summarizes research trends based on a high-level qualitative review. This initial overview is extended throughout this study by a text-mining approach.

Screening the 100 most cited scientific review articles containing the term “sustainable energy” indexed in the Scopus database (Digital Object Identifiers see Appendix A1) shows that the dominant themes are electricity generation by renewables, bioenergy, storage technologies, and especially materials science. A general observation is that the reviews largely take a techno-economic perspective. The majority focuses on individual technologies, discusses the technical energy infrastructure while considering the costs of energy generation, or envisions various technological pathways.

Regarding renewable energy generation, photovoltaic energy might develop to the primary future energy source due to expected efficiency improvements, especially through intensive research on advancing materials for solar cells [30,31,32,33,34,35]. Wind energy, in particular, direct-drive turbine technology, might be the major secondary source [31,32,33,34,35]. In general, solar and wind-powered systems are deemed to have tolerable effects on ecosystems [32, 33, 35]. However, these effects will require continued attention [34, 36]. Since fossil fuels will remain competitive in the near future, some articles also refer to efficiency measures for fossil power plants [34, 35]. For decarbonization, carbon capture, storage, and use (CCSU), as well as nuclear energy, are also considered, while acknowledging the lack of conclusive risk assessments [32,33,34,35]. Several articles consider geothermal energy as a technology that, despite the untapped potential, has received comparably low attention [33, 34, 37]. However, the expansion of deep geothermal power generation will require diligent risk assessments [34].

The complexity of renewable energy systems stemming from intermittent and decentralized generation has motivated research in the field of storage technologies, modeling, and smart energy. For encountering intermittency, electrochemical energy storage via batteries, fuel cells using various storable fuels, or supercapacitors is intensively investigated [35, 38,39,40]. Given the plethora of technological options, optimization modeling tools have become essential for the efficient, dynamic, and economically viable planning and operation of renewable energy systems [31, 35, 37]. In this context, some articles propose smart energy systems as a promising techno-economic approach for establishing efficient energy systems by integrating thermal, gas, and electricity infrastructure [41, 42].

The future of fuels in the transportation sector but also other sectors seems less clear than the future of electricity generation. Bioenergy and biotechnology for producing biofuels have received considerable attention [43,44,45], especially the production of bioethanol through fermentation of sugarcane or grains [31, 33, 46, 47]. Due to limited sustainable availability of these feedstocks [33, 34], research also investigates alternative feedstocks such as lignocellulosic materials or microalgae and conversion technologies such as biorefineries or microbial reactors [33, 46, 48,49,50,51,52,53,54,55,56]. Another technological pathway discussed is the hydrogen economy based on water splitting [33, 57,58,59,60,61,62]. The direct use of hydrogen in fuel cells is a desirable long-term option; however, establishing the required hydrogen infrastructure is challenging [34, 39, 57, 63]. Therefore, synthesizing hydrocarbon fuels and distributing them via existing infrastructures is discussed [33]. Another pathway would be the methanol economy based on the yet impracticable artificial photosynthesis [63,64,65,66]. Considering this diversity of research on fuels, the electrification of the transportation sector might be achieved via fuel cells in the long-term but will probably be dominated by the already mature battery technologies in the short-term [35, 39].

Beyond discussing energy systems at large scale, the major share of highly cited reviews covers research on improving or creating advanced materials for energy technologies. Research has particularly focused on materials for batteries, fuel cells, or supercapacitors as well as hydrogen production and storage, thermoelectric devices, or solar cells [39, 40, 58, 63, 67,68,69,70]. In these applications, new materials can improve the performance of anodes, cathodes, electrolytes, catalysts, photoactive layers, diffusion layers, or storage structures [55, 58, 63, 69,70,71,72,73]. Materials science further has the potential to find replacements for materials with limited abundance such as noble metals in catalysts or electrodes [61, 63, 69, 71,72,73,74,75,76], lithium in batteries [39], or rare-earth magnetic materials in wind turbines [35, 63]. However, this field of materials science is often experimental, and no straightforward pathway regarding the choice of materials has emerged [69]. As a special field, nanoscience has become crucial for energy technologies [63, 68]. Nanotechnology allows synthesizing organic, inorganic, or composite structural elements such as particles, fibers, grids, thin-films or three-dimensional structures such as nanotubes, porous membranes, metal-organic frameworks, or carbon gels [63, 68, 69, 75, 77,78,79]. Controlling the geometric, physical, chemical, or electrical properties of materials can significantly increase the efficiency or functionality of various technologies regarding, e.g., surface to volume ratio, kinetics, conductivity, storage capacities, or stability of materials [39, 68, 69, 75].

Beyond the above themes that represent the main focus of the examined review articles, several themes receive less attention. Only a few articles discuss details regarding the conditions and developments in individual end-use sectors. There is only one article dedicated to a specific sector, i.e., the building sector [80]. Furthermore, despite the focus on materials science, only a few articles explicitly address the scalability of technologies considering the availability of chemical elements [81]. Non-technological aspects such as potential rebound effects, consumer behavior and energy-saving lifestyles, or political measures are only marginally discussed [34, 35, 82]. However, regarding issues of decision-making, a few articles deal with the details of advanced multi-criteria decision-making methods, especially for energy system planning [83, 84].

For extending the insights gained from the above qualitative review, this study uses a quantitative exploratory text mining approach. Qualitative reviews provide valuable insights. However, they are limited in the number of articles that can be analyzed and are, thus, selective to a certain extent. Therefore, they might not cover the full thematic breadth in a representative way. Considering the potential that large-scale text-based mappings of academic fields offer [29, 85,86,87,88], this study applies a text mining approach for detecting unknown patterns from text [89,90,91,92]. This approach does not replace the qualitative review method but offers a different integrated perspective that allows large-scale quantitative analyses and is unbiased regarding the selection of articles.

For reflecting latent paradigms in the academic field of sustainable energy and triggering further questions from an overarching perspective, this study quantitatively maps the scientific discourse with regard to prevalent topics, trends, and research communities. For this purpose, it applies a probabilistic topic modeling approach [93,94,95]. Several studies used topic modeling for investigating, e.g., research on hydropower [96], transportation [97], or knowledge flows in energy research in general between researchers in Asia and the USA [98]. However, topic modeling has not yet been applied for a broad mapping of research on *sustainable energy*. This study uses this method for analyzing research trends quantitatively without specifying themes a priori. In addition, it highlights the interconnections between topics and detects research communities. Thereby, it extends other applied topic modeling studies. There are a few studies dealing with correlations of topics that, however, follow a methodological but less a content-related interest [85]. So far, applied topic modeling studies usually do not highlight topic co-occurrence [87, 88, 96,97,98]. Moreover, while other text mining studies often focus on reporting quantitative results [86, 96,97,98], this study goes further. It critically reflects the modeling results by a detailed qualitative discussion from a sustainability perspective.

Using this large-scale approach, this study provides a new overall picture of the scientific discourse on sustainable energy. Beyond reporting and discussing themes side by side as it is done, e.g., in several of the studies screened above, it ranks thematic trends and provides a not yet available quantitative indication where the discourse is heading. It improves the understanding of the structure of the research field and assesses the integration of sustainability elements therein. This study can confirm several of the trends identified in the above literature review, show some in a different light, identify new trends, and point out blind spots to support advancing research on sustainable energy. In general, this study shows that the discourse is latently adopting a technology-oriented paradigm and is moving away from the multi-faceted concept of sustainability. Based on this empirical evidence, it highlights several important perspectives to be considered in future research and enables adjusting research priorities from a holistic sustainability perspective.

The rest of this paper is organized as follows. The section "Materials and methods" provides details on the text data used. It also explains and reflects the text mining methodology. The section "Results" presents the output of topic modeling regarding the timely trends, thematic fields, and the network of topics. The section "Discussion" examines the findings concerning selected *energy* system stages and principles of *sustainability*. It further relates the results to the above background and selected literature. The final section provides summarizing conclusions.

6.2. MATERIALS AND METHODS

This section summarizes the applied text mining methodology and provides reflections on methodological limitations and prospects. Appendix A3 provides comprehensive technical details on the methodology and underlying statistical models. The code for this study was written in R [99]. The code and, to the extent permitted by copyright, the data used are available in an open-source repository [100].

6.2.1. Data - Scopus abstracts

The database of this study consists of 26,533 Scopus-indexed abstracts of original journal articles published in the period from 1990 to 2016 whose abstracts, titles, or keywords contain the terms *sustainab** and *energy*. The exact search phrase used in November 2017 for collecting data was *"TITLE-ABS-KEY(sustainab* AND energy) AND NOT INDEX(medline) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "ip")) AND (LIMIT-TO(SRCTYPE, "j"))"*. The following pre-selection criteria served to exclude non-representative or low-quality entries: (i) minimum length of 200 characters per abstract and (ii) no duplicate entries regarding title, abstract content, or EID number. By using Scopus as a bibliometric database with less strict criteria for entering the index system in contrast to, e.g., Web Of Science, this study potentially covers a broad range of emerging lines of thought [101, 102]. A disadvantage of Scopus is the current limitation of bulk downloads making manual iterative downloading necessary.

6.2.2. Overview of the topic modelling methodology

The core of the methodological sequence programmed for this study is the basic latent Dirichlet allocation (LDA) [103] model. Considering the family of probabilistic topic models [93,94,95], LDA is one of the basic models that has successfully been applied for, e.g., identifying key topics in scientific discourses [87, 88, 96,97,98]. Given a corpus, i.e., a collection of documents, LDA assumes that each document is a mixture of topics and that each topic is a mixture of words [93]. These mixtures are probability distributions. Each topic has a certain probability of appearing in a specific document. Also, each term of the whole corpus has a certain probability of belonging to a specific topic. The posterior distributions inferred by LDA are stored in probability matrices. For instance, the document topic matrix has rows representing documents and columns representing topics, while each entry shows the prevalence of a topic in a given document. LDA uses a generative algorithm for inferring the posterior distributions that represent a fitted model for a corpus. This kind of distributions can be analyzed and coupled with other meta-data of documents, e.g., the year of publication. For this study, the methodological sequence covers (i) pre-processing the raw abstracts for increasing the quality of the input data, (ii) topic modeling using LDA, and (iii) analysis of the output regarding topic trends over time, differing thematic fields in the corpus, and topic communities emerging from the network of topics.

6.2.3. Pre-processing

An advanced pre-processing procedure served for increasing the data quality of the raw texts. First, several natural language processing (NLP) steps served for standardizing the symbolic representation and harmonization of individual terms. Second, using the TreeTagger software [104,105,106] and the koRpus package [107], a part-of-speech (POS) model served for identifying the grammatical structure of sentences in order to discard irrelevant word classes, here, everything but nouns, verbs, adjectives, and adverbs, and to lemmatize terms. An example of lemmatization, a method for the unification of terms, is provided in Appendix A3. Third, a collocation model detected n-grams, i.e., multi-word terms occurring to a statistically relevant degree in the corpus, to mitigate the assumption regarding the irrelevance of grammar by LDA (explanation see the following section). Collocation detection was performed for noun compounds [108] using pointwise mutual information (PMI) [109] and log-frequency biased mutual dependency (LFMD) [110] as statistical metrics for detecting meaningful collocations. In the final pre-processing step, the vocabulary of the corpus was pruned by setting thresholds for document occurrence of terms and term length and by removing stopwords, e.g., “and,” “the,” or “methodology.” By using this kind of advanced pre-processing procedure beyond common methods such as stemming or setting minimum term length thresholds, this study advances pre-processing procedures of previous studies with similar scope [87, 88, 96, 97].

6.2.4. Topic modeling

6.2.4.1. Latent Dirichlet allocation

As input to LDA, the pre-processed corpus was vectorized to a document-term-matrix (DTM) representing the counts of individual terms per document. The pre-processed corpus contained 2,018,059 terms in total and 28,768 unique terms. Vectorizing text means that, before topic modeling, a bag-of-words model is adopted assuming that grammar is negligible. The collocation model used here (see the previous section) mitigates this assumption.

For finding a suitable LDA model, several models were created by varying one of the key parameters, i.e., n, the number of topics assumed for the corpus. A common challenge of any modeling approach is that there is not only one single model that potentially fits the data. Varying n served to create a set of models, from which a model with a potentially good fit could modeling. LDA models were generated for n from 5 up to 1100 in steps of 5. Apart from the parameter n, there are two additional key parameters of LDA models. The hyper-parameter α, which determines the granularity of the topic distribution over documents, was set to $\alpha = 50/n$, and β, which determines the specificity of topics, was set to $\beta = 0.1$. These hyper-parameter settings have been proposed by Griffiths and Steyvers in a study with similarly broad scope and size of the corpus [88], which is one of the central references in the field of topic modeling. The chosen values create a model assuming that documents consist of a few key topics and topics consist of a few key terms. This assumption behind these values fits the characteristics of scientific abstracts covering a broad field, here, sustainable energy. For comparison, setting smaller values can be reasonable for studying specific narrower fields. For instance, a study of

17,163 scientific articles on transportation research applied values of $n = 50$, $\alpha = 5/n$, and $\beta = 0.01$ for modeling sparser distributions of topics and words [97]. Having adjusted the above settings, the comparably fast WarpLDA algorithm [111, 112] served for creating the LDA models. This algorithm allowed creating a large set of models within an acceptable time.

6.2.4.2. Model selection via coherence

Six different topic coherence metrics programmed in R for this study [100, 109, 111, 113,114,115,116,117,118,119] and a Wikipedia-based reference corpus served for selecting the most suitable LDA model from the set of models created. The maximum model likelihood or subjective choices are often the basis for model selection [88, 96, 97]. Maximum likelihood models may produce topics with comparably low interpretability [112]. Therefore, this study uses coherence metrics as rational selection criteria. Considering general consistency metrics for evidential support [116, 120], Röder et al. proposed a framework for calculating coherence scores of topic models [115]. The basic idea is to pick the top topic terms and to check to what extent their co-occurrence in a reference corpus is statistically related. This study uses the top 10 words per topic. For calculating the coherence of the complete LDA models, the mean was used for aggregating topic scores.

For the intrinsic coherence metrics, logratio [114, 115] and probabilistic difference (DIF) [116, 117], the corpus of the investigation itself served as the reference corpus. For the extrinsic metrics, 1,737 thematically related Wikipedia articles served as the reference corpus. The extrinsic used metrics are pointwise mutual information (PMI) [109, 118], normalized PMI (NPMI) [119], cosine similarity of NPMI vectors (NMPI COSIM) [111], and cosine similarity of NPMI vectors to the sum of the NPMI vectors [115]. These reference articles were selected via snowball sampling, beginning with manually selected thematically relevant portal pages. A web scraping algorithm using the WikipediR package [121] served for downloading these articles.

6.2.5. Methods for analyzing the topic model

6.2.5.1. Topic trends

This study examines the timely trends of individual topics by coupling the date of publication of individual documents with the posterior probability distribution matrix of topics over documents. For revealing “hot topics” and “cold topics” with increasing or decreasing trends

[88], linear models were fit for each topic over the selected time period from 1990 to 2016. This approach has been used in other studies [88, 96, 97, 122]. In addition, this study facilitates the visual inspection of trends by generating smoothed trend lines using locally weighted polynomial regression (LOESS) applied to the mean values of topic probabilities per year [123, 124]. The corrected Akaike Information Criterion (AIC_c) served for automatically selecting the smoothing span [125, 126].

For highlighting key trends, this study focuses on the topics with the strongest positive or negative trends as well as on topics with the highest abundance. Here, a strong positive trend means that the slope of the linear trend line was equal to or above the 95% quantile regarding the slopes of all topics. The topics with the strongest negative trend were identified using the 5% quantile as a threshold. Further, the abundance of a topic is defined here as the cumulative sum of topic probability over all years and documents. Topics with the highest abundance were identified by limiting the topic selection to the topics with a positive linear trend and setting the 95% quantile regarding abundance as a threshold.

6.2.5.2. Inter-topic distance and thematic fields

The next analytical step analyzes how individual topics are embedded in the context of all other topics and highlight differing thematic fields. For this purpose, the inter-topic distance, hence, the content-related (dis-)similarity between each pair of topics, was calculated. On this basis, the topics can be clustered into the most different thematic fields of the corpus. For evaluating the distances between the probability distributions given in the columns of posterior distribution matrix of terms over topics, i.e., the topic pairs, the Jensen Shannon Divergence was used as a symmetric similarity metric [127, 128]. Classical multidimensional scaling of similarities [129,130,131], also called principal coordinates analysis [132], then served to project the distance between topics into a two-dimensional space. This step uses an adaption of the code of the LDAvis package [133, 134]. In addition, hierarchical clustering using Ward’s method [135, 136] was applied to the resulting coordinates for detecting the most different thematic fields or discourses.

6.2.5.3. Topic network and topic communities

A network analysis served for analyzing connections between topics within the individual documents and for identifying major research communities. The co-occurrence of topics, which indicates how often each topic co-occurs with each other topic, can be calculated as the cross product of the posterior document topic distribution matrix. The resulting adjacency matrix constitutes the network of topics. Since LDA assumes a distribution of all topics over all documents, the network is very dense. Documents usually include few topics with high probability but also many with low probability. Hence, following the assumptions of LDA, all topics are somehow connected to all other topics.

For a focused analysis of key linkages only, the study applies several restrictions. To highlight stable or emerging trends, the network is restricted to topics with a positive trend. Furthermore, two types of thresholds serve for pointing out the strongest connections. First, only the top topics per document were included. Second, only co-occurrence values equal or larger than a pre-defined co-occurrence threshold were considered, whereas values below the thresholds were set to zero. Setting thresholds in network analyses is a sensitive issue. Therefore, several networks were generated and compared by setting different thresholds. The comparison included a variation of the top topics per document threshold between 2, 5, and 10 and of the co-occurrence threshold between the 0%, 25%, 50%, and 75% quantile respectively.

The analysis of the resulting network was carried out by calculating the betweenness centrality metric for each topic and applying network community clustering. Topics with high betweenness may be interpreted as bridges [137] or influential nodes regarding network communication [138]. Finally, the Louvain hierarchical clustering algorithm [139, 140] served for detecting communities of multiple topics, which represent research communities. The algorithm uses the idea of maximizing the modularity of a partitioned network [141]. Modularity measures the degree of cross-linking within communities in relation to the degree of cross-linking between communities [141,142,143]. Communities of topics represent sub-networks that stand out of their environment due to their high within-community cross-link density [139].

6.2.6. Methodological limitations and prospects

A basic limitation arises from the database that covers a specific type of research output. Beyond journal articles, the scientific discourse comprises other relevant communication channels not covered here such as conferences, open web archives, or websites. Hence, this study provides a comprehensive review of relevant research but is limited to the part of the discourse accessible via standardized databases. Furthermore, the study is based on a single search phrase. A more complex but laborious approach might use a variation of search phrases and comparatively analyze the resulting sets of documents for establishing an even more differentiated picture.

Key methodological limitations stem from using a particular type of topic model with a specific set of model parameters. As in several other studies with similar scope [87, 88, 96, 97], the basic LDA model produced reasonable insights. Variations of the basic model might provide extended insights, e.g., the dynamic topic model that allows studying the internal development of topic topics over time [144]. Furthermore, varying the hyper-parameters or even using asymmetric hyper-parameters [145] leads to a broader set of topic models, from which a potentially improved model might emerge. For selecting the most appropriate model, this study applies an advanced approach based on coherence metrics. Research regarding suitable combinations of metrics, reference corpora, and parameter settings for different contexts is ongoing [115] and might lead to improved or more broadly proven options for identifying good models.

The probably most notable limitation is the human factor deciding whether the chosen LDA model based on machine learning creates a reasonable lens for interpreting the data. Computers perform a significant dimensional reduction of the complex meanings contained in texts via LDA. Human interpretations of resulting topics have to be made carefully and might even be misleading [146]. Topic models are a “lens” for understanding a corpus [147]. For finding a sufficiently clear lens that allows for useful interpretations, a suitable combination of the data set, model parameters, and content-related background knowledge is required [147, 148]. This study is not exempt from criticism regarding the combination applied. This study uses a lens created by iterative model adaption based on the interaction between machine learning and human interpretations. Admittedly, not all of the resulting individual topics were perfectly interpretable. However, for the majority of topics, the general meaning seemed to be clear intuitively. Since this study aims at identifying large-scale patterns, the lens adopted here was deemed an acceptable basis for further high-level interpretations.

6.3. RESULTS

6.3.1. Number of articles over time

For an overview of publication dynamics, the cumulative number of abstracts over time was modeled as an exponential curve shown in Figure 6-1a. Publication activities before 1990 were sparse. To avoid fitting noise around the baseline, the models created for this study, including the topic models, only consider the documents published since 1990. For modeling publication dynamics, different models were compared, of which the exponential model $cum\_n = 8.6037\mathrm{e}-158 * \exp(0.18445 * \mathrm{Year})$ had the best fit with a high R^2 of 0.9996 and a mean relative error of 10%. This accuracy seems acceptable for a simple descriptive purpose. In addition to the cumulative numbers, Figure 6-1b shows the number of publications per year. Furthermore, Figure 6-1c shows the steep growth compared to the publication dynamics retrieved by using only the search term energy.

6.3.2. LDA model coherence

After having evaluated the coherence scores and screened the top topic terms of the various LDA models, the model with 300 topics appeared to be the most appropriate. The coherence metrics DIF, NPMI, and NPMI COSIM were the most informative in the sense of showing comparably clear maxima. Figure 6-2 shows the scores of the fitted LDA models. For direct comparison, scores are normalized. For all metrics, maxima are recognizable for models with up to 55 topics. Manually examining the top topic terms of the corresponding models revealed easily interpretable topics. However, these general topics with a coarse resolution did not provide sufficient insights for investigating, e.g., individual disciplines or technologies. Aiming at a higher level of detail here, the models with the clearest maxima beyond 55 topics were examined manually. The DIF metric, which measures coherence on a document level, proposed to use the model with 200 topics, whereas the NPMI metric, which measures coherence at the sentence level, proposed to use the model with 300 topics. Manual inspection of these models led to the decision to study the model with 300 topics since it provides a higher resolution regarding individual fields. As an example, the model with 200 topics contains an integrated topic on solar energy addressing photovoltaic systems and solar thermal energy together. The model with 300 topics generated two separate topics for these two fields.

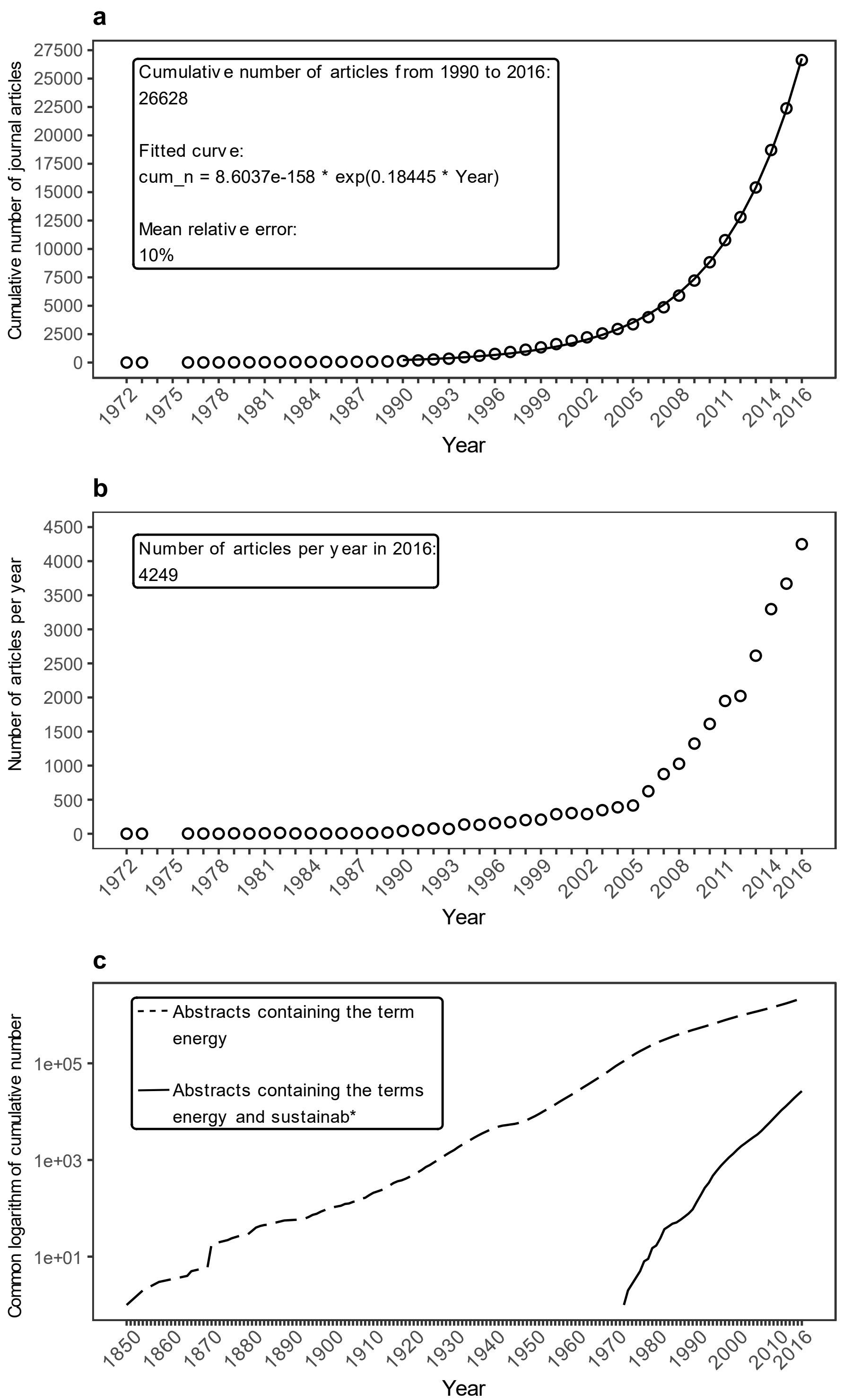


Figure 6-1: ***a*** *Cumulative number of Scopus-indexed journal articles per year, which contain the search terms sustainab* and energy; records before 1990 are just shown as supplementary information and have not been included in any of the modeling procedures of this study.* ***b*** *Number of articles per year.* ***c*** *Comparison of the cumulative number from* ***a*** *on a semi-logarithmic scale to the cumulative number of articles retrieved from using the single search term energy; the graphical presentations in* ***a*** *and* ***b*** *are inspired by and allow a direct comparison to [96]*

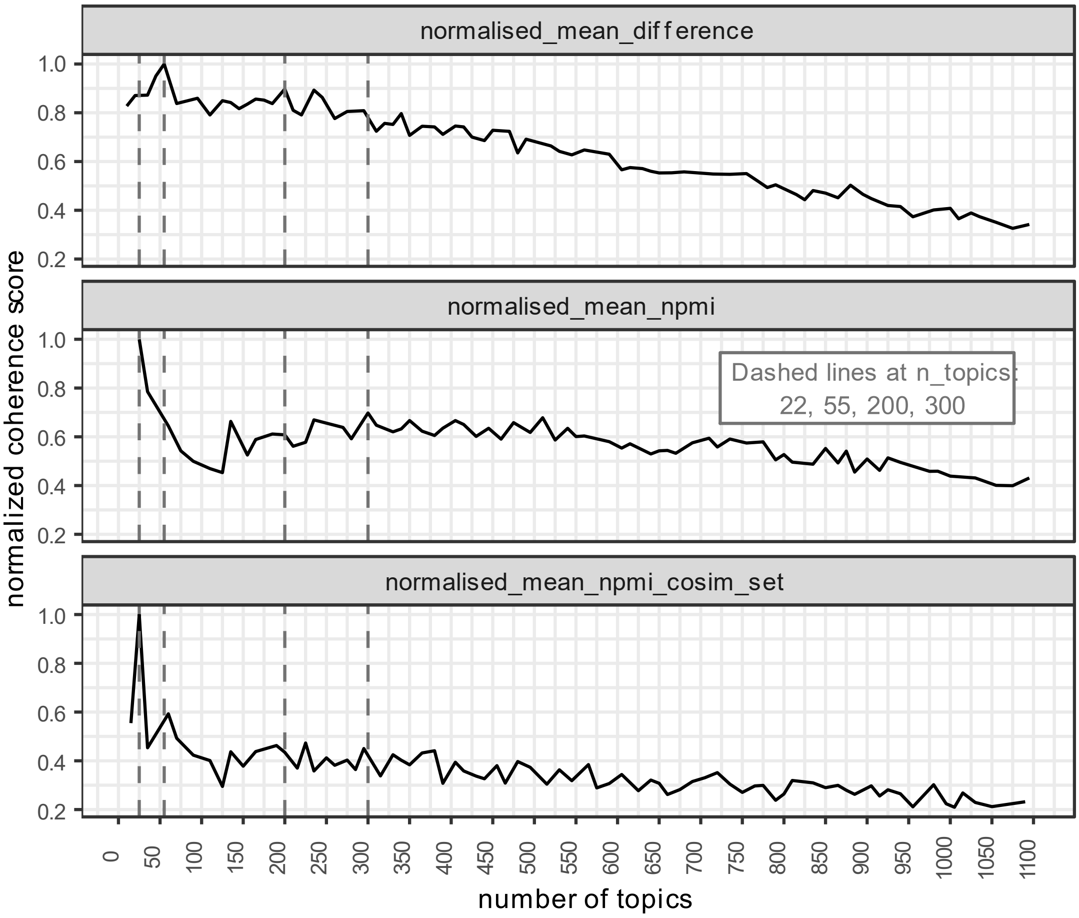


Figure 6-2: Normalized coherence metrics for a varying number of topics based on Wikipedia reference corpus; vertical dashed lines mark peaks indicating potentially optimal numbers of topics proposed by different metrics

6.3.3. Topic trends

There are 137 hot topics, of which the 15 topics with the strongest positive trends address specific technical fields revolving around the following superordinate themes: electrical energy storage, fuel cells, photocatalytic hydrogen production, nanotechnology, chemical catalysis, digital network communication, motion energy harvesting, sustainable concrete, biofuels, optimization, and modeling. Generally, the topics tend towards materials science. Table 6-1 lists information on the 15 topics with the strongest positive trend. Figure 6-3a visualizes the topic trends of the top 5 hot topics. Details on p values and the linear slopes of the trend lines are available in the Appendix A4. The p values for the slopes are all below p = 1e-12 and indicate the significance of the trends.

The topics with the highest abundance include topics speaking of life cycle assessment, heating systems, and urbanization. Table 6-2 lists information on the highly abundant topics. Four topics with high abundance also belong to the group of topics with the strongest positive trends (see Table 6-1). Those address energy storage, catalysis, building materials, and general aspects concerning optimization. The three additional topics without such overlap address: sustainable urbanization at city and neighborhood scale at rank 2, life cycle analysis with a focus on environmental impacts at rank 3, and heating systems including cooling options at rank 6.

There are 163 cold topics, of which the 15 topics with the strongest negative trends address a mixture of aspects regarding sustainable development and related economic, environmental, and political issues from a practical and theoretical perspective. This includes issues of international cooperation and trade, legislation and regulation, electricity markets, economic growth and quality of life, rural areas, agricultural systems, and forestry. Also, nuclear energy is among the cold topics. Table 6-3 lists information on the 15 coldest topics with the strongest negative trend. The p values for the slopes are all below p = 1e-6 and indicate the significance of the trends. The topic trends of the top 5 cold topics are visualized in Figure 6-3b.

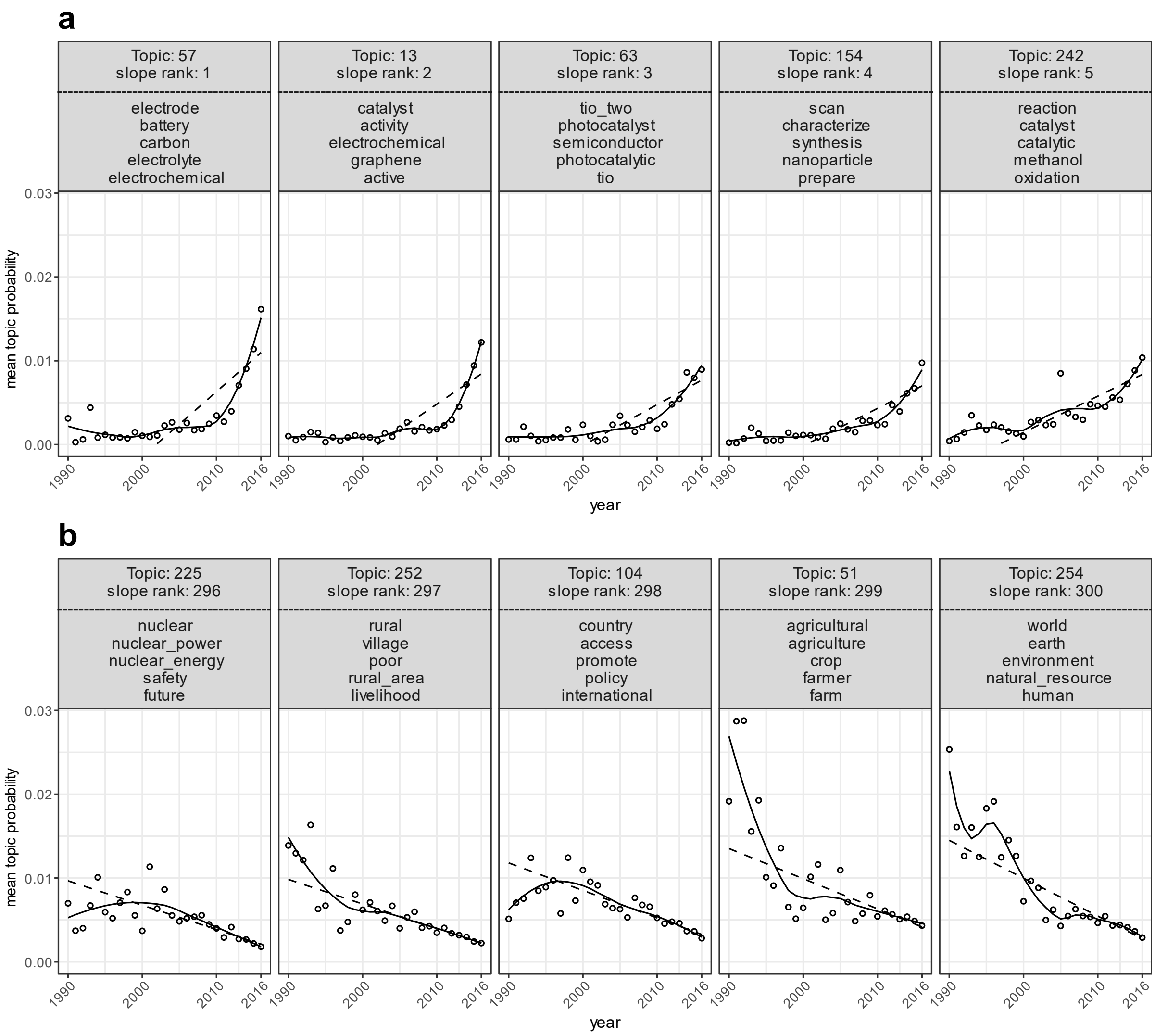


*Figure 6-3: Topic trend plot; the 5 topics with the strongest positive trend (**a**) or strongest negative trend (**b**); the slope rank of 1 indicates that the slope of the linear trend line has the highest overall value and a rank of 300 indicates the lowest value; dots represent the mean topic probability per year; the solid lines show AICc-optimized LOESS-smoothed trend lines; the dashed lines show the linear trend lines based on fitting linear models on the topic probabilities per year (not the mean values); since publication rates increase over the years (see Figure 6-1b), the recent years have a stronger influence on the linear trend lines than earlier years*

Table 6-1: Hot topics with the strongest positive trend; topics equal to or above the 95% quantile regarding the slope of the linear models; topics are clustered according to superordinate themes; the order of themes follows the topic with the highest rank belonging to a theme; rank 1 indicates the topic with the strongest positive trend

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
57	1	Electrical energy storage	Materials for electrochemical energy storage via batteries or supercapacitors	electrode, battery, carbon, electrolyte, electrochemical, cycle, cell, cathode, energy_storage, low_cost, electrode_material, report, anode, discharge, lithium, exhibit, supercapacitor, material, redox, graphene
13	2	Fuel cells	Materials for catalysis in fuel cells	catalyst, activity, electrochemical, graphene, active, electrocatalyst, cobalt, efficient, surface, exhibit, highly, stability, report, electrode, platinum, fuel_cell, oxidation, active_site, superior, catalytic
63	3	Hydrogen production	Photosensitive materials and photocatalysis for water splitting	tio_two, photocatalyst, semiconductor, photocatalytic, tio, water_splitting, visible_light, photo, cds, exhibit, photocatalysis, degradation, electron, solar_energy, dye, light, photoanode, band, photocurrent, report
154	4	Nanotechnology	Synthesis of nanomaterials	scan, characterize, synthesis, nanoparticle, prepare, sample, characterization, technique, synthesize, zno, obtain, confirm, property, morphology, precursor, material, ion, x_ray_diffraction, observe, oxide
109	12	Nanotechnology	Properties of materials	material, structure, property, nanomaterial, molecule, bond, nano, functional, compound, shell, sulfur, molecular, formation, exhibit, surface, unique, excellent, electron, report, layer
262	15	Nanotechnology	Structure of nanomaterials	particle, polymer, nanoparticle, nanocomposite, preparation, fabrication, powder, size, prepare, porous, spray, synthesis, matrix, agent, formation, poly, highly, silica, simple, rgo
242	5	Chemical catalysis	Chemical catalysis for various types of reactions	reaction, catalyst, catalytic, methanol, oxidation, ligand, conversion, complex, compound, intermediate, selective, catalysis, acid, synthesis, yield, oxygen, chemical, highly, metal, molecular

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
255	6	Digital network communication	Wireless sensor networks and real-time data for energy applications	algorithm, node, power, network, wireless, transmission, protocol, energy_harvesting, user, communication, technique, sensor, sensor_node, spectrum, data, scheme, channel, battery, maximize, distribute
111	7	Mechanical energy harvesting	Triboelectric nanogenerator and piezoelectric effect for small scale applications	mechanical, power, teng, powered, harvest, device, motion, vibration, energy_harvesting, sensor, flexible, output, generate, electrical, circuit, electronics, power_source, magnetic, drive, piezoelectric
125	8	Sustainable building materials	Alternative blendings or replacement materials for cement	concrete, cement, brick, material, aggregate, strength, fly_ash, property, durability, mortar, compressive_strength, binder, block, sand, produce, lime, replacement, clay, replace, specimen
253	9	Biofuels	Biofuel from algal biomass	biodiesel, microalgae, algae, biodiesel_production, lipid, cultivation, algal, yield, produce, feedstock, culture, microalgal, transesterification, nutrient, biofuel, oil, fuel, potential, algal_biomass, content
251	10	Biofuels	Production of biomethanol by fermentation of biomass	fermentation, sugar, pretreatment, glucose, enzyme, yield, obtain, cellulose, hydrolysis, produce, lignin, substrate, lignocellulosic_biomass, g_l, pulp, carbohydrate, biomass, pretreated, ethanol, acid
172	13	Biofuels	Bio-based materials from lignocellulosic feedstocks	extraction, separation, solvent, extract, acid, lignin, recovery, cellulose, liquid, leach, water, yield, ionic_liquid, compound, chemical, surfactant, step, distillation, separate, recover
74	14	Biofuels	Biogas production from anaerobic digestion	bioga, anaerobic_digestion, produce, methane, manure, sludge, biogas, fertilizer, substrate, bioga_production, digestate, biomethane, organic_waste, food_waste, digester, bioga_plant, anaerobic, digestion, biogas_production, compost
90	11	Modeling and optimization	Optimization models and algorithms for power systems operation and markets	optimal, optimization, optimize, constraint, minimize, algorithm, objective, maximize, solution, scheduling, multi_objective, optimization_model, solve, minimization, formulate, objective_function, search, simultaneously, trade, genetic_algorithm

Table 6-2: Highly abundant topics; topics equal to or above the 95% quantile regarding the cumulative sum of topic probability (quantile is based on topics with positive slope only); rank 1 indicates the topic with the highest cumulative sum; topic marked with an asterisk also belong to the topics with the strongest positive trend (see Table 6-1)

Topic no.	Abundance rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
57*	1	Electrical energy storage	Materials for electrochemical energy storage via batteries or supercapacitors	See Table 6-1
100	2	Urbanization	Cities, districts, and urban planning	city, urban, urban_area, urban_development, urban_planning, urbanization, urban_metabolism, urban_form, urban_sustainability, neighbourhood, district, sustainable_urban, density, urban_environment, urban_design, sustainable_urban_development, residential, scale, urban_ecosystem, spatial
276	3	Life cycle assessment	Environmental life cycle assessment with focus on carbon footprints	lca, environmental_impact, impact, life_cycle_assessment_lca, life_cycle, impact_category, life_cycle_assessment, emission, environmental_performance, stage, global_warming_potential, gwp, functional_unit, assess, environmental_burden, category, environmental, impact_assessment, perform, phase
242*	4	Chemical catalysis	Chemical catalysis for various types of reactions	See Table 6-1
90*	5	Modeling and optimization	Optimization models and algorithms for power systems operation and markets	See Table 6-1
30	6	Heating and cooling	Low temperature heating, cooling and efficiency technologies	heat, cool, heating, heat_pump, temperature, cooling, thermal, fluid, performance, heat_exchanger, heating_system, waste_heat, heat_recovery, absorption, air, heat_transfer, operate, low_temperature, cycle, condenser

Topic no.	Abundance rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
125*	7	Sustainable building materials	Alternative blending or replacement materials for cement	See Table 6-1

Table 6-3: Cold topics; topics equal to or below the 5% quantile regarding the slope of the linear models; rank 300 indicates the topic with the strongest negative trend

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
254	300	Sustainable development	Global developments of humanity and natural resource use	world, earth, environment, natural_resource, human, future, global, sustainable_development, resource, energy_resource, man, population, planet, nature, humanity, today, problem, life, population_growth, future_generation
280	291		Development in Asia[4]	sustainable_development, promote, japan, environmental_protection, put, forward, comprehensive, progress, economic_development, promotion, utilization, japanese, coordination, government, national, realize, establishment, protection, country, developmental
51	299	Agriculture	Production of food crops and the extent of using agrochemicals	agricultural, agriculture, crop, farmer, farm, farming, organic, input, agricultural_production, food, cultivation, pesticide, productivity, crop_production, production_system, agricultural_system, fertilizer, farming_system, intensive, agroecosystem
104	298	International cooperation	International technology transfer and financial support mechanisms	country, access, promote, policy, international, support, government, incentive, mechanism, priority, market, technology_transfer, clean_development_mechanism, institution, lack, domestic, finance, encourage, provision, experience
252	297	Rural areas	Livelihood and development of rural communities	rural, village, poor, rural_area, livelihood, people, local, traditional, income, district, settlement, poverty, region, area, rural_development, access, indigenous, situation, population, rural_community
225	296	Nuclear energy	Potentials and risks of nuclear power	nuclear, nuclear_power, nuclear_energy, safety, future, japan, nuclear_power_plant, korea, risk, disaster, energy_source, electricity, fossil_fuel, option, korean, plan, safeguard, today, energy_mix, century
10	289	Nuclear energy	Nuclear energy technology	reactor, fuel, fuel_cycle, core, fusion, uranium, fast_reactor, spend, advanced, safety, plutonium, nuclear_energy, reprocess, cycle, neutron, thorium, nuclear, nuclear_fuel, lwr, nuclear_fuel_cycle

[4] The top topic terms refer to Japan, however, examining the abstracts associated with the topic showed that the topic addresses the geographical context of Japan including, e.g,. China

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic
207	295	Population	Quality of life in the context of population growth	population, people, live, world, life, grow, century, billion, planet, today, society, billion_people, poverty, living, quality_life, health, decade, bring, old, global
31	294	Welfare	Welfare effects of economic growth and green growth	economy, economic, growth, employment, economic_growth, gdp, economic_activity, job, welfare, income, economics, wealth, decoupling, country, social, industrial, labor, green_growth, natural_resource, create
161	293	Human environment systems	Relationship between human activities and ecosystems	human, natural, ecosystem, nature, ecological, biological, human_activity, relationship, organism, biophysical, matter, theory, natural_capital, life, resilience, human_society, biosphere, natural_environment, regenerative, environment
185	292	International economic relations	International trade with a focus on the USA and Asia[a]	country, trade, domestic, export, import, international, world, global, cooperation, economic_development, asia, usa, asian, developed_country, nation, economy, foreign, commodity, international_trade, trading
221	290	Regulation	Legislation and institutional authority	regulation, law, regulatory, government, legal, institutional, institution, international, rule, political, act, public, legislation, policy, protection, authority, state, reform, effort, national
85	288	Turkish energy system	Potentials and resources of the Turkish energy system	turkey, renewable_energy_source, fossil_fuel, country, energy_demand, import, renewable_energy, energy_source, renewable_energy_resource, domestic, grow, world, energy_supply, energy_resource, potential, rapidly, turkish, renewable_source, renewable, supply
49	287	Energy markets	Restructuring of electricity markets and competition	market, industry, competition, reform, producer, sale, competitive, electricity_market, competitiveness, restructuring, create, price, sell, revenue, trading, promote, demand, enter, expansion, government
217	286	Forestry	Forest management for biomass production	forest, wood, forestry, timber, harvest, forest_biomass, forest_management, harvesting, management, wood_product, log, deforestation, finland, forest_resource, woody_biomass, fire, manage, forest_ecosystem, forest_product, conservation

6.3.4. Inter-topic distance and thematic fields

The topics with a positive trend may be clustered into four major thematic fields highlighting the general topic (dis-)similarity. The inter-topic distance presented in Figure 6-4 is independent of the prevalence of topics. It merely shows the content-related distance (see also section "Materials and methods"). The clustering dendrogram, which is provided in Appendix A4, suggested to partition into the following clusters: (1) low-carbon transitions and decision-making, (2) monitoring and optimization, (3) materials science and process engineering, and (4) (renewable) power systems. While highlighting thematic fields, Figure 6-4 also provides a more general overview of topics with a positive trend that is not limited to the top trends as the results of the previous section.

6.3.5. Topic network and topic communities

Connections between topics and resulting topic communities were studied by means of the network generated from the top 10 topics per document with the co-occurrence threshold set to the 50% quantile. The reasoning for selecting this network by manual inspection from the variation of networks was to study a network that potentially includes broad thematic connections that, at least, have a medium connection strength. Figure 5 shows the network with a focus on topic communities and betweenness centrality scores. The figure only shows a selection of the strongest connections between individual topics for providing a general impression of the interconnectedness. A detailed analysis of individual connections is not provided here and might be the subject of future studies. The emerging topic communities discussed below were similar in meaning across the generated network variations. Hence, the information provided on topic communities can be considered robust within the range of the tested parameters. However, the betweenness centrality scores changed with varying co-occurrence thresholds. The findings based on the analysis of these scores are only valid for the specific parameter settings used here.

Inspecting the labels of the network community vertices (Figure 6-5) reveals four topic communities A to D addressing biofuels, materials science, renewable power systems, and sustainability transitions. *Community A* links topics about feedstocks and biological process engineering for biofuels to reduce greenhouse gas emissions. In this context, a vital task of process engineering is optimizing operational performance for achieving the maximum yield. Target products are biomass or liquid and gaseous biofuels, including hydrogen. *Community B* focuses on materials science for different fields of application. This community involves the highest number (8 out of 15) of topics with strong trends (Table 6-1) in comparison to other communities. Aspects covering chemical synthesis and catalysis in general, thermal treatment, or peculiarities at the nanoscale are linked to more specific fields of application such as photochemistry and photonics, electrochemistry, building, or composite materials.

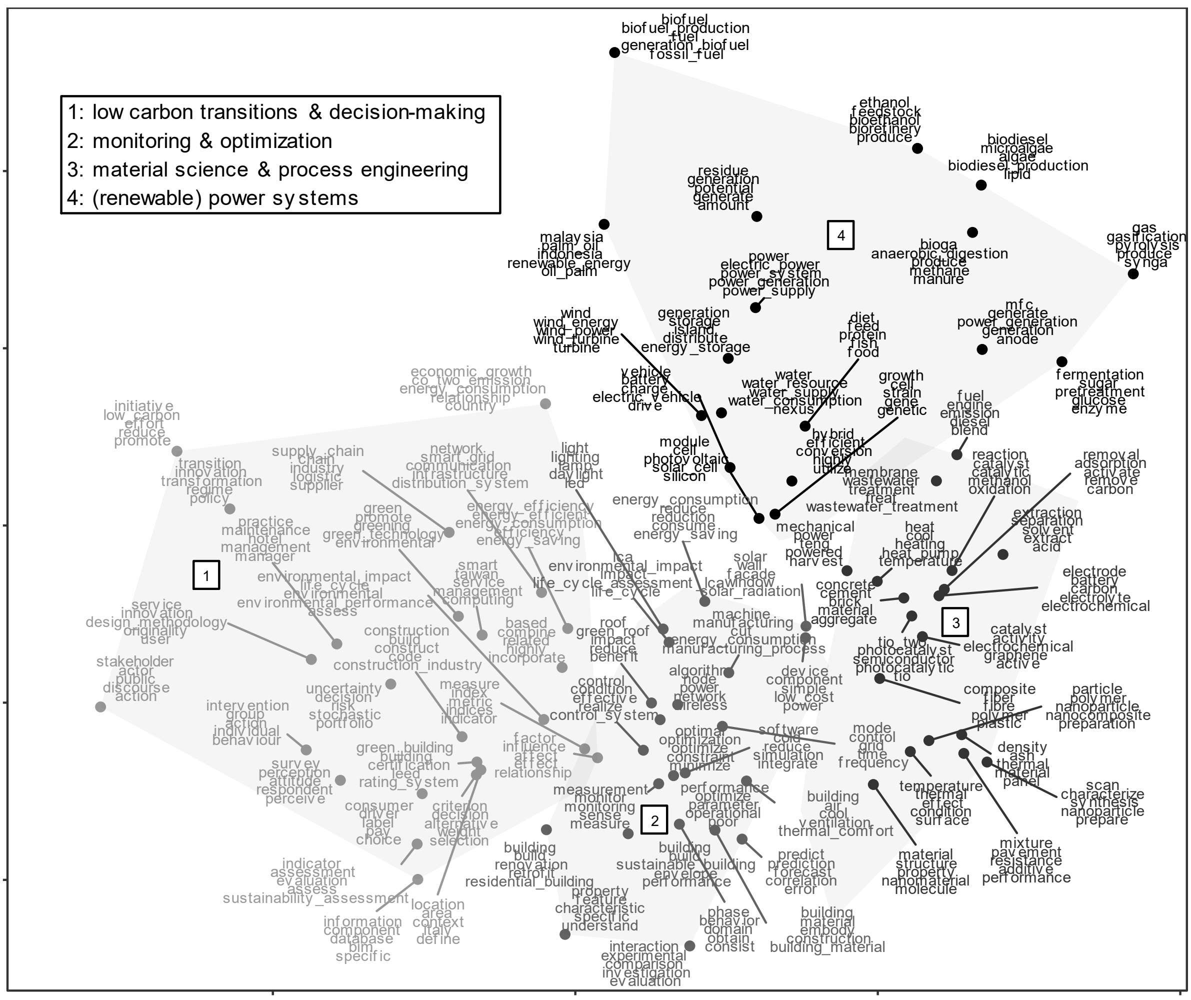
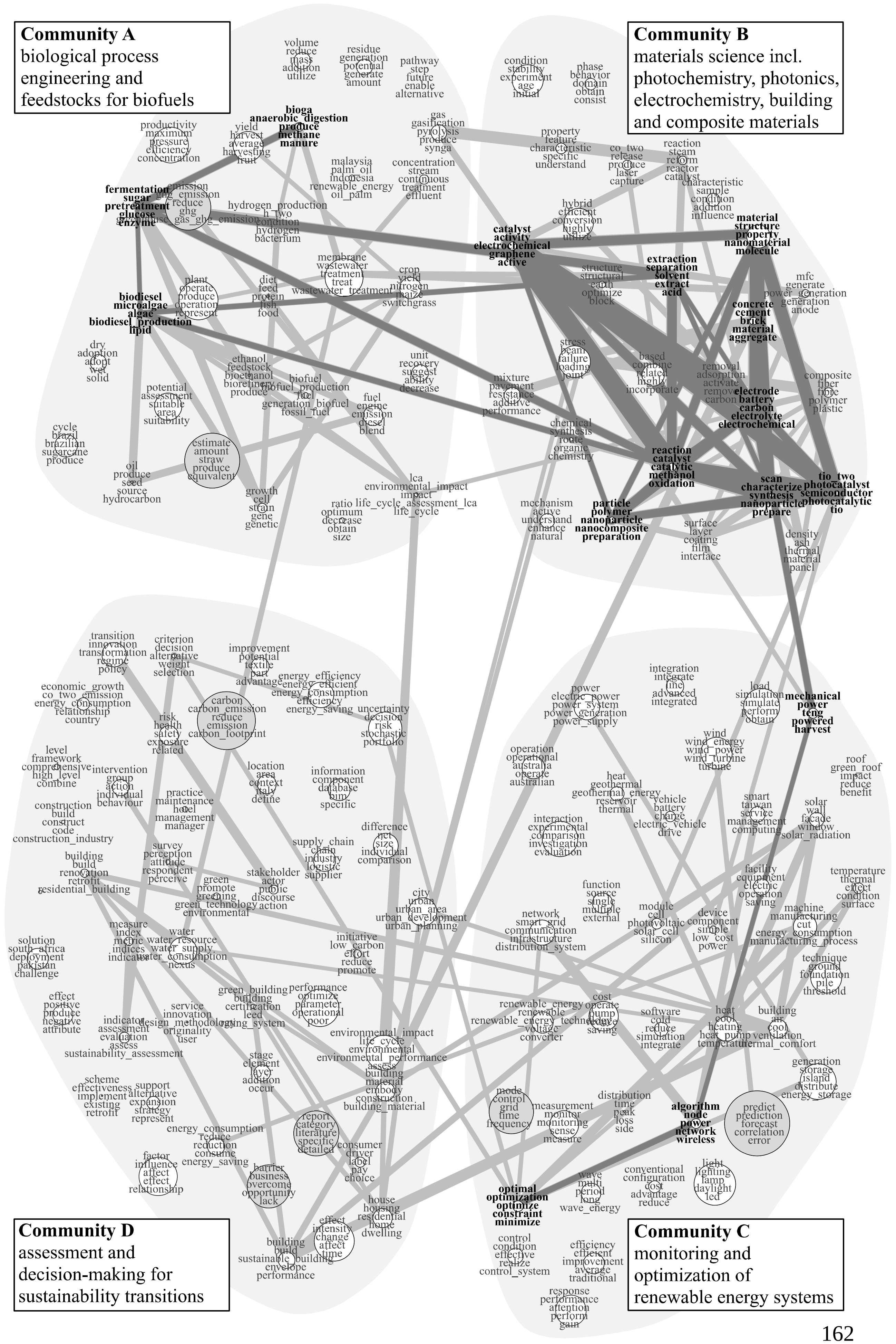


Figure 6-4: Inter-topic distance or principal coordinates plot of the hot topics, i.e., topics with a positive trend, showing the top 5 terms per topic; for better readability, only the top 60% of these topics are shown; main thematic gradients or differences may be identified by inspecting the topics along the principal coordinates from left to right and from top to bottom; terms are colored from light to dark grey according to their membership to clusters resulting from clustering the coordinates; the 4 cluster areas indicating main differing thematic fields are highlighted in grey; for avoiding text overlapping several topic terms are moved from their original positions, which are shown as dots, to which they are linked via a straight lines

Community C links topics concerned with monitoring and optimization of renewable power systems considering technologies such as wind, photovoltaic, or geothermal energy, but also electric vehicles. For this dynamic task, the topics of this community address digital monitoring solutions for analyzing, simulating, and forecasting production and demand in order to optimize operational performance, e.g., in smart grids. *Community D* revolves around assessment and decision-making for sustainability transitions. This community does not include any of the topics with the strongest positive trends (Table 6-1). The community involves setting up transition initiatives, strategies, or frameworks. These activities are informed by life cycle assessments regarding environmental impacts from energy consumption, especially in terms of carbon footprints, as well as water consumption. The community particularly considers consumer decisions in an urban context as well as business development, e.g., regarding supply chains or business barriers and opportunities.

Analyzing betweenness centrality scores provides indications concerning key bridging topics in the network. Topics dealing with simulation and forecasting, especially in the context of controlling electric grids, have a strong interconnecting role. This also applies to carbon footprints and climate change mitigation. In this context, business opportunities and barriers are other cohesive themes. Appendix A4 provides further details on betweenness centrality scores and the topics with high scores.

Figure 6-5: Topic network highlighting four topic communities A to D that emerge from Louvain network clustering; network generated by limiting to top 10 topics per document and setting minimum threshold for co-occurrence to the 50% quantile (see section "Methods for topic model analysis" for details); plotting parameters: (i) line width of connections proportional to co-occurrence, (ii) plot limited to the top 1.5% strongest connections, (iii) topics with strongest positive trends (see Table 6-1) in bold letters, (iv) graph shows two link types, connections are plotted in dark grey when both topics of a pair have a strong positive trend; connections are plotted in light grey if only one of the topics has a strong positive trend, (v) vertex size proportional to betweenness centrality, (vi) top 5% vertices regarding betweenness centrality (see Appendix A4.3) marked in grey


Community A
biological process engineering and feedstocks for biofuels
Community B
materials science incl. photochemistry, photonics, electrochemistry, building and composite materials
Community C
monitoring and optimization of renewable energy systems
Community D
assessment and decision-making for sustainability transitions
bioga anaerobic_digestion produce methane manure
fermentation sugar pretreatment glucose enzyme
biodiesel microalgae algae biodiesel_production lipid
catalyst activity electrochemical graphene active
material structure property nanomaterial molecule
extraction separation solvent extract acid
concrete cement brick material aggregate
electrode battery carbon electrolyte electrochemical
reaction catalyst catalytic methanol oxidation
scan characterize synthesis nanoparticle prepare
tio_two photocatalyst semiconductor photocatalytic tio
particle polymer nanoparticle nanocomposite preparation
mechanical power teng powered harvest
algorithm node power network wireless
optimal optimization optimize constraint minimize

6.4. DISCUSSION

The selected LDA model with 300 topics provides indications on the strongest topic trends, inter-topic distances or general thematic areas, and topic communities in the research field dedicated to sustainable energy. Regarding the high publication rates (Figure 6-1), this research field can be considered as dynamically growing. This is encouraging considering the severe global sustainability problems caused by the current energy system [5]. For solving these problems, it will be crucial that energy research further contributes to a transformation towards sustainability and advances its research structure.

In this context, the following sections discuss selected results of this study critically. The patterns recognizable in the results are starting points for various interpretations that emerge when relating these patterns to or underlining them with selected literature, including but not limited to some of the articles reviewed in the "Background" section. As indicated already, this study can confirm several of the trends summarized in the "Background" section, show some in a different light, identify new trends, and point out blind spots. For example, for electricity generation, the discourse clearly focuses on photovoltaic and wind energy, whereas highly cited reviews dedicated to sustainable energy still discuss conventional options [32,33,34,35]. Further, this study can confirm the dominance of batteries for electrifying the transportation sector [35, 40, 63, 68]. Interestingly, regarding fuel cells, the discourse tends to associate them with biofuels rather than hydrogen, which indicates that a comparably low realization potential is ascribed to the vision of a hydrogen economy [33, 57,58,59,60,61,62]. This study further detects the silent rise of research on mechanical energy harvesting as a potentially relevant new trend. Regarding blind spots, this study validates the concerns that have been anticipated already, e.g., regarding the availability of material resources for energy transitions [81, 149,150,151], and points out a lack of attention to the role and structure of different end-use sectors. Beyond dealing with these thematically specific trends, this study can, with its holistic approach, show that the discourse is moving away from the multi-faceted concept of sustainability to a more narrow technological perspective.

It should be noted again that the topic model serves for identifying average trends regarding the increase or decrease of attention to specific topics. Thus, if certain themes seem to be missing in the academic landscape, it can only be concluded that the majority of articles do not refer to these themes, but not that none refers to them.

Considering the hybrid nature of the field involving energy research and sustainability science, the discussion addresses these two fields separately. The first part of the discussion is organized along key energy system stages: conversion, storage and distribution, markets, and end-use sectors [152,153,154]. The second part provides reflections from an overarching sustainability perspective. Acknowledging the various conceptualizations of sustainability [13, 14, 155,156,157,158,159], this study focuses on selected elements: justice between generations, societal sub-systems, levels or scales, and the operational principles of strong sustainability.

6.4.1. Energy system

If the trends identified via topic modeling became reality, the future energy system would be highly electrified using photovoltaic and wind energy but would also intensively make use of bioenergy (compare: cluster 4 in Figure 6-4; community C in Figure 6-5; hot topics in Table 6-1). This observation is largely in line with the trends in the literature highlighted in the "Background" section [30,31,32,33,34,35]. The research field seems to be distancing itself from technologies with high damage potential in the case of failure. For instance, expanding deep geothermal energy might be connected to high risks [33, 34, 37]. This might explain why geothermal energy only receives an accompanying role here (only present in community C in Figure 6-5 but not in Figure 6-4 using a threshold regarding the strength of trends). Furthermore, topics on nuclear energy or fossil power plants, e.g., in combination with CCSU, which are part of several reviews addressed in the "Background" section [32,33,34,35], did not emerge from this study as prominent topics (compare: cold topics 225, 10 in Table 6-3). Instead, the results of this study suggest that the focus lies on improving technologies with potentially lower direct risks. The discourse seems to perceive the basic renewable energy conversion as a mastered task and now traverses on the learning curve to a phase focusing on optimization (compare: topic 90 in Table 6-1, community C in Figure 6-5). This involves more detailed technological development and physico-chemical advancement of materials and processes. This study indicates that, in the near future, improvements might be expected, in particular, for biotechnology and photovoltaics (compare: community A and community B in Figure 6-5).

While advancing conversion technologies with low direct risks, long-term or latent risks connected to the upstream or downstream energy system stages might require greater attention and accompanying strategies. Due to the urgency to decarbonize the energy system and the renewable energy potential, the recent focus on advancing energy conversion is justifiable. However, the material basis for renewable power generation units seems to be taken for granted and potential social or environmental conflicts arising from their construction and operation have not been prominent topics. This study shows that current research already deals with advancing material properties in the production phase and, to a certain extent, considers life cycle assessment in connection with biomass from microalgae and building materials (compare: community A and community C in Figure 6-5). However, research does not seem to apply a comprehensive life cycle perspective for discovering latent risks. Furthermore, the topic model does not identify direct attention to the supply and recycling of materials, especially metals, for energy systems. Several studies, including a few of the reviews screened for the "Background" section, underline the relevance of these issues [81, 149,150,151]. However, the results of this study indicate that these topics generally receive low attention. Future research on energy systems might be broadened and based on a more integrated energy and materials perspective.

In parallel to research on energy conversion, intensive research on energy storage and non-fossil fuels contributes to establishing renewable energy systems. The research on battery or supercapacitor technologies advances crucial elements of future electric grids, which need to be capable of integrating and balancing fluctuating renewable energy generation at large scale. The reviews screened for the "Background" section [35, 38,39,40] as well the topic model highlight the efforts made in these fields (compare: hot topics 1, 109 in Table 6-1). Even more challenging might be decarbonizing the transportation sector using small storage units and alternative fuels. Concerning the assumption that batteries might precede fuel cells in the near future [35, 39], the results of this study point in the same direction (compare: rank of hot topics 57 and 13 in Table 6-1). However, they also indicate significant progress in fuel cell technology. The hot topics identified here suggest that the fuel converted in these cells will probably not be hydrogen from electrolysis but biofuels (compare: hot topics in Table 6-1, community A in Figure 6-5). This assumption results from the observation that topics addressing a large-scale hydrogen infrastructure, which is a major bottleneck for establishing a hydrogen economy, do not emerge as prominent topics. Instead, the topic model reveals a strong focus on bioenergy. Although the availability of sustainable biomass is limited [160], the progress of biotechnology for different feedstocks identified here could boost the biofuels pathway. In line with other studies [161], this indicates that it is unclear whether the transportation sector will follow the bioenergy or battery pathway, or which type of mix thereof. This emphasizes that scenarios and decision-making on the future of transportation are very sensitive and need to take into account the uncertainty regarding the learning curves of various technologies.

In the context of complex renewable energy systems, digital technologies and artificial intelligence for optimizing performance are already incorporated as future-oriented solutions and will require continued attention. The main application of digital technologies identified here is the optimization of renewable energy systems (compare: hot topic 255 and community C in Figure 6-5). In this field, digitalization is expected to have a net positive effect regarding climate change mitigation [162] and promises further improvements for planning, operating, and managing energy systems including the various end-use sectors [162,163,164,165,166,167,168,169,170]. However, potential negative effects need to be taken into account such as rebound effects, e.g., in the transportation sector [167, 171], or socio-economic concerns regarding the replacement of human labor by machines [167]. With the increasing digitalization of the energy system, accompanying strategies that support the beneficial effects and decrease the adverse effects will be crucial [162, 167, 172].

While being concerned with technological progress, the academic field seems to perceive the task of establishing energy markets as an operational or political one. A possible interpretation of the prominence of optimization methods (compare: hot topics 90, 255 in Table 6-1, community C in Figure 6-5) and the emergence of business environments as a bridging topic (compare: topic with high betweenness centrality at the bottom of community D in Figure 6-5) is that the research field takes for granted that energy markets are functioning reliably. Efforts for optimizing business operations would probably be less evident if the reliability of markets would be questioned fundamentally. Also, the observation that topics on electricity markets and regulation receive declining attention strengthens this assumption (compare: cold topics 49, 221 in Table 6-3). A possible interpretation is that, in the context of increasing liberalization [173], science tends to see the responsibility of establishing markets with politics [35]. However, establishing decentralized renewable energy markets that fit the different regional requirements is challenging [173, 174]. Therefore, strengthening cooperative research between science and politics might be reasonable [174]. Such research efforts might examine, in particular, the social, economic, and political struggles of implementation for facilitating the establishment of sustainable markets. Further, in the context of increasing decentralization, the declining attention to international trade, e.g., in global energy markets, appears logical (compare: cold topics 104, 185 in Table 6-3). However, considering the uneven global distribution of material resources and possible political or economic tensions, the international resource markets might become a decisive factor for developing the future energy infrastructure and, as this and other studies highlight, require increased attention [175, 176].

Regarding the end-use stage, research focuses on energy end-use by residents in urban areas (cluster 1, 4 in Figure 6-4; community B and community C in Figure 6-5; abundant topics in Table 6-2). Green buildings and electric vehicles are addressed as two key end-use sectors associated with the technical urban environment of individual consumers. Another very prominent topic is concerned with harvesting mechanical or motion energy (hot topic 111 in Table 6-1). The latter is identified here as a growing research field that does, however, not appear prominently in review articles on sustainable energy yet such as the ones referred to in the “Background” section [30,31,32,33,34,35]. The above topics indicate that research on sustainable energy pays increasing attention to urban living environments and, thus, is connecting to the level of individual consumers. A part of the research is also concerned with raising consumer awareness via product labeling (compare: bottom of cluster 1 in Figure 6-4 or bottom of community D in Figure 6-5). However, in sum, technological research seems to prevail. For instance, as discussed above, efforts for increasing sustainability in the transportation sector are primarily seen in improving fuel technologies. This and other studies show that systemic or behavioral energy-saving potentials that do not primarily stem from advancing individual technologies have received comparably low attention, e.g., traffic planning, improving public transport systems, or increasing vehicle occupancy [34, 97, 161] (compare: no corresponding links in community D in Figure 6-5). This seems surprising considering the high relevance of urbanization identified (compare: abundant topic 100 in Table 6-2). A possible interpretation is that research has not yet sufficiently understood the complex modern urban systems and transportation systems for establishing a consolidated research structure. More research will be needed for unraveling this complexity and understanding the interactions between these fields.

The majority of energy-intensive industries receive comparably low attention, except the cement industry and, to a certain extent, the manufacturing industry (compare: hot topic 125 in Table 6-1, community D in Figure 6-5). Several energy-intensive industrial branches that have significant carbon dioxide emission reduction potentials, especially the steel sector [177, 178], are not among the prominent topics. Only non-metallic building materials, especially concrete, receive high attention. Although a similar potential exists in the steel industry [178], a reason for the cement industry standing out might be its potentials at the material level. The cement industry offers comparably high potential for reducing carbon dioxide emissions, e.g., by using replacement materials [178,179,180]. Due to the tendency of the discourse towards materials science, potentials connected thereto might receive higher attention than process technology options. This might be an indication that, to a certain degree, research distances itself from the traditional industry. Only one of the topics in Figure 6-4 (compare: top of cluster 2) directly refers to another industrial branch, i.e., the manufacturing industry, but is rather connected to the micro-level of energy-efficient machines than to a meso- or macro-perspective as applied, e.g., in the field of industrial ecology [181, 182] or circular economy [183, 184]. Also, only a few reviews presented in the "Background" section deal with industry as part of the energy system [33, 63]. Further, the ones that do so only apply a technological perspective regarding decarbonization opportunities. These observations emphasize that future research will have to understand better the different industrial sectors and their interactions with the energy system for leveraging decarbonization potentials and for supporting the industrial transition towards sustainability. In this context, research should not only focus on the production phase in value chains. This proposal is in line with other studies calling for a more integrated perspective on sustainable product-service systems that consider the interplay of consumers, i.e., the users of energy-consuming products, with the phases of product design, manufacturing, and recycling [185].

6.4.2. Sustainability

This study indicates that research on sustainable energy is navigating towards a technology-oriented perspective (compare: hot topics in Table 6-1) and is moving away from the normative concepts connected to sustainability and sustainable development that have initially motivated this research field (compare: cold topics in Table 6-3). This becomes apparent when examining the various cold topics related to sustainable development. An alternative interpretation would be that the normative concepts have been integrated to an extent that makes the need for explicitly referencing conceptual ideas obsolete. However, based on the following discussion, this study tends to conclude that conceptual ideas of sustainability actually have decreasing influence.

Research on sustainable energy is clearly concerned with inter-generational justice, whereas the attention to intra-generational justice seems less apparent. The strong focus on renewable energies represents efforts to ensure the availability of energy while limiting the negative effects of climate change. These efforts do not guarantee to secure a livelihood for future generations but have the potential to contribute to it. However, as shown in the previous section, the attention to depletable material resources is low. The physical availability of raw materials might not be the major bottleneck in the near future for establishing a low-carbon economy, whereas environmental, social, and economic issues of resource extraction seem to be more relevant [150]. Therefore, the latter might deserve greater attention. Turning to intra-generational justice, there are no prominent topics addressing, e.g., energy poverty or land-use conflicts. This indicates that issues of intra-generational justice might be underrepresented. For not leaving anybody behind, research on, e.g., the relationship between developed and developing countries might be strengthened.

Regarding the systemic perspective adopted, research seems to follow a socio-technical system perspective, which might benefit from increased attention to the environmental system (compare: communities A, B, C vs. D in Figure 6-5; cold topics in Table 6-3). This study identifies a focus on infrastructural and technological systems (compare: hot topics in Table 6-1). However, topic community D also refers to several societal sub-systems, especially the economic, the social, and the government system. The consideration of operational aspects of transition processes involving these systems indicates an action-oriented research agenda, which matches the scholarly tradition of transition management for socio-technical systems (STS) [186, 187]. This match is more obvious than it would be for, e.g., the research tradition on social-ecological systems (SES) [1, 157]. While in research on SES and STS parts of the societal subsystems considered are similar, research on SES ascribes a stronger role to the ecological system. In the discourse investigated here, the environment system is considered by several topics addressing assessment of environmental footprints (compare, e.g., topic 276 in Table 6-2). However, apart from referring to such aggregated indicators, explicit considerations on specific elements of the natural system appear to be missing among the major topics. Independent of which research tradition will prevail in future research, it is vital to strengthen the focus on interactions of modern energy systems with nature for not overseeing potential harmful effects.

Although a social science perspective is clearly present in research on sustainable energy (compare: cluster 1 in Figure 6-4 and community D in Figure 6-5), it could experience a higher degree of integration with the strongly growing technological perspectives. A key indication for this can be derived by studying the four most distant thematic fields (Figure 6-4) and the communities in the topic network (Figure 6-5) in parallel. Technology-related topics from the thematic fields mix up across the topic communities. Hence, an achievement of research on sustainable energy is that research has become interdisciplinary in terms of technology. However, the majority of topics of the theme about low carbon transitions and decision-making mainly end up in one single topic community. This community incorporates aspects related to the social sciences. Since it shows weak interconnections with technological themes, there seems to be potential for improving the interdisciplinary collaboration between technological research and the social sciences. Other studies have already found that there is a lack of social science perspectives in the general field of energy research [188,189,190]. This study shows that in research on sustainable energy, the integration of the social sciences is higher but could still be improved. A starting point might be the bridging topics related to data science (compare: bottom right of community C in Figure 6-5). Data science is common to technical but also social science domains. Connecting different domains might happen based on connected data infrastructures accompanied by personal interdisciplinary exchange for making sense of, e.g., prediction models.

Regarding the levels or scales considered, the global perspective seems to fade and might be reinforced (compare: abundant topics in Table 6-2; cold topics in Table 6-3). Considering the increasing urbanization trend [191, 192], the abundance of topics dealing with urban areas seems reasonable for addressing critical sustainability problems that affect a high share of the global population. Engaging with the local level for providing insights into bottom-up developments and understanding the respective local dynamics is of significant importance. However, at the same time, successful approaches for sustainability also require an integrated global perspective and a top-down perspective [6]. This kind of aggregated perspective is necessary for avoiding isolated knowledge processes but instead integrating the valuable insights from the local level. The global perspective was key for supporting the normative sustainability agenda that is increasingly integrated into human society. In research on sustainable energy, this kind of global perspective seems to fade and might be reinforced by connecting the various available local perspectives in order to support solutions to sustainability problems, e.g., via intergovernmental cooperation and regulation.

Regarding the triad of operational principles of strong sustainability, i.e., consistency, efficiency, and sufficiency, a clear focus lies on the first two (compare: community C in Figure 6-5; abundant topics in Table 6-2). Consistency is clearly addressed through research on renewable energy technologies using non-depletable energy resources. However, as already mentioned above, more attention should be paid to the availability, consumption, and recycling of depletable material resources. Turning to the next principle, efficiency receives high attention for optimizing power systems and saving energy in the end-use sector. This principle is connected to advanced technologies that save costs while keeping the level of comfort. In contrast, the presence of the principle of sufficiency, which favors foregoing consumption instead of only optimizing it, is not as clear, although the literature has highlighted it as a necessary companion of efficiency [41, 42, 172, 193]. In summary, this indicates that research on sustainable energy has not yet integrated all the principles in a balanced way that are necessary for heading towards a steady-state-economy that is not governed by a paradigm of growth but of (sustainable) development [194].

6.5. CONCLUSIONS

This study provides a review of research on sustainable energy based on an advanced latent Dirichlet allocation topic modeling approach for detecting high-level patterns. The main overarching pattern identified is that the discourse is latently adopting a technology-oriented paradigm and is moving away from the multi-faceted concept of sustainability. The study highlights that the research field on sustainable energy is focusing on finding ways to establish and optimize renewable energy systems by reverting to materials science, (biological) process engineering, and digital monitoring and control systems. From a technological perspective, research on sustainable energy seems to keep up with technological progress and has the potential to contribute to climate change mitigation. However, given the complexity of renewable energy systems, no straightforward technological pathway could be identified. Therefore, this study recommends improving horizontal integration of the various valuable vertical research strands for preparing scientific-technological knowledge in a way that enables efficient and far-sighted decision-making. For establishing sustainable energy systems, advancing research on sustainable energy will require not only targeting the core technical energy infrastructure, for which many solutions have been proposed already, but strengthening the focus on issues that can be perceived from a holistic second-order perspective. Therefore, this study further recommends to re-strengthen a holistic ecological perspective on energy systems considering the global scale, e.g., by considering the complete material and environmental life cycle of the energy infrastructure. Beyond considering the physical dimensions of energy systems, another key recommendation of this study is to strengthen the existing links of the research field to the social sciences. This will be crucial for a balanced discourse completing the technology-orientated agenda that research has increasingly been adopting in recent decades. Extending the research scope in this way would support an explicit consideration of all societal subsystems required for a sustainability transformation.

6.6. AVAILABILITY OF DATA AND MATERIALS

The datasets generated and analyzed during the current study and the code used in the study are available in the Github repository https://github.com/manuelbickel/textility in form of an R package. The data and code are further archived in the Zenodo online library https://zenodo.org/record/2550719#.XGsmr6BCckI. The doi number is https://doi.org/10.5281/zenodo.2550718.

Due to copyright restrictions, the raw abstract texts could not be included in the dataset. However, the dataset includes the document-term-matrix used as the basis for the analysis. The dataset also includes the doi numbers of the abstracts analyzed, so that the original text data may be accessed by users with the required access rights.

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APPENDICES

A1. DOIs of the most cited review articles containing "sustainable energy" in their Abstract

The search for review articles was performed in July 2019.

10.1038/nmat2090; 10.1126/science.1137016M 10.1038/nature11475; 10.1126/science.1103197; 10.1038/nchem.2085; 10.1039/c4cs00103f; 10.1016/j.rser.2003.12.007; 10.1016/j.biortech.2009.10.017; 10.1016/j.rser.2009.06.021; 10.1126/science.1217412; 10.1016/j.rser.2010.12.008; 10.1016/j.apenergy.2009.09.026; 10.1016/j.carbon.2010.10.010; 10.1016/j.biotechadv.2011.05.005; 10.1038/nrm2698; 10.1021/es801553z; 10.1016/j.nanoen.2011.11.006; 10.1016/j.energy.2014.02.089; 10.1039/b809074m; 10.1002/anie.201306588; 10.1038/nmat4834; 10.1039/c3ee43463j; 10.1021/cr500023c; 10.1016/j.rser.2006.10.001; 10.1039/c3cs60199d; 10.1021/jz1015372; 10.1016/j.apcata.2010.06.049; 10.1016/j.rser.2010.09.018; 10.1016/j.rser.2005.12.004; 10.1002/adma.201503270; 10.1016/j.jpowsour.2006.02.054; 10.1016/j.ijhydene.2008.08.054; 10.1021/cs500070x; 10.1021/ef060097w; 10.1021/cr500232y; 10.1039/b902343g; 10.1016/j.ccr.2012.04.018; 10.1002/aenm.201600943; 10.1002/anie.201504830; 10.1016/j.ijhydene.2010.04.137; 10.1016/j.energy.2012.04.003; 10.1016/j.rser.2011.08.018; 10.1016/S1369-7021(08)70251-7; 10.1016/j.rser.2015.12.112; 10.1016/S1364-0321(02)00008-4; 10.1039/c2ra20839c; 10.1016/j.fuel.2015.10.111; 10.1111/j.1365-2486.2006.01163.x; 10.1016/0169-5347(92)90009-Z; 10.1002/cssc.201000023; 10.1002/cssc.201100571; 10.1021/acs.chemrev.6b00299; 10.1016/j.rser.2009.06.003; 10.3390/ijms9071188; 10.1098/rsta.2010.0119; 10.1039/c4ee00450g; 10.1016/j.chempr.2016.12.002; 10.1016/j.apenergy.2009.08.014; 10.1016/j.rser.2004.05.003; 10.1149/2.0151514jes; 10.1039/c1ra00839k; 10.1039/c0ee00176g; 10.1002/adma.201604563; 10.1016/j.rser.2012.12.062; 10.3390/en3050899; 10.1039/c1ee02734d; 10.1016/j.rser.2012.03.048; 10.1016/j.rser.2011.05.005; 10.1016/j.nanoen.2017.05.022; 10.1016/j.ccr.2010.06.004; 10.1021/acs.chemrev.6b00504; 10.1039/c4cs00116h; 10.1016/j.jiec.2013.07.037; 10.1002/elsc.201100225; 10.1016/j.rser.2010.09.043; 10.1016/j.mattod.2014.02.014; 10.1016/j.rser.2013.05.029; 10.1021/es800812m; 10.1039/C6TA08075H; 10.1002/aenm.201200065; 10.1016/j.rser.2009.12.003; 10.1080/07352680500316334; 10.1016/j.rser.2013.11.045; 10.1039/c5ee02474a; 10.1039/b922656g; 10.1016/j.rser.2014.09.026; 10.1016/j.rser.2011.05.003; 10.2193/2007-248; 10.1039/c4cs00223g; 10.1039/c4ta05565a; 10.1016/j.rser.2014.12.040; 10.1016/j.mattod.2015.10.009; 10.1002/adma.201601727; 10.1039/c0cs00208a; 10.1016/j.bej.2013.01.012; 10.1007/s00253-011-3394-0; 10.1002/pip.1254; 10.1038/natrevmats.2015.5; 10.1088/1758-5082/1/2/022001; 10.1016/j.tree.2009.11.007

A2. Hardware requirements

The study was performed on a standard office laptop that runs on a 2 gigahertz dual core processor with 4 threads and is equipped with 8 gigabytes of random-access memory (RAM).

A3. Technical details on statistical models and methods of investigation

A3.1 Summary of the pre-processing procedure

For standardizing the symbolic representation of individual terms several NLP steps were applied. These steps comprised: (i) harmonizing character encoding (ii) keeping only characters from the basic Latin alphabet, and (iii) unification of the representation of acronyms and of contracted negations. As an additional step for an initial reduction of noise in the data, undesired known phrases were removed, e.g., copyright information at the end of abstracts.

The next step was setting up a part-of-speech (POS) model for discarding irrelevant word classes and lemmatization of terms. Part-of-speech (POS) tagging algorithms identify the grammatical structure of sentences. For this purpose, the TreeTagger software [1–3] was used, which is made available via the koRpus package [4]. After POS tagging the text data could be limited to the word classes carrying the most relevant information, here, noun, verb, adjective, and adverb. Furthermore, POS tagging allowed simplifying terms to their lemmata. This is an important step for unification of terms. An example of lemmatization is provided below in section "Part-of-Speech Tagging" in the last sub-section "Lemmatization".

A collocation model was created for detecting n-grams, i.e., multi-word terms, to mitigate the assumption regarding the irrelevance of grammar by LDA (explanation see Section 2.4.1). Individual terms, whose co-occurrence in the corpus was statistically more than random, were bound together as collocations. It has been shown that collocation models have reasonable performance, especially for noun compounds [5]. This study limits collocation detection to nouns and adjectives. Two common statistical metrics served for assessing the co-occurrence of terms: pointwise mutual information (PMI) [6] and log-frequency biased mutual dependency (LFMD) [7]. The thresholds for binding terms were a minimum co-occurrence of 8 in the whole corpus, a PMI score of at least 1.959, and an LFMD score of at least -28.8. These values were found by an iterative process including manual screening of results of collocation models with different parameter settings. The goal was to find a model that detects sustainable_energy as a target collocation but to discard all potential collocations with worse PMI or LFMD score.

In the final pre-processing step, the vocabulary of the corpus was pruned by setting thresholds for document occurrence of terms and term length and by removing specific stopwords. Pruning consisted of (i) removing unigrams occurring in less than 3 documents or with less than 3 characters, (iii) removing irrelevant n-grams by manual screening, especially collocations including sequences of single characters originating from formulas or physical units, e.g., velocity_m_s, and (iii) removing standard stopwords, e.g., “the” or “and”, stopwords commonly used in abstracts, e.g., paper or methodology, and stopwords with high overall frequency but with low informative value or distinguishing meaning for the present study, e.g.,“energy” or “system”

A3.2 Part-of-Speech Tagging

The following summary is based on [1–3, 8–10].

Part-of-speech (POS) tagging algorithms predict the roles of words within a sentence. This information may be used to filter out the relevant POSs, e.g., only adjectives and nouns, to reduce noise in the data with respect to the focus of analysis and, thus, to increase accuracy. Furthermore, POS tagging serves as the basis for lemmatization. Lemmatization turns inflected words into their uninflected form, i.e., their lemma. Hence, words with the same meaning are mapped to a single textual item. This increases the analytical accuracy for this specific meaning.

There is a variety of probabilistic taggers that use Markov models to solve the task of POS tagging. Given a sequence of words w_n that are annotated with the tags t_n the probability to be estimated by a POS tagger is:

$$P_{POS} = P(w_1, \dots, w_n, t_1, \dots, t_n) \qquad \text{Eq. (A.1)}$$

Using Bayes’ theorem recursively under the strong but practicable assumption, which makes the model a Markov Model, that the probability of a word w_n only depends on t_n and the probability of t_n only depends on the POSs of the k preceding words this probability may be estimated by the following model as:

$$P_{POS} = \prod_{i=1}^{n} P(w_i|t_i) P(t_i|t_{i-k}, \dots, t_{i-1}) \qquad \text{Eq. (A.2)}$$

where $P(w_i|t_i)$ is the conditional probability of the occurrence of the word w_i conditioned on the occurrence of the tag t_i and $P(t_i|t_{i-k}, \dots, t_{i-1})$ is the conditional probability of the tag t_i

conditioned on the occurrence of the k preceding tags in the sequence $t_{i-k}, \dots, t_{i-1}$. This model assumes that the words $w_i$can directly be observed but the tags, i.e., the states of the words, cannot and are, thus, hidden. Therefore, the model is a Hidden Markov Model (HMM). From the available taggers the TreeTagger program [3] was applied, which is related to a trigram tagger and uses the following slightly adapted HMM with $n = 2$:

$$P_{POS} = \prod_{i=1}^{2} \{P(t_i|w_i)/P(t_i)\} P(t_i|t_{i-k}, \dots, t_{i-1}) \qquad \text{Eq. (A.3)}$$

Finally, the best tag sequence for a given corpus has to be found. This may be referred as the “decoding procedure” [8]. The TreeTagger uses the Viterbi Algorithm [11, 12] for this purpose, which finds the sequence of tags with the highest probability for a given sequence of words. For each word, i.e., observation, various states, i.e., tags, are possible. The algorithm iteratively finds the path through the states that maximizes the overall probability of the complete path.

Before the corpus under investigation can be tagged by applying the HMM via the Viterbi algorithm, the values of the model’s probability parameters have to be estimated in a training phase. This methodological choice concerning estimation is reflected in the name of the program. The TreeTagger uses a binary decision tree to estimate the transition probabilities for the Markov Model by an adapted version of the Iterative Dichotomiser 3 algorithm (ID3) [13], a predecessor of the C4.5 algorithm [14] or the most recent version, i.e., the C5.0 algorithm [15], applied on the Penn Treebank Corpus as training data.

As the name of the algorithm indicates, the algorithm recursively divides the training set into two sets with maximum distinctness, so that at each node a yes/no decision is made concerning questions such as “Is the first tag of the trigram an adjective?” or “Is the second tag of the trigram a determiner?”. Here, distinctness is meant with respect to the probability distribution of the third tag in the given training trigrams. Usually it is not possible to achieve an absolute answer, i.e., full disambiguation of the tag, at the terminal nodes. Therefore, the probability distribution of tags in the tagsets that have reached the terminal nodes are used to identify the most likely tag. In other words, the terminal nodes include the probability information on the third tag for a given preceding sequence of tags.

Each recursion step of the algorithm tests which division creates the maximum information gain IG_{node} at each node. The division for testing is performed for each tag available in the set of all possible individual tags, i.e., the overall tagset T. The information gain is the difference of information entropy between the "yes" and "no" path at a decision node. The main equation solved at each node is shown below in pseudo-code to allow a basic understanding. Readers interested in more details are kindly referred to the original papers of Schmid. In pseudo-code, the main equation during training is:

$$IG_{node} = -P(yes|\ node\ tagset) \sum_{t \in T} P(t|yes\ tagset) \log_2 P(t|yes\ tageset) - P(no|node\ tagset) \sum_{t \in T} P(t|no\ tagset) \log_2 P(t|no\ tagset) \quad \text{Eq. (A.4)}$$

The English parameter file for the TreeTagger was built from a set of about 2 million words from the Penn Treebank [9]. This corpus contains raw texts from various fields and sources such as News from Dow Jones, abstracts from the American Department of Energy, or the famous Brown Corpus [9]. These texts have been tagged automatically using "stochastic and rule-driven taggers" with an "error rate of 2-6%" [9]. This step is followed by a manual correction step, so that the corpus can be considered a manually tagged corpus or at least a corpus whose tags involve human judgement. Among other corpora, the latest version of the Penn Treebank is provided by the University of Pennsylvania [10].

The final lexicon used for decoding the corpus of investigation includes the Penn Treebank based tag parameters and, in addition, includes information on tag probabilities based on word endings, i.e., a "suffix lexicon" [1]. The suffix lexicon was also built from the Penn Treebank Corpus and is used if the word in focus during the analysis is not found in the primary lexicon [1]. In this case, the tag probabilities for specific word endings are used, which are again stored in a decision tree built under consideration of information gain similar to the procedure described above [1].

Lemmatization

Apart from tagging words according to their POS, an additional benefit of POS tagging is that it allows to turn words to their lemmata. The TreeTagger lexicon includes information on lemmata of words allowing to map inflected words forms to a unique uninflected form.

Lemmatization is a more gentle form of simplifying terms in comparison to stemming. Stemming is a common strategy that is faster than lemmatization via POS tagging but may lead to less interpretable topics. The difference between stemming and lemmatization is exemplified by means of two phrases in Table A3.2. The table shows, that stemming may remove parts of words that are relevant for the meaning. For example, the terms production and product are both reduced to the stem product, which does not allow to judge whether the term refers to a production process or a final product.

Table A3.2: Comparison between stemming and lemmatization

No.	**Phrase**	**Phrase after stemming**	**Phrase after lemmatization**
1	energy consumption for production of goods	energy consumpt for product of good	energy consumption for production of goods
2	energy consumption from using products or goods	energy consumpt from us product or good	energy consumption *use product* or goods

A3.3 Collocation Model

The following summary is based on [6, 7, 16–19].

For detecting collocations, various metrics may be applied to assess whether two individual terms co-occur across the documents of a corpus to a statistically relevant degree and should be bound together as n-gram. The n in n-grams stands for the number of terms bound together. For example, in a simple bag of words, which considers a document as an unordered collection terms, the terms sustainable and development would be considered as two separate terms. If their co-occurrence is relevant according to the applied metric, these terms are bound together as a fixed n-gram and represented as sustainable_development.

The basic idea of metrics for detecting collocations is to compare the total occurrence of individual terms to the co-occurrence of terms while applying suitable transformations to these values. This kind of metrics originate from information theory. Therefore, they usually use term probabilities instead of the raw term counts. By dividing the total term count n_i of a given term t_i over the whole corpus by the total number of terms N_C of the corpus, the probability of a single term appearing in the corpus can be calculated as:

$$P(t_i) = n_i / N_C \qquad \text{Eq. (A.5)}$$

Analogously the probability of the total co-occurrence counts n_{ij} of two terms t_i and t_j may be represented as a probability as follows:

$$P(t_i, t_j) = n_{ij} / N_C \qquad \text{Eq. (A.6)}$$

These probabilities may then be used in various metrics. In this study, two metrics have been used for detecting collocations. They are presented in the following.

Pointwise Mutual Information

Based on research by Fano [18] and the definition of Church and Hanks [6] pointwise mutual information for two terms may be calculated as:

$$PMI(t_i, t_j) = log_2(P(t_i, t_j) \,/\, P(t_j)P(t_i)) \qquad \text{Eq. (A.7)}$$

It should be noted that some authors also use other bases in the logarithm. This changes the unit of measurement or scale, but not the general logic of the metric [17]. For higher numerical robustness the formula may be reformatted and a smoothing constant may be introduced to avoid building the logarithm of zero [16], so that the equation may be expressed as:

$$PMI_{nr}(t_i, t_j) = log_2(P(t_i, t_j) + s) - log_2(P(t_i)) - log_2(P(t_j)) \qquad \text{Eq. (A.8)}$$

The probability of individual terms is never zero (each term appears at least once), therefore, the smoothing constant only needs to be added to the probability of co-occurrence.

(Log Frequency Biased) Mutual Dependency - LFMD

Based on the ideas of Gallager [19], Thanopoulos et al. defined the mutual dependency (MD) metric that is the PMI minus the “self-information” contained therein [7] as follows:

$$MD(t_i,t_j) = PMI(t_i,t_j) - \left(-log_2\left(P(t_i,t_j)\right)\right) \qquad \text{Eq. (A.9)}$$
$$= \ log_2\left(P^2(t_i,t_j)\ /P(t_j)P(t_i)\right)$$

By empirical investigations they showed that the log-frequency biased mutual dependency (LFMD) metric has high performance for extracting collocations. This metric is defined as follows:

$$LFMD(t_i,t_j) = \ MD(t_i,t_j) + log_2\left(P(t_i,t_j)\right) \qquad \text{Eq. (A.10)}$$
$$= \ log_2\left(P^3(t_i,t_j)\ /\ P(t_j)P(t_i)\right)$$

A3.4 Latent Dirichlet allocation for topic modeling

The following summary is based on [20–25].

For describing latent Dirichlet allocation (LDA) [24] the notation as shown in Table A3.4 is used in the following. LDA serves for probabilistic generative modelling of individual documents d of a corpus C, i.e., a collection of D documents, as mixtures of K topics k. The number of topics K is a key parameter of LDA that needs to be set by the modeler. The document-topic distribution θ_d defines the mixture of topics for each document d. Considering the number of N_V unique terms in the corpus, i.e., the vocabulary, each topic is assumed to be a mixture of these terms. The topic-term distribution ϕ_k defines this mixture for each topic k. LDA makes another key assumption. It uses a bag-of-words model of documents. This means that it does not pay attention to the order of words in a document. A document is considered as a sequence of length N_d with the terms $t_d = \{t_{d1}, \dots,\ t_{dn}\}_{n=1}^{N_d}$ taken from the vocabulary of the corpus.

As a Bayesian model, LDA works with a prior belief about the distributions θ_d and ϕ_z. LDA assumes that they follow a Dirichlet Distribution $Dir()$ with the hyper-parameters α and β that have to be set by the modeler. These hyper-parameters reflect the prior belief about the distributions, in particular, regarding the topic density or sparsity in individual documents. The distribution of topics over documents follows $Dir_K(\alpha)$ and the distribution of words over topics follows $Dir_V(\beta)$. Two key characteristics of $Dir_K(\alpha)$, and analogous of $Dir_V(\beta)$, are that its values x_i are all greater or equal to 0 and they sum up to 1. Expressed in formulas this translates to $x_i \geq 0 \, \forall \, x_i \in [1, K]$ and $\sum_{i=1}^{K} x_i = 1$.

The key idea of LDA is that assumes the following generative process that creates individual documents of a corpus:

1. Draw a multinomial topic-word distribution $\phi_k \sim Dir_V(\beta)$
2. Draw a multinomial document-topic distribution $\theta_d \sim Dir_K(\alpha)$
3. For each term position $n \in \{1, \ldots, N_d\}$ in each document
    a. Choose a topic $z_{dn} \sim Multinomial_K(\theta_d)$
    b. Choose a term $t_{dn} \sim Multinomial_V(\phi_{z_{dn}})$

The modeler is finally interested in estimating the posterior distributions of topics over documents $\Theta = \{\theta_d\}_{d=1}^{D}$ and terms over topics $\Phi = \{\phi_k\}_{k=1}^{K}$. The starting point for this estimation is the likelihood of the complete corpus considering the relevant variables, which can be written as follows:

$$p(T, Z, \Theta, \Phi) = \prod_{k=1}^{K} p(\phi_k) \prod_{d=1}^{D} p(\theta_d) \left(\prod_{n=1}^{N_d} p(z_{dn} | \theta_d) p(t_{dn} | \Phi, z_{dn}) \right) \qquad \text{Eq. (A.11)}$$

Marginalizing z_{dn} this may be written concisely as:

$$p(T | \Theta, \Phi) = \prod_{d=1}^{D} \prod_{n=1}^{N_d} p(t_{dn} | \theta_d, \Phi) \qquad \text{Eq. (A.12)}$$

The algorithms to approach the estimation task are either sampling-based such as the commonly used Gibbs sampling [23] or variational such as variational expectation maximization [24]. This study is based on the fast WarpLDA algorithm, which is a Metropolis-Hastings based algorithm [25].

Table A3.4: Notation for latent Dirichlet allocation, the format of this table is inspired by [20]

Notation	Description
Basic notation regarding data structure	
t_d	Collection of N_d terms $t_d = \{t_{d1}, \dots, t_{dn}\}_{n=1}^{N_d}$ representing a document
N_d	Number of terms in a document, i.e., the length of a document
d	document index
n	term index within a document
C	A corpus, i.e., a collection of D documents $C = \{t_1, \dots, t_d\}_{d=1}^{D}$
D	Number of documents in corpus C, i.e., the size of the corpus
N_V	Number of unique terms in the vocabulary, i.e., the size of the vocabulary
Specific notation regarding LDA modelling	
K	Total number of topics
k	Topic index
θ_d	Mixture of topics for a document, in other words, the distribution of topics over the document
ϕ_k	Mixture of terms for a topic, in other words, the distribution of terms over a topic
α	Dirichlet prior for θ_d
β	Dirichlet prior for ϕ_k
Θ	The document-topic matrix incorporating all distributions of topics over documents $\Theta = \{\theta_d\}_{d=1}^{D}$
Φ	The topic-term matrix incorporating all distributions of terms over topics $\Phi = \{\phi_k\}_{k=1}^{K}$
$z_d = \{z_{dn}\}_{n=1}^{N_d}$	The topic assignments, each taken from [1,K], for each term in a document
$Z = \{z_d\}_{d=1}^{D}$	The collection of topic assignments for each document

A3.5 Coherence of LDA models

In this study the scores of six different coherence metrics were used. The scores were based on the 10 top words per topic and a Wikipedia based reference corpus. Several coherence metrics were programmed in R for this study [16, 26], i.e., LOGRATIO also referred to as UMass [27, 28], probabilistic difference (DIF) [29, 30], pointwise mutual information (PMI) also referred to as UCI [6, 31], normalized PMI (NPMI) [17], cosine similarity of NPMI vectors (NMPI COSIM) [32], cosine similarity of NPMI vectors to the sum of the NPMI vectors (NPMI COSIM SET), originally referred to as V [28]. Regarding the type of reference corpus, the metrics LOGARTIO and DIF are so-called intrinsic metrics and use the corpus of investigation itself as reference corpus. For the other metrics, which are extrinsic, Wikipedia articles served as reference corpus. For constructing this corpus, several portal pages listing many Wikipedia sub-sites and selected individual Wikipedia articles were specified manually. A web scraping algorithm was programmed using the WikipediR package [33] for automatically downloading these articles and, in the sense of a snowball sampling, the articles linked on these pages. The final reference corpus consisted of 1737 Wikipedia articles.

In the following, details are provided for the metrics that have been used in this study. Readers interested in other metrics are kindly referred to literature. As a starting point, a review of coherence metrics is provided by Röder et al. [28]. The following summary is based on [6, 16, 27–31].

For measuring the coherence of a modelled topic, the statistical relatedness of the n_{top} top terms of this topic in a reference corpus C_{ref} is evaluated based on their occurrence and co-occurrence. For external coherence metrics, the reference corpus may be the corpus of investigation itself and, for internal metrics, it may be an external corpus, i.e., a suitable collection of secondary documents. The reference corpus is used to construct the reference term co-occurrence matrix TCM_{ref} (technical details below). For coherence metrics, the co-occurrence of the n_{top} terms in the sliding window defined for the reference corpus is only counted once. Hence, it is only counted if the terms co-occur in the window, not how often. Depending on the metric applied, the sliding window, which runs over the individual documents of the reference corpus, is set to either the full length of the document for evaluating coherence at the document level or smaller values, e.g., 10 terms, to evaluate coherence at the sentence level. A summary of the coherence metrics and their settings for constructing the TCM_{ref} is shown in Table A3.5.

This is a reasonable approach for assessing whether there is a general relation between the terms. The strength of the relation is of minor importance for assessing the coherence of a collection of terms. Following these considerations, e.g., the collections {energy, energy, power} and {power, power, energy} have the same coherence. The coherence of a topic may be evaluated by means of different metrics for assessing the statistical relatedness of terms in the reference corpus. The scores for the individual term pairs are aggregated to a score for the whole topic. For evaluating the coherence of a complete topic model, the scores of the individual topics are again aggregated. In this study the mean is used for aggregation. Technical details on the selected metrics in this study are provided in the following sections. Before, the construction of the TCM_{ref} is described.

The basis for creating the TCM_{ref} is the document term matrix of the reference corpus (DTM_{ref}). In a first step, the $sign$ is applied to the DTM_{ref} turning all values greater than one to one in order to only count if terms co-occur at least once (Boolean co-occurrence of terms). Then, the reference TCM_{ref} is created as the cross-product of this matrix as follows:

$$DTM_{ref,sgn} = sign(DTM_{ref}) \qquad \text{Eq. (A.13)}$$

$$TCM_{ref} = crossprod\left(DTM_{ref,sgn}\right) = DTM_{ref,sgn} \cdot DTM^{T}_{ref,sgn} \qquad \text{Eq. (A.14)}$$

In its diagonal the TCM_{ref} contains the total Boolean counts $c_b(t_i)$ of individual terms t_i in the sliding windows. The entries in the lower and upper triangles represent the co-occurrence $co_B(t_i, t_j)$ of term pairs t_i and t_j.

By dividing the values in the TCM_{ref} by the number of sliding windows, a probabilistic form of this matrix may be established, which provides information on the term probabilities $P_B(t_i)$ or co-occurrence probabilities $P_B(t_i, t_j)$:

$$TCM_{ref,p} = TCM_{ref} \,/\, n_{sliding\ windows} \qquad \text{Eq. (A.15)}$$

It should be noted that the probabilities in this matrix are not the same as the ones used for collocations models, since they are only based on Boolean counting.

Since the values of $co_B(t_i, t_j)$ or $P_B(t_i, t_j)$ may be zero if the respective terms do not co-occur in any sliding window, a smoothing constant $s = 10^{-12}$ is added in some of the metrics. The constant avoids dividing by zero or taking the logarithm of zero.

Table A3.5: Standard settings for creating the TCMref for different coherence metrics

Coherence Metric	**Type of reference corpus**	**Size of sliding window for counting co-occurrence**	**Level at which coherence is measured**
LOGRATIO	Internal	Length of document	Document
DIF	Internal	Length of document	Document
PMI	External	10	Sentence
NPMI	External	10	Sentence
NPMI COSIM	External	5	Sentence
NPMI COSIM SET	External	110	Paragraph

Logratio

The logratio metric may also be referred to as the UMass metric [27], although, some adaptions have been applied in this study (see below). It is calculated here as follows:

$$LOGRATIO(t_i, t_j) = log_2(co_B(t_i, t_j) + s) - log_2(c_B(t_j)) \qquad \text{Eq. (A.16)}$$

This metric is an asymmetric metric. It uses a TCM_{ref} that is ordered by the the values in the diagonal, i.e., the term counts c_b. The term indices i and j, need to be evaluated according to a certain order, here, a so-called preceding order. This means that given the indices $\{1, 2, 3\}$, the following term index combinations would be evaluated $\{2, 1\}, \{3, 1\}, \{3, 2\}$.

In this study, the differences to the UMass metric are that a smaller smoothing constant was used and that the mean instead of the sum was used for aggregation.

Pointwise Mutual Information (PMI)

The PMI metric may also be referred to as UCI metric [6, 31], although, some adaptions have been applied in this study (see below). It is calculated analogously to the PMI for collocation models, but with the different definition of term probability that was introduced above, as:

$$PMI_{coh}(t_i, t_j) = log_2(P_B(t_i, t_j) + s) - log_2(P_B(t_i)) - log_2(P_B(t_j)) \qquad \text{Eq. (A.17)}$$

In this study, the differences to the UMass metric are that a smaller smoothing constant was used and that the mean instead of the sum was used for aggregation.

Normalized Pointwise Mutual Information

Based on the PMI_{coh} the normalized pointwise mutual information $NPMI_{coh}$ as a metric for measuring coherence [17] may be calculated as follows:

$$NPMI_{coh}(t_i, t_j) = PMI_{coh}(t_i, t_j) \; / -log_2(P_B(t_i, t_j) + s) \qquad \text{Eq. (A.18)}$$

Probabilistic Difference (DIF)

Using information on probability differences in metrics has been discussed, e.g., by Eells and Fitelson in a comparison of various metrics [29]. An adapted version of this metric has been implemented as a coherence metric, e.g., in the R package textmineR [30] or later in the package text2vec [16], as the probabilistic difference. It may be expressed as:

$$DIF(t_i, t_j) = P_B(t_i, t_j)/P_B(t_i) - P_B(t_j) \qquad \text{Eq. (A.19)}$$

NPMI Cosine Similarity (NPMI COSIM)

The NPMI COSIM metric is a combination of the NPMI metric and the cosine similarity. First, the NPMI of all term pairs of the top topic terms in the reference corpus is calculated. The results may be represented as a symmetric matrix providing information on the NPMI for each pair. Regarding an individual term, each row of the matrix is a vector of NPMI values between a specific term and all other terms. It has the follow form:

$$NPMI_{mat} = \begin{pmatrix} & v_1 & \cdots & v_{n_{top}} \\ v_1 & NPMI_{coh}(t_1, t_1) & \cdots & NPMI_{coh}(t_1, t_{n_{top}}) \\ \cdots & \vdots & \ddots & \vdots \\ v_{n_{top}} & NPMI_{coh}(t_{n_{top}}, t_j) & \cdots & NPMI_{coh}(t_{n_{top}}, t_{n_{top}}) \end{pmatrix} \qquad \text{Eq. (A.20)}$$

The cosine similarity is an established metric of similarity which basically uses the cosine of the angle between two vectors as information on their similarity. The dot product (or scalar product) is the basis for the calculation, which is calculated for two Euclidean vectors a and b as follows:

$$a \cdot b = ||a|| \cdot ||b|| \cdot \cos\varphi \qquad \text{Eq. (A.21)}$$

In an n-dimensional space the cosine similarity is then calculated as:

$$cosim(a,b) = \cos\varphi = \frac{a \cdot b}{||a|| \cdot ||b||} = \frac{\sum_{i=1}^{n} a_i \cdot b_i}{\sqrt{\sum_{i=1}^{n}(a_i)^2} \cdot \sqrt{\sum_{i=1}^{n}(b_i)^2}} \qquad \text{Eq. (A.22)}$$

For calculating the NPMI COSIM, the cosine similarity between each row of the $NPMI_{mat}$ is calculated:

$$NPMI\ COSIM_{mat} = \begin{pmatrix} & w_1 & \cdots & w_{n_{top}} \\ w_1 & cosim(v_1, v_1) & \cdots & cosim\left(v_1, v_{n_{top}}\right) \\ \cdots & \vdots & \ddots & \vdots \\ w_{n_{top}} & cosim\left(v_{n_{top}}, v_1\right) & \cdots & cosim\left(v_{n_{top}}, v_{n_{top}}\right) \end{pmatrix} \qquad \text{Eq. (A.23)}$$

Finally, for calculating the coherence $NPMI\ COSIM_{coh}$ of a topic, the scores in the upper triangle of the $NPMI\ COSIM_{mat}$ are aggregated by calculating the mean.

NPMI COSIM SET

This metric is calculated similarly to the $NPMI\ COSIM_{coh}$ metric. The difference is the way of calculating the cosine similarity. For $NPMI\ COSIM\ SET_{coh}$ is not calculated between each row of the $NPMI_{mat}$. Instead, the column sums of the $NPMI_{mat}$ are calculated for creating a reference vector representing the aggregated $NPMI_{coh}$values of the complete set of n_{top} terms. Then, the cosine similarity of each row v in the $NPMI_{mat}$ to this reference vector is calculated.

A3.6 Modelling topic trends

The following summary is based on [34–42].

For evaluating the trend of a topic k, linear regression models were fit for Θ_k as the response variable, i.e., the probabilities of topic k over all documents, using the time t in years y as explanatory variable. The resulting magnitude and the sign of the slope of the trend line indicate whether topic k has strong positive or negative trend in comparison to other topics.

For visualizing topics trends, the mean values of $\overline{\Theta_k}$ per year y were used, i.e., the mean topic probability per year. In addition to plotting the mean values, a smoothed trend curve was drawn using locally weighted regression (LOESS) optimized by the corrected Akaike information criterion (AIC_c). The general procedure for drawing these curves is explained in the following. The smoothed curves neglect oscillations to a certain extent and, therefore, may facilitate grasping the general timely trend during visual inspection of the scatter plot. Hence, the smoothed curves fulfill a descriptive purpose here and do not have any predictive power.

Regression methods may be used to fit curves through data points, e.g., in a scatter plot. Standard regression methods seek for one fitting function, e.g., a linear or polynomial function, with the lowest error to the true data points while considering all data points at once. In contrast, a local regression uses a combination of multiple local polynomial functions. For each data point a polynomial function is sought while considering information on the neighboring data points within a specified span. Local regression methods are particularly useful for analyzing time series, since very distant points in time usually have less influence on each other than closer points in time. Therefore, local regression may perform well in resolving short term dynamics.

This study applies the locally weighted regression proposed by Cleveland [37, 38], which is implemented in R in the stats package as the function “loess” [36]. Since this is a standard procedure in statistics technical details are not repeated here. For details, readers are kindly referred readers to literature, e.g., Cleveland and Devlin [37, 38] or the R documentation [36].

A critical step in locally weighted regression is the selection of the span parameter h. Varying the span parameter produces a family of loess models from which the most informative one should be selected for downstream analysis. Expressed the other way round, the approximating model with the lowest loss of information should be selected. For this purpose, a metric to compare the information content of the approximating models is needed. In this study, the corrected Akaike Information Criterion (AIC_c) for smoothing parameter selection was used.

Akaike created the basic Akaike Information Criterion (AIC) [35] by combing the Kullback-Leibler-Divergence (KLD) [34], a metric for evaluating the divergence of information between two models or probability distributions, and the likelihood function $\mathcal{L}$, which may be used for maximum likelihood estimates based on data. The AIC provides information on the loss of information when modelling data. Considering a family of models that might potentially fit the data, the AIC allows to select the most appropriate model, i.e., the one with the lowest loss of information, by taking likelihood estimates and the complexity of the model into account [39]. The AIC may be used to compare the goodness of fit of different models. Comparing a family of models with regard to their AIC, the one with the lowest AIC is considered as the most appropriate model. The basic AIC may be expressed as

$$AIC = -2\ln\big(\mathcal{L}(\theta|data)\big) + 2k, \qquad \text{Eq. (A.24)}$$

$\mathcal{L}(\theta|data)$ is the value of the likelihood function using the estimated parameters θ for modelling the given data and k is the number of estimated parameters of the approximating model.

For cases with smaller sample size, a corrected version of the AIC, the AIC_c, is to be used preferably. It was found that model selection based on the AIC may lead to overfitting, i.e., the selection of a model with too many parameters, for small sample sizes [40, 41]. The AIC is a first-order estimate. For avoiding overfitting AIC_c [43] may be used, which is a second-order estimate. It does not only consider k but k^2. For large values of n, i.e., the sample size, it converges to the basic AIC. For parametric linear regression, the AIC_c may be expressed as follows [39, 40, 42]:

$$AIC_c = AIC + \frac{2k^2 + 2k}{n - k - 1} \qquad \text{Eq. (A.25)}$$

For the specific case of smoothing parameter selection, the AIC_c takes the following form [43], which was used in this study:

$$AIC_c = \log(\hat{\sigma}^2) + 1 + 2(tr(H) + 1)(n - tr(H) - 2)^{-1} \qquad \text{Eq. (A.26)}$$

$\hat{\sigma}^2$ is the mean residual sum of squares, i.e., the variance, and H is the hat matrix, i.e., the projection matrix projecting the data points to the fitted values, whose trace $tr(H)$ represents the number of parameters of the approximating model, and n is the sample size.

A3.7 Network community detection based on modularity

The following summary is based on [44–46].

The modularity metric for networks has been defined by Newman [45] and can be described using the following notation. c_i is the community to which vertex i belongs. A_{ij} is the weight of the edge between the vertices i and j. The sum of the edges connected to vertex i, i.e., its degree, is $k_i = \sum_j A_{ij}$. The total number of edges in the network is $m = \frac{1}{2}\sum_{ij} A_{ij}$. On this basis, the modularity of the network is defined as:

$$Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{wm}\right]\delta(c_i, c_j) \qquad \text{Eq. (A.27)}$$

δ- function $\delta(u, v)$ is 1 if $u = v$ and 0 otherwise.

When investigating networks, an analytical step may be to identify clusters or communities in the network. This may be achieved by algorithms identifying high (potentially maximum) modularity partitions of networks. This study is based on an algorithm proposed by Blondel et. al [44] that fulfills this task. It is implemented in the R igraph package [46]. The algorithm first assigns a different community to each node and, in the following twofold iterative procedure agglomerates the vertices into communities: in the first step it maximizes modularity locally and in the second step globally on the basis of the partitions resulting from local maximization [44].

A4. Extended results

A4.1 Clustering dendrogram

The following dendrogram results from clustering the coordinates that that emerge from multi-dimensional scaling applied to the intertopic distances (see main article Section "Materials and methods - Inter topic distance and thematic fields").

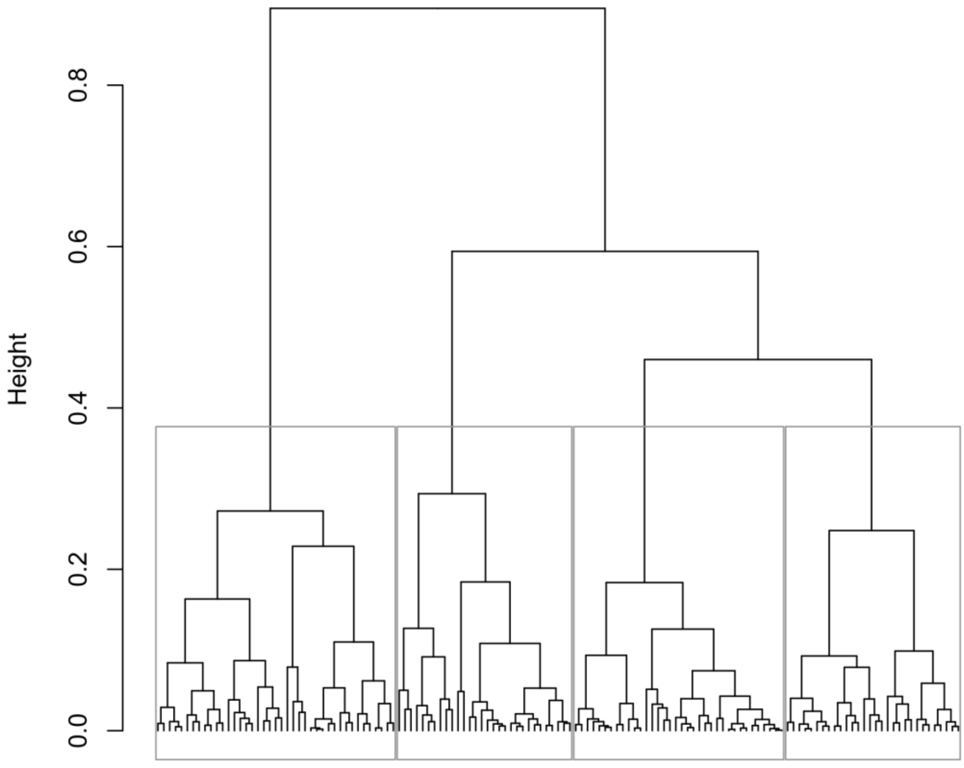

Figure A4.1: Dendrogram resulting from hierarchical clustering of topic (dis-)similarity based on the principal coordinates resulting multidimensional scaling using the Jensen-Shannon Divergence as distance metric; partitioning rectangles highlight 4 major clusters

A4.2 Topics with strongest positive trend

The following Table A4.2 is a copy of the Table 6-1 in the main article. However, Table A4.2 includes additional information regarding the slopes of the linear models and the p-values for the slopes.

Table A4.2: Hot topics with the strongest positive trend: topics equal to or above the 95% quantile regarding the slope of the linear models; topics are clustered according to superordinate themes; the order of themes follows the topic with the highest rank belonging to a theme; rank 1 indicates the topic with the strongest positive trend

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
57	1	Electrical energy storage	Materials for electrochemical energy storage via batteries or supercapacitors	electrode, battery, carbon, electrolyte, electrochemical, cycle, cell, cathode, energy_storage, low_cost, electrode_material, report, anode, discharge, lithium, exhibit, supercapacitor, material, redox, graphene	7.77e-04	2.65e-39
13	2	Fuel cells	Materials for catalysis in fuel cells	catalyst, activity, electrochemical, graphene, active, electrocatalyst, cobalt, efficient, surface, exhibit, highly, stability, report, electrode, platinum, fuel_cell, oxidation, active_site, superior, catalytic	6.02e-04	3.35e-35
63	3	Hydrogen production	Photosensitive materials and photocatalysis for water splitting	tio_two, photocatalyst, semiconductor, photocatalytic, tio, water_splitting, visible_light, photo, cds, exhibit, photocatalysis, degradation, electron, solar_energy, dye, light, photoanode, band, photocurrent, report	4.86e-04	1.12e-24
154	4	Nanotechnology	Synthesis of nanomaterials	scan, characterize, synthesis, nanoparticle, prepare, sample, characterization, technique, synthesize, zno, obtain, confirm, property, morphology, precursor,	4.48e-04	3.40e-33

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
				material, ion, x_ray_diffraction, observe, oxide		
109	12	Nanotechnology	Properties of materials	material, structure, property, nanomaterial, molecule, bond, nano, functional, compound, shell, sulfur, molecular, formation, exhibit, surface, unique, excellent, electron, report, layer	2.34e-04	8.26e-18
262	15	Nanotechnology	Structure of nanomaterials	particle, polymer, nanoparticle, nanocomposite, preparation, fabrication, powder, size, prepare, porous, spray, synthesis, matrix, agent, formation, poly, highly, silica, simple, rgo	2.24e-04	4.30e-19
242	5	Chemical catalysis	Chemical catalysis for various types of reactions	reaction, catalyst, catalytic, methanol, oxidation, ligand, conversion, complex, compound, intermediate, selective, catalysis, acid, synthesis, yield, oxygen, chemical, highly, metal, molecular	4.33e-04	2.95e-21
255	6	Digital network communication	Wireless sensor networks and real-time data for energy applications	algorithm, node, power, network, wireless, transmission, protocol, energy_harvesting, user, communication, technique, sensor, sensor_node, spectrum, data, scheme, channel, battery, maximize, distribute	3.75e-04	7.89e-20
111	7	Mechanical energy harvesting	Triboelectric nanogenerator and piezoelectric effect for small scale applications	mechanical, power, teng, powered, harvest, device, motion, vibration, energy_harvesting, sensor, flexible, output, generate, electrical, circuit, electronics, power_source, magnetic, drive, piezoelectric	3.51e-04	3.94e-16

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
125	8	Sustainable building materials	Alternative blendings or replacement materials for cement	concrete, cement, brick, material, aggregate, strength, fly_ash, property, durability, mortar, compressive_strength, binder, block, sand, produce, lime, replacement, clay, replace, specimen	3.35e-04	6.54e-13
253	9	Biofuels	Biofuel from algal biomass	biodiesel, microalgae, algae, biodiesel_production, lipid, cultivation, algal, yield, produce, feedstock, culture, microalgal, transesterification, nutrient, biofuel, oil, fuel, potential, algal_biomass, content	3.10e-04	1.44e-16
251	10	Biofuels	Production of biomethanol by fermentation of biomass	fermentation, sugar, pretreatment, glucose, enzyme, yield, obtain, cellulose, hydrolysis, produce, lignin, substrate, lignocellulosic_biomass, g_l, pulp, carbohydrate, biomass, pretreated, ethanol, acid	3.08e-04	5.30e-14
172	13	Biofuels	Bio-based materials from lignocellulosic feedstocks	extraction, separation, solvent, extract, acid, lignin, recovery, cellulose, liquid, leach, water, yield, ionic_liquid, compound, chemical, surfactant, step, distillation, separate, recover	2.27e-04	2.00e-14
74	14	Biofuels	Biogas production from anaerobic digestion	bioga, anaerobic_digestion, produce, methane, manure, sludge, biogas, fertilizer, substrate, bioga_production, digestate, biomethane, organic_waste, food_waste, digester, bioga_plant, anaerobic, digestion, biogas_production, compost	2.24e-04	7.41e-13
90	11	Modeling & Optimization	Optimization models and algorithms for	optimal, optimization, optimize, constraint, minimize, algorithm,	3.01e-04	3.34e-23

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
			power systems operation and markets	objective, maximize, solution, scheduling, multi_objective, optimization_model, solve, minimization, formulate, objective_function, search, simultaneously, trade, genetic_algorithm		

A4.3 Topics with high abundance

The following Table A4.3 is a copy of the Table 6-2 in the main article. However, Table A4.3 includes additional information regarding the cumulative sum of the probability.

Table A4.3: Highly abundant topics: topics equal to or above the 95% quantile regarding the cumulative sum of topic probability (quantile is based on topics with positive slope only); rank 1 indicates the topic with the highest cumulative sum; topic marked with an asterisk also belong to the topics with the strongest positive trend

Topic no.	Abundance rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Cumulative sum of probability
57*	1	Electrical energy storage	Materials for electrochemical energy storage via batteries or supercapacitors	electrode, battery, carbon, electrolyte, electrochemical, cycle, cell, cathode, energy_storage, low_cost, electrode_material, report, anode, discharge, lithium, exhibit, supercapacitor, material, redox, graphene	190.9
100	2	Urbanization	Cities, districts, and urban planning	city, urban, urban_area, urban_development, urban_planning, urbanization, urban_metabolism, urban_form, urban_sustainability, neighbourhood, district, sustainable_urban, density, urban_environment, urban_design, sustainable_urban_development, residential, scale, urban_ecosystem, spatial	169.3
276	3	Life cycle assessment	Environmental life cycle assessment with focus on carbon footprints	lca, environmental_impact, impact, life_cycle_assessment_lca, life_cycle, impact_category, life_cycle_assessment, emission, environmental_performance, stage, global_warming_potential, gwp, functional_unit, assess, environmental_burden, category, environmental, impact_assessment, perform, phase	169.2
242*	4	Chemical catalysis	Chemical catalysis for various types of reactions	reaction, catalyst, catalytic, methanol, oxidation, ligand, conversion, complex, compound, intermediate, selective, catalysis, acid, synthesis, yield, oxygen, chemical, highly, metal, molecular	166.1
90*	5	Modeling & Optimization	Optimization models and	optimal, optimization, optimize, constraint, minimize, algorithm,	164.3

Topic no.	Abundance rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Cumulative sum of probability
			algorithms for power systems operation and markets	objective, maximize, solution, scheduling, multi_objective, optimization_model, solve, minimization, formulate, objective_function, search, simultaneously, trade, genetic_algorithm	
30	6	Heating & Cooling	Low temperature heating, cooling and efficiency technologies	heat, cool, heating, heat_pump, temperature, cooling, thermal, fluid, performance, heat_exchanger, heating_system, waste_heat, heat_recovery, absorption, air, heat_transfer, operate, low_temperature, cycle, condenser	157.5
125*	7	Sustainable building materials	Alternative blending or replacement materials for cement	concrete, cement, brick, material, aggregate, strength, fly_ash, property, durability, mortar, compressive_strength, binder, block, sand, produce, lime, replacement, clay, replace, specimen	146.4

A4.4 Topics with the strongest negative trends

The following Table A4.4 is a copy of Table 6-3 in the main article. However, Table A4.4 includes additional information regarding the slopes of the linear models and the p-values for the slopes.

Table A4.4: Cold topics with the strongest negative trend: topics equal to or below the 5% quantile regarding the slope of the linear models; rank 300 indicates the topic with the strongest negative trend

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
254	300	Sustainable development	Global developments of humanity and natural resource use	world, earth, environment, natural_resource, human, future, global, sustainable_development, resource, energy_resource, man, population, planet, nature, humanity, today, problem, life, population_growth, future_generation	-4.52e-04	1.38e-79
280	291		Development in Asia[5]	sustainable_development, promote, japan, environmental_protection, put, forward, comprehensive, progress, economic_development, promotion, utilization, japanese, coordination, government, national, realize, establishment, protection, country, developmental	-3.60e-04	9.70e-27
51	299	Agriculture	Production of food crops and the extent of using agrochemicals	agricultural, agriculture, crop, farmer, farm, farming, organic, input, agricultural_production, food, cultivation, pesticide, productivity, crop_production, production_system, agricultural_system, fertilizer, farming_system, intensive, agroecosystem	-3.28e-04	1.68e-34
104	298	International cooperation	International technology transfer and financial support mechanisms	country, access, promote, policy, international, support, government, incentive, mechanism, priority, market, technology_transfer, clean_development_mechanism,	-2.92e-04	2.75e-40

[5] The top topic terms refer to Japan, however, examining the abstracts associated with the topic showed that the topic addresses the geographical context of Japan including, e.g,. China.

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
				institution, lack, domestic, finance, encourage, provision, experience		
252	297	Rural areas	Livelihood and development of rural communities	rural, village, poor, rural_area, livelihood, people, local, traditional, income, district, settlement, poverty, region, area, rural_development, access, indigenous, situation, population, rural_community	-2.91e-04	1.51e-31
225	296	Nuclear energy	Potentials and risks of nuclear power	nuclear, nuclear_power, nuclear_energy, safety, future, japan, nuclear_power_plant, korea, risk, disaster, energy_source, electricity, fossil_fuel, option, korean, plan, safeguard, today, energy_mix, century	-2.88e-04	2.03e-41
10	289	Nuclear energy	Nuclear energy technology	reactor, fuel, fuel_cycle, core, fusion, uranium, fast_reactor, spend, advanced, safety, plutonium, nuclear_energy, reprocess, cycle, neutron, thorium, nuclear, nuclear_fuel, lwr, nuclear_fuel_cycle	-2.69e-04	1.45e-32
207	295	Population	Quality of life in the context of population growth	population, people, live, world, life, grow, century, billion, planet, today, society, billion_people, poverty, living, quality_life, health, decade, bring, old, global	-2.60e-04	1.53e-37
31	294	Welfare	Welfare effects of economic growth and green growth	economy, economic, growth, employment, economic_growth, gdp, economic_activity, job, welfare, income, economics, wealth, decoupling, country, social, industrial, labor, green_growth, natural_resource, create	-2.31e-04	2.19e-28
161	293	Human environment systems	Relationship between human activities and ecosystems	human, natural, ecosystem, nature, ecological, biological, human_activity, relationship, organism, biophysical, matter, theory, natural_capital, life, resilience, human_society, biosphere, natural_environment, regenerative, environment	-2.31e-04	4.03e-32
185	292	International economic relations	International trade with a	country, trade, domestic, export, import, international, world, global, cooperation,	-2.25e-04	2.18e-20

Topic no.	Slope rank	Superordinate theme	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Linear slope	p-value slope
			focus on the USA and Asia	economic_development, asia, usa, asian, developed_country, nation, economy, foreign, commodity, international_trade, trading		
221	290	Regulation	Legislation and institutional authority	regulation, law, regulatory, government, legal, institutional, institution, international, rule, political, act, public, legislation, policy, protection, authority, state, reform, effort, national	-2.23e-04	2.04e-06
85	288	Turkish energy system	Potentials and resources of the Turkish energy system	turkey, renewable_energy_source, fossil_fuel, country, energy_demand, import, renewable_energy, energy_source, renewable_energy_resource, domestic, grow, world, energy_supply, energy_resource, potential, rapidly, turkish, renewable_source, renewable, supply	-2.20e-04	3.04e-11
49	287	Energy markets	Restructuring of electricity markets and competition	market, industry, competition, reform, producer, sale, competitive, electricity_market, competitiveness, restructuring, create, price, sell, revenue, trading, promote, demand, enter, expansion, government	-2.05e-04	7.96e-22
217	286	Forestry	Forest management for biomass production	forest, wood, forestry, timber, harvest, forest_biomass, forest_management, harvesting, management, wood_product, log, deforestation, finland, forest_resource, woody_biomass, fire, manage, forest_ecosystem, forest_product, conservation	-2.04e-04	3.02e-15

A4.5 Topics with high betweenness centrality

Table A4.5 lists the topics equal or above the 95% quantile regarding betweenness centrality. Reference to these topics is made in the Section "Topic network and topic communities" in the main article.

Table A4.5: Topics with betweenness centrality score equal or above the 95% quantile

Topic no.	Betw. rank	Topic interpretation	Top 20 topic terms ordered by decreasing probability for each topic	Betw. centrality
8	1	Forecasting	predict, prediction, forecast, correlation, error, accuracy, accurate, actual, coefficient, accurately, obtain, forecasting, estimation, equation, average, linear, validate, statistical, relationship, algorithm	158
134	2	Reducing carbon footprints	carbon, carbon_emission, reduce, emission, carbon_footprint, offset, global, accounting, climate_change, reduction, carbon_reduction, net, atmosphere, carbon_sequestration, low_carbon, emission_reduction, sequester, emit, sink, greenhouse_gas_emission	141
227	3	Quantification & Estimation	estimate, amount, straw, produce, equivalent, county, average, potential, ton, approximately, annually, consume, quantity, account, collect, annual, collection, availability, calculate, quantify	134
67	4	Greenhouse gas inventories	emission, ghg_emission, reduce, ghg, greenhouse_gas_ghg_emission, reduction, emission_reduction, allocation, impact, pollutant, co_emission, inventory, emit, ghg_emission_reduction, indirect, abatement, air_pollutant, greenhouse_gas, co_two_eq, baseline	112
147	5	Reporting	report, category, literature, specific, detailed, orientation, guide, information, benefit, shs, specifically, discussion, part, classify, recent, note, esd, list, reduction, relevant	111
42	6	Grid control	mode, control, grid, time, frequency, dynamic, operate, characteristic, parallel, voltage, fast, dual, real_time, transient, connect, distribute, critical, driven, operation, simulation	109
211	7	Business	barrier, business, overcome, opportunity, lack, business_model, implementation, implement, create, obstacle, company, stakeholder, smes, driver, strategy, sector, uptake, successful, institutional, prevent	106

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CHAPTER 7

CASE STUDY 3 - MULTILEVEL KNOWLEDGE MANAGEMENT FOR MUNICIPAL CLIMATE ACTION: LESSONS FROM EVALUATING THE OPERATIONAL SITUATION OF CLIMATE ACTION MANAGERS IN THE GERMAN FEDERAL STATE OF LOWER SAXONY

7. CASE STUDY 3 - MULTILEVEL KNOWLEDGE MANAGEMENT FOR MUNICIPAL CLIMATE ACTION: LESSONS FROM EVALUATING THE OPERATIONAL SITUATION OF CLIMATE ACTION MANAGERS IN THE GERMAN FEDERAL STATE OF LOWER SAXONY

BIBLIOGRAPHIC DATA

Bickel, M. W., Caniglia, G., Weiser, A., Lang, D. J., & Schomerus, T. (2020). Multilevel knowledge management for municipal climate action: Lessons from evaluating the operational situation of climate action managers in the German Federal State of Lower Saxony. *Journal of Cleaner Production, 277*.
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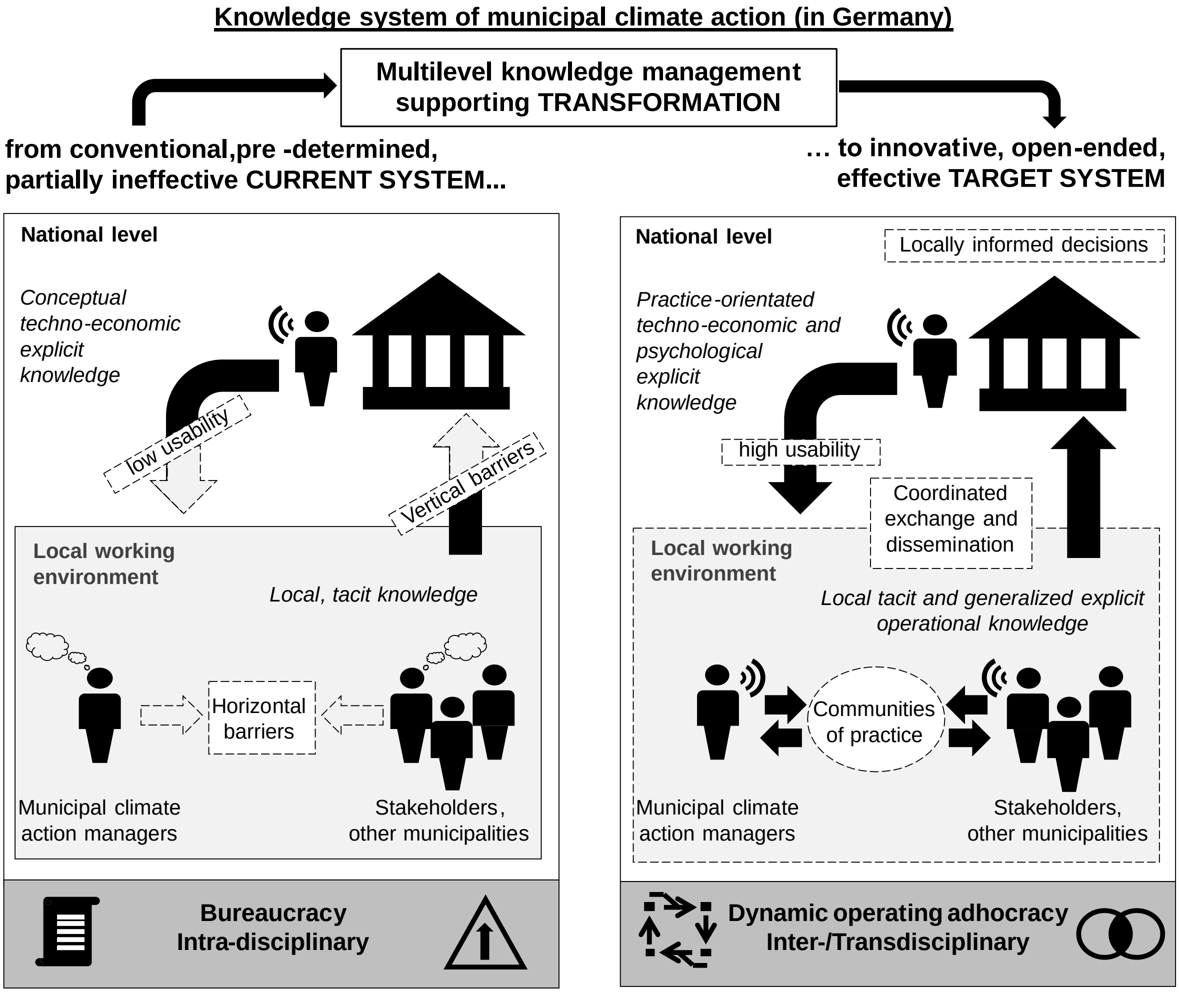
ABSTRACT

Effective actions to mitigate climate change are urgently needed, especially in the context of cities, which are major sources of global CO2 emissions. Establishing and managing knowledge systems that integrate local knowledge can contribute to establishing more effective responses to climate change as well as transformative change towards sustainability. However, it is still unclear how new forms of urban governance should acquire, store, create, or disseminate knowledge for fostering sustainability transitions effectively. In this study, we present a multilevel knowledge system approach based on design principles informed especially by the knowledge management literature. These address (i) working environments across multiple levels, (ii) knowledge forms and types, and (iii) knowledge processes. We apply this approach to municipal climate action in the German energy transition. In particular, we focus on the operational work of municipal climate action managers of regional centers of Lower Saxony, one of the largest of the 16 federal states, and investigate their involvement in knowledge processes. Based on semi-structured interviews in 14 of the 17 regional centers, we show that structural pre-conditions for successful knowledge management and organizational learning are present. However, we also show that there is a need for improvement regarding (i) the multilevel coordination for accelerating routine operation, (ii) the persistence of local operational knowledge, and (iii) the exploitation of local innovations. Relying on these results, we offer general recommendations for municipal climate action and suggest that policies should (i) rely on local knowledge for effective decision-making, (ii) foster multilevel exchanges of explicit and tacit knowledge for implementation, and (iii) enable open-ended learning processes that leverage local innovations for creating usable transformational knowledge.

Graphical Abstract



ABBREVIATIONS

CAM	Climate action manager
MCAP	Municipal climate action plan
MUCA	Municipal climate action

7.1. INTRODUCTION

A broad spectrum of societal responses has emerged for addressing the harmful effects of climate change (IPCC, 2015; Steffen et al., 2011). Knowledge systems, which involve dynamic processes such as acquiring, storing, creating, or disseminating knowledge, are the basis for many of such responses. Therefore, rethinking, designing, and managing knowledge systems can support climate action (Alves et al., 2020; Cash et al., 2003; Jasanoff, 2010; Martins et al., 2019; Muñoz-Erickson et al., 2017). This is particularly true regarding the governance of cities because of their significant contributions to global CO2 emissions (Edenhofer, 2014, p. 935; Grubler et al., 2012, pp. 1332–1335; IEA, 2008, p. 390; Wang et al., 2019). Over the past decades, cities have been dealing with this challenge proactively and have turned into vibrant fields of action, interventions, experimentation, and knowledge creation (Caniglia et al., 2017; Castán Broto and Bulkeley, 2013; Dignum et al., 2020). However, it is still unclear how the related contents, processes, or organizational structures as part of the knowledge system can best be managed for governing cities and for leveraging their full transformational potential. Indeed, such processes are often dispersed and fragmented, and it is increasingly difficult to link the work of city administration, societal and academic stakeholders, and decision-makers in ways that can foster mutual learning for sustainability transformations (Grubler et al., 2012, p. 1391; Muñoz-Erickson et al., 2017).

A key strategy of cities is Municipal Climate Action (MUCA) (Bulkeley, 2010; Castán Broto and Bulkeley, 2013). MUCA comprises analyzing the status quo, setting targets, preparing an action plan, and implementing individual measures. Various cities have carried out MUCA successfully. The Global Covenant of Mayors for Climate & Energy documents gives examples of over 9000 municipalities in 127 countries (GCoM, 2018). MUCA merges the work of informal and flexible local experimentation with the work of formal and stable public administrative structures. This convergence has the potential to foster generating, sharing, and using the knowledge that supports effective actions across different actors and scales (Betsill and Bulkeley, 2006; Bulkeley and Betsill, 2005; Lenhart et al., 2014).

This study examines the knowledge processes of MUCA in the German energy transition from the perspective of municipal climate action managers (CAMs). As an essential instrument in the German energy transition, MUCA is financed out of the national energy and climate fund as part of the National Climate Protection Initiative (Bickel, 2017; BMUB, 2015; German

Federal German Federal Government, 2011). Through this initiative, 2180 municipalities have developed municipal climate action plans (MCAPs) and employed 650 CAMs since 2008 (BMU, 2019; BMUB, 2015). CAMs represent the lower end of public administration for operationalizing MUCA, e.g., by advancing the implementation of action plans. They carry crucial operational knowledge and work at the interface of strategic planning and implementation. Their tasks include, for instance, internal and external communication and networking, the coordination of integrated collaboration, or the initiation of individual processes and comprehensive technical or non-technical projects (BMUB, 2016). Their cross-cutting agenda as “change agents” (Battilana et al., 2009) is atypical for traditional structures in public administrations and makes CAMs an interesting study example regarding institutional change towards effective climate action.

In this context, this study asks: How can we systematically understand and evaluate the way how knowledge is managed in MUCA in the public sector? What can we learn from current practices and experiences of CAMs about effective ways to manage knowledge in MUCA? Which challenges and opportunities can we identify in MUCA from a knowledge system perspective for designing or supporting societal responses to climate change? For addressing these questions, we compiled design principles for multilevel knowledge systems from the literature and interviewed 14 CAMs in the German Federal State of Lower Saxony (Lower Saxony).

With this study, we leverage the potential of knowledge management for sustainability transitions to contribute to the multilevel analysis of MUCA. Research on MUCA calls for more integrated multilevel analyses that can leverage the innovation potential of experimental approaches (Bickel, 2017; Bulkeley, 2010; Hildén et al., 2017). Further, research is needed regarding the challenges and opportunities that professionals face in municipal transition activities (Feagan et al., 2019). This study contributes to closing this gap with empirical insights into the operational work of CAMs using a knowledge management approach that identifies critical spots in the knowledge system. Knowledge management approaches for climate action are sparse, especially regarding the municipal context (Massaro et al., 2015). In Germany, there is hardly any research focusing on knowledge in a climate action context[6]. The empirical study

[6] This conclusion is based on querying the Scopus database in January 2020. One of the search phrases we used to come to this conclusion is: TITLE-ABS ((knowledge AND climate W/5 mitigation) OR (knowledge AND

most related to the present one investigates how “knowledge orders” influence the preparation of municipal climate policies (Zimmermann, 2018). The present study puts a stronger focus on multilevel and operational aspects and, thus, provides new insights and recommendations that might be relevant for other transition contexts.

The rest of this study is organized as follows. Section 7.2 first introduces the methodological approach for conducting the empirical work in Lower Saxony. It then summarizes various features for systematically analyzing multilevel knowledge systems. Section 7.3 present the interview results. Section 7.4 discusses the results and highlights general challenges and opportunities for CAMs in Germany and MUCA more generally. Section 7.5 concludes with a summary of the main findings and recommendations. It also discusses limitations of this study and points out research needs.

7.2. MATERIALS AND METHODS

7.2.1. Study cases and general methodological approach

7.2.1.1. Cases in Lower Saxony

The theory of central places (Christaller, 1966; Getis and Getis, 1966) defines municipalities that fulfill vital functions for their regions as regional centers. Their situation affects their entire regions and is an indicator of the average regional municipal situation. Due to the number of over 150 regional centers in Germany (BBSR, 2018), this study focuses on a single federal state. There are 16 federal states in Germany, which are key administrative and political units. This study concentrates on Lower Saxony, which belongs to the largest states. German municipalities share many commonalities regarding the conditions for MUCA (Kern et al., 2005). Thus, despite the geographical limitations, the present study still reflects patterns that might be encountered in the whole of Germany.

In Lower Saxony, the regional development plan (Lower Saxony Ministry of Food, Agriculture, Consumer Protection, 2017) defines 17 regional centers. These include Hanover, the state capital, which was excluded from the analysis. As the capital, it benefits from more

("energy transition" OR "climate action"))) AND TITLE (knowledge OR information OR learning OR "co-production") AND (LIMIT-TO (AFFILCOUNTRY , "Germany")) AND (LIMIT-TO (DOCTYPE , "ar")) advantageous conditions than other municipalities. Another exclusion criterion was its size. This study focuses on cities with fewer than 300,000 inhabitants. This city class is currently dominating globally (UN DESA, 2019, pp. 55–58). Appendix A provides the detailed population statistics of the cities examined. Other researchers also recommend not focusing exclusively on forerunners or large cities (Hoppe et al., 2016; Kern et al., 2005).

For this study, interviews with CAMs in 14 cities were conducted. On a map, Figure 7-1**Fehler! Verweisquelle konnte nicht gefunden werden.** provides an overview of Lower Saxonian regional centers where interviews were conducted. At the time of conducting the interviews, Göttingen had no CAM, and the one in Wolfsburg was not available. In 2016, there were around 60 CAMs in Lower Saxony financed by the national funding scheme (KEAN, 2016). In several German municipalities and some of the ones examined here, environmental officers or energy managers fulfill comparable functions as CAMs, although they are not CAMs in the strict sense of the funding scheme. This study refers to all of them as CAMs.

This study considers three of the selected municipalities as advanced in terms of MUCA. They base their activities on comparably detailed MCAPs and targets with political backing. On this basis, they have achieved an active involvement of various sectors and local stakeholders. Moreover, they have received awards from external bodies for their success. This study refers to selected developments in these municipalities as distinguishing examples in the results and discussion sections.

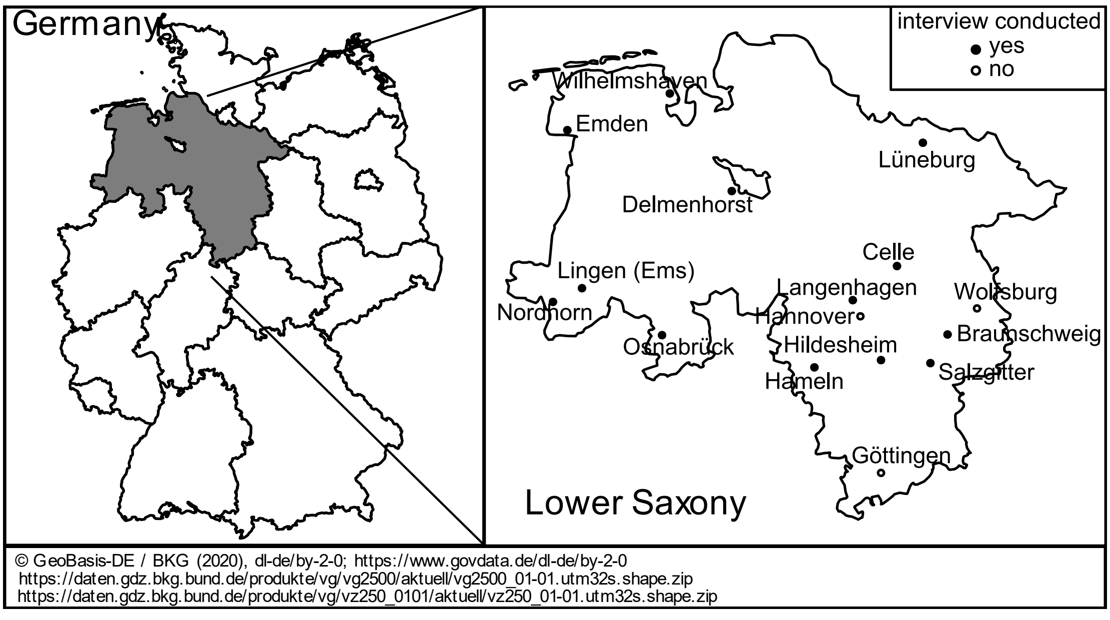


Figure 7-1: Map of Lower Saxonian regional centers created using the R (R Core Team, 2019) package rgdal (Bivand et al., 2020) and public geospatial data

7.2.1.2. Semi-structured interviews

For this study, semi-structured interviews were used as a flexible and effective method of investigation (Steinar and Brinkmann, 2009). For improving the preliminary understanding of the regional situation, the authors of this study personally visited the regional energy agency of Lower Saxony (KEAN). This agency is a regional facilitator of MUCA (KEAN, 2016). Making this contact should contribute to being perceived, to a certain extent, as an insider during the interviews. This precondition should further increase the quality of the knowledge shared by CAMs.

The 90–120 min interviews took place in the CAMs' offices in 2016. Through this face-to-face exchange, a vital factor for knowledge sharing (Krogh et al., 2000, pp. 82–92; Nonaka and Krogh, 2009), the authors sought to increase the quality of the interview results. Phone interviews, for instance, might not have produced the same high quality. To ensure privacy and comply with good research practice, a non-disclosure agreement was signed. The interviews consisted of open-ended questions about organizational structures, available knowledge types, and the involvement in knowledge processes. They were based on a set of standard questions on knowledge management (Probst et al., 2012) and that was extended to cover context-specific aspects. After a pre-check with one of the municipalities, the final interview guideline was prepared. Appendix B contains the final version. As a good precondition for this study, the education and professional backgrounds of all interviewees, which are summarized in Appendix C, enable them to engage in advanced knowledge processing potentially.

7.2.1.3. Content analysis

All interviews were transcribed, coded for content analysis, and analyzed following the principles summarized in Table 7-2 in Section 7.2.2.5. Using qualitative content analysis (Baxter and Jack, 2008; Mayring, 2014, pp. 10–15, p. 10–15), the interviews were coded in an iterative exploratory process for deriving findings at a higher order of abstraction. Where necessary, additional background information was considered, e.g., from websites of municipalities or institutions such as regional energy agencies[7], the German Institute for Urban

[7] Examples of regional energy agencies are the one of Lower Saxony (https://www.klimaschutz-niedersachsen.de/) or of Northrhine-Westphalia (https://www.energieagentur.nrw/).

Affairs[8] (Difu), or the German National Climate Protection Initiative[9]. The software MAXQDA (VERBI, 2017) supported the coding process and the analysis of code frequencies.

7.2.2. Features of multilevel knowledge systems for systematic analyses

In the German energy transition, MUCA is embedded in the national administrative structure, an organization with a multilevel knowledge system. To systematically analyze the latter, this study mainly relies on the literature on organizational knowledge management. The following section first present a working definition of knowledge and, secondly, a multilevel knowledge system approach considering: (i) working environments across horizontal and vertical levels (ii) knowledge forms and types, (iii) knowledge processes, and (iv) design principles for evaluating knowledge systems.

7.2.2.1. Information and knowledge

Knowledge has a human character. It resides in individuals and their interactions. People create or utilize knowledge when they act, whether intentionally or not. (Nonaka, 1994; Probst et al., 2012, p. 23; Wiig, 1993, pp. 68–69). Individuals receive information flows, in other words, messages or signals, from external sources, e.g., by personal exchange, reading texts, or consuming media. Information flows may restructure existing knowledge and may serve to create new knowledge (Dretske, 1981, pp. 44, 82; Machlup, 1983; Nonaka, 1994). If and how information flows influence knowledge depends on experiences and beliefs, which act as a filter, as well as on the situational context in which information is received (Krogh et al., 2000; Nonaka, 1994; Venzin et al., 1998). Thus, knowledge carries a normative character (Nonaka, 1994). For evaluating the knowledge system of organizations, analyzing the "semantic aspects of information," i.e., the meaning conveyed in action-oriented contexts, can provide helpful indications as long as the human characteristics of information processing are recognized (Nonaka, 1994).

7.2.2.2. Working environments across horizontal and vertical levels

Organizations consist of groups or teams of individuals that are usually formally structured and that dynamically interact in networks (Hannah and Lester, 2009; Pentland, 1995; Yang and

[8] https://difu.de/

[9] https://www.klimaschutz.de/

Maxwell, 2011). Regarding the multilevel structure of organizations, a distinction can be made between static structural units defined by the prescribed horizontal and vertical structure and dynamic functional units formed for addressing specific tasks or fields, often project-based (Nonaka, 1994). These units are the individual working environments shaped by the context-specific (administrative) rules, processes, or working culture. An organization may create and advance knowledge or, in other words, learn from exchange processes across both, horizontal levels, e.g., across departments, and vertical levels, e.g., from local to national, (Probst, 1998; Senge, 2006; Yeo, 2005).

7.2.2.3. Knowledge forms and types

Knowledge forms and types are features of the static structure of knowledge. Table 7-1 provides a summary of these features, including references and practical examples. The table categorizes knowledge regarding (i) the continuum between explicit and tacit forms of knowledge, (ii) the content types of knowledge with a focus on aggregated types that are particularly relevant in sustainability science, i.e., system, target and transformational knowledge, and (iii) the generalizability of knowledge.

Table 7-1: Forms of knowledge and aggregated types of knowledge

	Short explanation	**Exemplary references**	**Practical examples**
Knowledge forms			
Explicit	- Codified knowledge that is formally transmittable, e.g., via numbers or words - Conscious embrained knowledge of individuals		Text in MCAPs, disciplinary facts or calculation formulas
Along the continuum between explicit and tacit knowledge, there is a point where both forms converge, and tacit knowledge can be shared through interaction.		(Ambrosini and Bowman, 2001; Anderson, 1983; Krogh et al., 2000, pp. 82–84; Lam, 2000; Nonaka and Krogh, 2009; Polanyi, 1966, 4–6, 14–16; Spender, 1996)	
Tacit	- Unconscious, embodied, action-orientated know-how or routines learned from practical activity or bodily experience		Practical skills or experience of individual CAMs

	Short explanation	Exemplary references	Practical examples
	- Personally bound to the human body and mind - Cannot be shared directly - May manifest in shared norms within organizations		
Aggregated knowledge types composed of basic types			
System	- Detailed understanding of the initial system state or status quo - In the optimum case, comprehensively considering the more basic knowledge types such as descriptive, relational, temporal, or causal knowledge.	(Alavi and Leidner, 2001; Chandrasekaran et al., 1999; Preisinger-Kleine, 2013; ProClim, 1997; Venzin et al., 1998; Wiek et al., 2006; Wiig, 1993, 119, 137–139).	Local infrastructure statistics; estimated municipal greenhouse gas emissions
Target	- Definition of a desirable future system state - Basis for envisioning the future or setting goals		Municipal emission targets
Transformational	- Comprehensive sets of processes, actions, or pathways for reaching a desired future system state from the initial state		Project ideas or methodological pathways for realizing projects
Generalized	- Knowledge with more general applicability, usually condensed from multiple cases - Condensed to the point but may lack specificity	(Raymond et al., 2010)	Guidelines for municipal climate action issued at national level
Contextual	- Case-specific knowledge emerging from a specific context of a multilevel organization, e.g., local knowledge - Detailed but may lack general validity		MCAPs that translate national guidelines to the local level for reflecting the local characteristics

7.2.2.4. Input-output model for knowledge processes

Individuals and organizations process and create knowledge through different interlinked steps (Fazey et al., 2013; Pentland, 1995; Probst, 1998). The literature conceptualizes knowledge processes in a multiplicity of ways (Fazey et al., 2013; Holzner and Marx, 1979; Nonaka and Toyama, 2003; Probst, 1998; Wiig, 1993, p. 53; Yang and Maxwell, 2011). This study uses of a simple input-output model to analyze knowledge processes of organizational units comprising the steps: input, conversion and creation, storage, and output (Figure 7-2).

Strictly speaking, with reference to Section 7.2.2.1, the input and output are information flows, not knowledge flows. Mechanistically applying input-output models is not reasonable for analyzing knowledge systems (Nonaka, 1994). This study uses an input-output model as this model can be easily linked to the practical context of MUCA, which strongly relies on the structure of public administration that explicitly defines various organizational units, e.g., for receiving or disseminating information. This study avoids a mechanistic perspective by acknowledging the meaning and purpose of information flows and the relevance of different forms and types of knowledge.

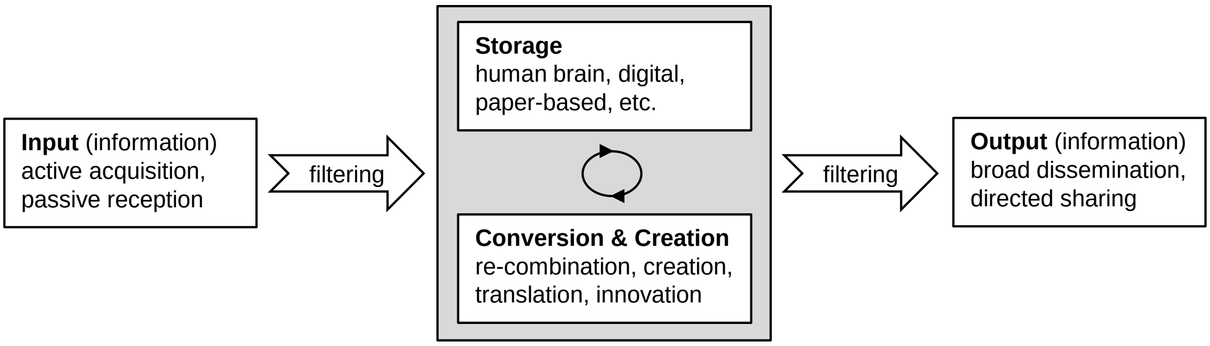


Figure 7-2: Knowledge processing steps of an organizational unit; in practice, these steps are interlinked and may coincide (coincidence not shown in the figure)

7.2.2.5. Design principles for multilevel knowledge systems

High interconnectedness is an essential feature of a multilevel knowledge system that effectively makes use of the innovations created in diverse teams (Dyer and Nobeoka, 2000; Hannah and Lester, 2009; Nonaka, 1994; Phelps et al., 2012). Figure 7-3 provides a scheme of such a knowledge system. Ideally, knowledge processes at different levels are designed and interconnected in a way that the knowledge required for finding solutions to complex problems is exchanged and available across all vertical and horizontal levels in suitable forms and types. Table 7-2 summarizes design principles for highly interconnected multilevel knowledge systems. The principles in the table do not represent an exhaustive list. They were tailored to the evaluation of the MUCA knowledge system in Germany.

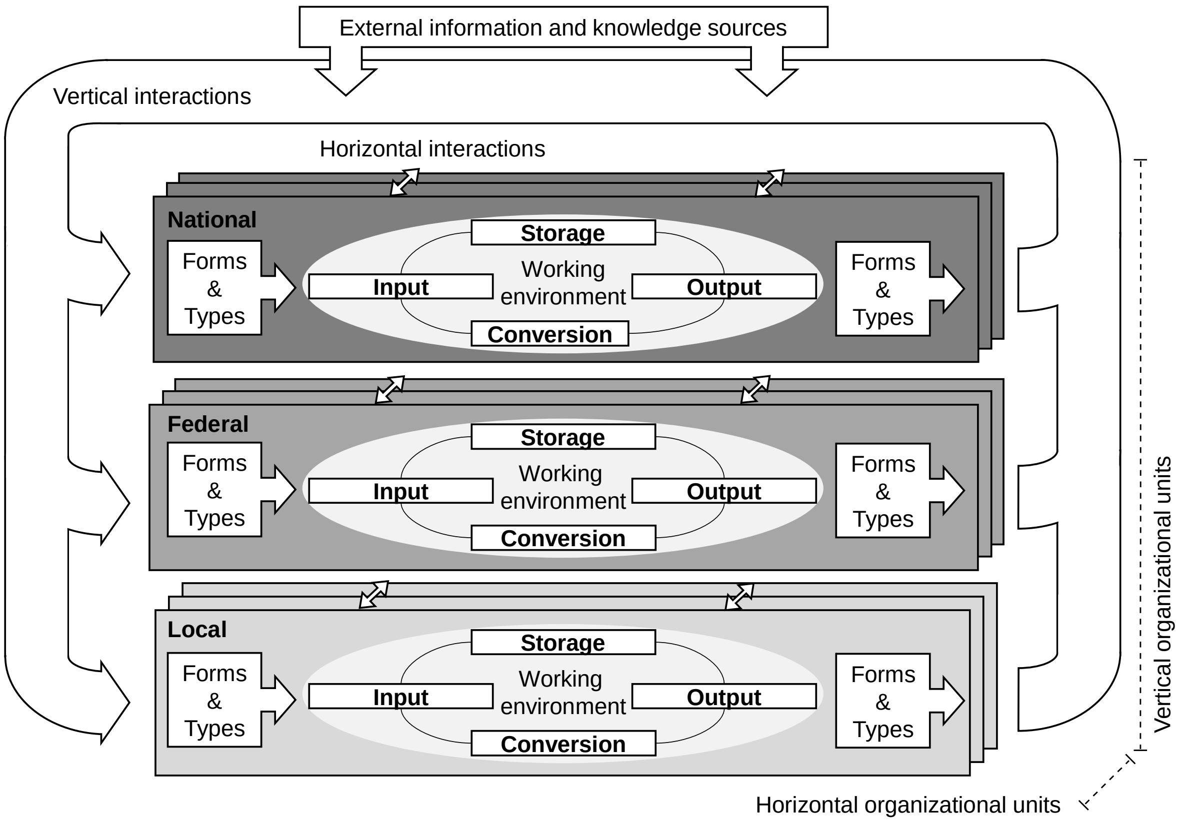


Figure 7-3: Scheme of a highly interconnected multilevel knowledge system

Table 7-2: Aggregated design principles for a highly interconnected multilevel knowledge system grouped by the main knowledge systems elements

Element	Principle	Exemplary references
Working environments across horizontal and vertical levels		
Structural	STRUCTURAL OPENNESS: Overcome structural knowledge barriers across horizontal and vertical organizational units by close connections.	(Hansen, 1999; Probst et al., 2012, p. 168; Tortoriello et al., 2012; Yang and Maxwell, 2011)
Functional	FUNCTIONAL OPENNESS: Overcome functional knowledge barriers by close connections between disciplines or professions, e.g., by supporting a culture of interdisciplinary exchange.	(Hansen, 1999; Probst et al., 2012, p. 168; Tortoriello et al., 2012; Yang and Maxwell, 2011)
Individual	RULES: Create open communication channels by communication rules that secure a minimum level of connectedness of individuals working on related content.	(Dyer and Nobeoka, 2000; Yang and Maxwell, 2011)
	SUPPORT: Establish a supportive working environment that motivates to share information and to engage in learning and experimentation with appropriate ways of constructively dealing with mistakes or failure.	(De Angelis, 2013, p. 167; Probst et al., 2012; Shalley and Gilson, 2004; Yang and Maxwell, 2011)
	ROLES: Stay aware of the influence of roles and power positions within organizational units or across scales that may facilitate or block communication channels and the sharing of information.	(Fazey et al., 2013; Preisinger-Kleine, 2013; Probst et al., 2012: 168; Yang and Maxwell, 2011)
Knowledge forms and types		
Forms	FORM: Focus on and cultivate knowledge forms according to the problems to be solved and particularly consider the value of tacit knowledge.	(Lam, 2000; Raymond et al., 2010)
System, target, transform-ational	CONSISTENCY: Built system, target, and transformational knowledge consistently in a soft hierarchy from basic to more aggregated types, e.g., from descriptive over causal to system knowledge. This hierarchy is soft because types can be developed in parallel. Important is the consistency of the final structure of knowledge.	own consideration inspired by literature (Chandrasekaran et al., 1999; Forrest and Wiek, 2014; Preisinger-Kleine, 2013)
Target	VISION: Update and share an organizational vision based on multilevel participation for creating accepted target knowledge	(Nonaka, 1994; Preisinger-Kleine, 2013; Senge, 2006, pp. 5–12)
Transform-ational	USABLE: Create usable knowledge, not only useful knowledge.	(Lemos et al., 2012)

Element	Principle	Exemplary references
Knowledge processes		
Input	<u>COORDINATE</u>: Coordinate information flows and avoid information overload in the input processes across scales, e.g., by bundling or finding synergies.	(Eppler and Mengis, 2004)
Conversion and Creation	<u>COMBINE</u>: In conversion processes, (re-)combine knowledge from different contexts to innovate and to create new knowledge, e.g., by engaging in open-ended experimentation.	(Fazey et al., 2013; Mulgan et al., 2007; Nonaka and Toyama, 2003; Shalley and Gilson, 2004)
	<u>EXPERIENCE</u>: Make use of practical experience and operational knowledge, e.g., via communities of practice, best practices, or lessons learned during knowledge creation.	(Fazey et al., 2006; Raven et al., 2008; Wenger, 2000; Wenger and Snyder, 2000)
Storage	<u>PRESERVE</u>: For enabling storage of and steady access to knowledge, prepare, encode, and preserve it for practical use in collective open repositories or ensure continuity of staff carrying relevant tacit knowledge.	(Pentland, 1995; Probst, 1998)
Output	<u>TRANSLATE</u>: For the output process, translate knowledge in suitable processes (linguistic, networking, etc.) to reach potential receivers and coordinate dissemination of information across scales.	(Holden and von Kortzfleisch, 2004; Liyanage et al., 2009; Probst, 1998)

7.3. RESULTS

The following Section 7.3.1 provides a general overview of the multilevel knowledge system of MUCA in Germany with reference to Figure 7-2. This overview is independent of the interviews. Subsequently, Sections 7.3.2 to 7.3.5 present the findings from the interviews.

7.3.1. Multilevel knowledge system of MUCA in Germany

Regarding the local level of MUCA, CAMs use the information output from higher levels or other municipalities as input for their operational work. They further absorb input from various non-state sources, e.g., companies, civic organizations, press, or research institutes. Regarding knowledge conversion and creation, e.g., during project development with stakeholders, innovations may emerge by combining knowledge from different domains and groups (Fazey et al., 2013). Storing their knowledge can be a critical issue since the national scheme usually grants funding for the positions of CAMs for three years only. Afterward, not all municipalities can prolong their positions without funding. Considering knowledge dissemination, the multi-faceted knowledge of CAMs can be a valuable information output to higher levels concerning local innovations but also prevailing local conditions.

At the federal state level, information inputs include outputs from the national level, e.g., laws, policies, or guidelines, and outputs from the local level, e.g., concerning needs of municipalities or local innovations. At the federal level, organizational units such as the regional energy agencies (eaD, 2017) may serve as "intermediaries" (Matschoss and Heiskanen, 2017) between these two levels. Federal agencies collect information, store it, and translate the inputs from one level into outputs that the other level can better incorporate. For example, they may initiate networking events that support exchange between CAMs and, also, support the dissemination of information from the national to the local level.

At national level, the input covers all kinds of information from various levels and sources, e.g., reports from selected municipalities or regional energy agencies, position papers or reports from trade associations, or various research outputs. In a conversion step this input is turned into more aggregated, abstract forms. Typically, the aggregated parts serve for building general databases, i.e., storages, that lead to information outputs such as the database on funded projects for MUCA (BMU, 2018a). The abstract parts such as strategy papers lead to, e.g., laws and policies connected to climate action. The latter are elements of the comprehensive "organizational vision" (Nonaka, 1994) that, as explicit target knowledge, is a crucial national output setting the ground for knowledge processes across horizontal and vertical levels. The general national project management agency (Projektträger Jülich, 2018) or the national service center for climate protection (Difu, 2015) apply an additional conversion step towards operationalization. They are major organizational units for distributing the national output, e.g., in the form of guidelines or funding advisory services.

7.3.2. Empirical insights from the interviews

Based on the interviews with the 14 Lower Saxonian CAMs, the following sections present empirical insights into the dynamics of the knowledge system of MUCA. The results are structured according to the main knowledge system elements: the working environment of CAMs, types and forms of knowledge they need for supporting MUCA, and key multilevel knowledge processes. Table 7-3 provides a summary of the results. Appendix D contains the raw codes, their frequencies, and exemplary statements from the interviews.

Table 7-3: Summary of results from interviews with CAMs in Lower Saxonian regional centers describing the knowledge system from their local perspective

System element	Result
Working environments across horizontal and vertical levels	
	- Low formal position impairs involvement in administrative knowledge processes - Setting up informal personal information channels often is an interim solution
Knowledge forms and types	
Form	- Operational knowledge for MUCA is largely tacit
Type	- Constraints for creating transformational knowledge are vague target knowledge, limited usability of available methods, and limited focus on causal knowledge - Traditional techno-economic knowledge mostly available, but lack of usable knowledge in newly emerging domains
Multilevel knowledge processes	
Horizontal input	- Key knowledge fragments can usually be acquired, but data acquisition is challenging due to weak formal legitimization towards externals
Conversion	- Open-ended learning processes and transcending organizational or disciplinary boundaries are key for creating knowledge - Bureaucracy and disciplinary thinking insufficiently support this kind of environment
Storage	- Storage of local knowledge is a bottleneck; it is rather unsystematic and limited to descriptive knowledge, continuity of tacit knowledge is at risk
Horizontal output	- Only limited professional knowledge of communication strategies available despite frequent communication activities in daily work
Vertical Input	- Information overload regarding practice examples - Gaps in the coordination of information flows at the federal level
Vertical Output	- Local output reaching higher levels generates an incomplete and over-optimistic picture

7.3.3. Working environment of CAMs at local level

The interviews show that CAMs often face uncertainty concerning their legitimization in their working environment due to their low positions in local administrations in specialist departments. The degree of their official involvement in local knowledge processes depends on their formal position. Therefore, CAMs highlighted that their success in internal exchange strongly depends on personal contacts and sympathy. In several cases, this results in delayed or blocked information flows from other (disciplinary) departments towards CAMs. Also, the bureaucratic nature of administration often negatively influences information acquisition or innovative approaches, especially when the latter involves open-ended experimentation. In this context, several CAMs strategically set up information channels, usually on a personal basis, that are not foreseen by the standard procedures of administration. An interesting observation is that in all of the few advanced municipalities that have established structured adaptation processes concerning targets and transition pathways, CAMs had a solid argumentative stance independent of their formal position.

7.3.4. Knowledge forms and types at local level

Vague target knowledge and limited usability of methods or limited focus on building sound system knowledge are constraints for creating transformational knowledge. The answers of CAMs indicate that, in most of the municipalities, only rough qualitative visions or highly aggregated descriptive numbers concerning emission targets prevail. CAMs stated that they mostly adopt a step-by-step workflow instead of following a comprehensive work plan due to missing guidance or the vague definition of the target state. Concerning building up system knowledge, CAMs considered carbon accounting, one of the primary methods commonly used for MUCA, controversial due to missing or impracticable standards, and missing data. The limited usability of this methodology sometimes brought CAMs and municipalities in difficulties explaining or justifying published municipal emission balances.

The interviews indicate that the incomplete target and system knowledge complicates the creation of transformational knowledge. Concerning building causal knowledge, CAMs confirmed that unstructured approaches or ad-hoc information exchange prevail. This hampers, e.g., setting up procedures and initiating campaigns effectively since influencing factors concerning potential target groups are rarely clear. In the advanced municipalities, there was a clear consciousness for causal knowledge and using it for argumentation in local discussions. This indicates the relevance of causal knowledge.

Regarding the content of knowledge that CAMs need in their daily work, they stated a lack of usable knowledge in newly emerging domains and domains of communication. They assured that they carry the required traditional techno-economic or environmental domain knowledge themselves or have sufficient access to appropriate explicit knowledge sources. However, the availability of usable explicit knowledge in new domains such as e-mobility was not satisfactory. Although higher institutional levels make related explicit knowledge available, e.g., via national platforms, the latter is only partly usable for implementation. Furthermore, CAMs were aware of a knowledge gap in the domains of communication and psychology, e.g., operational transformational knowledge for actor-specific strategic communication, storytelling, or actor-network analysis. Only one CAM from an advanced municipality has systematically been acquiring knowledge in these domains. The fact that this has supported achieving the advanced status indicates the value of this kind of knowledge.

Turning to forms of knowledge, the interviews show that operational knowledge for MUCA is dominantly personal tacit knowledge of individual CAMs while encoding seems to be delayed or incomplete. Therefore, it is understandable that CAMs highlighted personal communication as the best way to exchange information and creating knowledge. They deemed the available codified knowledge, e.g., best practice examples, a good starting point. However, it is often not sufficiently usable in practice. In consequence, for acquiring the core usable knowledge, CAMs usually try to establish personal communication, which initiates turning tacit to explicit knowledge.

7.3.5. Multilevel knowledge processes

7.3.5.1. Horizontal processes at local level

Looking at the input process, CAMs stated that they usually manage to acquire the required key explicit knowledge fragments. However, they also stated that they have to deal with incomplete information input from external sources and several constraints regarding internal coordination. The acquisition of knowledge from external stakeholders depends on their willingness to share since there are few formal rules for such exchange. CAMs highlighted that this limits the input of information, e.g., for reliable CO2 accounting, and the creation of, e.g., causal knowledge.

In part, CAMs work on a fragmentary basis regarding external descriptive knowledge. However, when investing sufficient efforts, CAMs usually achieved to establish an information exchange with stakeholders that is just sufficient as a working basis. Especially CAMs of the advanced municipalities emphasized that, for a fruitful exchange, continuously showing presence and regular personal exchange is crucial.

Considering knowledge conversion and creation, CAMs described various projects from their work that they deemed creative. In these projects, overcoming organizational or disciplinary boundaries and the willingness to participate in open-ended learning processes was the most important way to create new knowledge. Yet, CAMs experienced that the current bureaucratic nature of administrations and adherence to disciplinary thinking, e.g., of external stakeholders, insufficiently support such conditions. CAMs in the few advanced municipalities stressed that creativity further needs individuals acting as a constant driving force, especially in situations when project teams experience a phase of discouragement. They also emphasized that teams need suitable constellations for triggering creativity. Therefore, it is crucial to know the local landscape of stakeholders for identifying and connecting appropriate combinations.

Storage of local knowledge is a bottleneck since the continuity of knowledge is at risk and storage is mostly limited to descriptive rather than causal knowledge. Knowledge of MUCA largely remains individual tacit knowledge of CAMs with limited-time contracts. Establishing suitable modes to handover knowledge personally, e.g., to successors, is difficult on this basis. Handovers can sometimes be realized merely in explicit form through written reports with limited possibilities for passing on relational knowledge, local network connections, or practical lessons learned.

In several cases, lessons learned were also stored in a generalized format as best practice examples for the use in other municipalities. However, CAMs highlighted that, beyond being a source of inspiration, such examples are usually not useful for concrete implementation. Their transferability is limited since they are often based on special financing or depend on site-specific local contexts. Hence, an important observation regarding storage is that the focus lies on descriptive explicit knowledge. The interviews show that documentation of context variables or even the impact of projects is unsystematic and that the idea of building causal knowledge is rarely present. Of course, basic evaluations of local projects are stored and used as a basis for argumentation already. However, municipalities hardly document real problems and success factors. This might be one reason why all CAMs emphasized that primary sources for this kind of knowledge are other CAMs met at networking events organized, e.g., by regional energy agencies. Again, this indicates that crucial parts of relevant knowledge are largely stored in tacit form.

The final part concerning horizontal knowledge processes deals with the local output of CAMs and shows that they mostly had limited knowledge of communication strategies available but often engaged in bilateral communication or municipal-wide campaigns. The interviews suggest that the most important strategy of CAMs is identifying advantages of policies or planned operational activities in the field of climate action for different stakeholders and, on this basis, convincing them to participate. They apply this strategy on various occasions such as internal administrative meetings, citizen campaigns, or roundtables with stakeholders from the industry. Some CAMs who achieved to position themselves well within their municipalities started to take a service-orientated role. Thereby, they consolidate and broaden the dissemination of their knowledge.

7.3.5.2. Vertical processes between local level and federal or national level

Regarding vertical aspects of the input process of CAMs, on the one hand, they face information overload; on the other hand, gaps in the coordination of information flows. CAMs generally appreciate available national or federal publications supporting implementation, e.g., of best practice examples. However, they criticize the overwhelming number of reports that complicate, e.g., the identification of truly best practices related to their local contexts. The input required by CAMs is coordinated to a certain extent, e.g., via regional energy agencies. However, for compiling codified knowledge, CAMs need to refer to many different (regional) agencies. Furthermore, CAMs stated few coordinated approaches for identifying synergy potential between municipalities or collective needs.

Concerning the output of the local level, an incomplete picture of the local situation arrives at higher levels. The majority of the local level reports that reach higher levels focus on innovative projects or best practices demonstrating general feasibility. However, these information flows concentrate on flagship projects that have benefited from special funding or conditions. They are not representative of the average situation. Since knowledge of CAMs is primarily individual tacit knowledge and personal contact to higher levels - especially the national level

- in structured dialogues is seldom, relevant local operational knowledge reaches higher levels only in a few instances.

7.4. DISCUSSION

The interviews on the knowledge system of MUCA indicate that (i) the working mode of the administrative system is often opposed to the requirements of advanced climate action, (ii) the vertical synchronization of local and national levels is incomplete, and (iii) the storage and transmission of CAM's operational knowledge are often not ensured. The following sections discuss challenges and opportunities for the German context in detail. Table 7-4 summarizes them and, in addition, Figure 7-4 visualizes the opportunities and required conditions.

Table 7-4: Challenges and opportunities for the knowledge system of MUCA in Germany

System element	**Challenges**	**Opportunities**	**Related principles** (see Table 7-2**)**
Working environments across horizontal and vertical levels			
Working Environ-ment	- Bureaucratic environment leading to structural knowledge barriers	- Providing a practice-orientated organizational vision beyond abstract goals for shaping supportive working environments and efficient horizontal and vertical workflows	VISION, ROLE, RULE, SUPPORT, STRUCTURAL OPENNESS
Knowledge forms and types			
Form	- Local tacit knowledge and information on local knowledge requirements receive insufficient attention in national processes	- Synchronizing knowledge processes vertically by structured personal exchange from local to the national level, e.g., via local mandates from communities of practice	STRUCTURAL OPENNESS, USABLE, FORM
Type	- Incomplete conversion between local contextual and generalized knowledge - Local system knowledge is fragmentary	- Supporting an evidence-based transition grounded in connected local databases accompanied by standardized reporting procedures - Emphasizing building of causal knowledge via qualitative and quantitative methods for creating reliable transformational knowledge - Identifying usable best practice examples by proven methodologies	CONSISTENCY, PRESERVE, USABLE

System element	Challenges	Opportunities	Related principles (see Table 7-2)
Multilevel knowledge processes			
Input	- Horizontally disconnected knowledge fragments across municipalities - Information overload regarding downstream information flows	- Providing a clear framework for operationalizing MUCA in terms of information flows - Closing knowledge gaps by extended duties for stakeholders to disclose environmentally relevant information - Strengthening the coordinating role of energy agencies as intermediaries and bundling information at federal level	VISION, COORDINATE, RULE, CONSISTENCY
Con-version	- Bureaucratic and disciplinary thinking hamper innovative knowledge creation	- Leveraging local innovations by supporting experimentation environments and valuing tacit knowledge	COMBINE, VISION, FORM, STRUCTURAL & FUNCTIONAL OPENNESS
Storage	- Structured storage of operational knowledge with proven usability is limited	- Connecting local knowledge processes and establishing collective storing approaches - Focusing on usability when storing operational knowledge from local project experience - Planning for handover procedures that enable sharing tacit knowledge	PRESERVE, FORM, EXPERIENCE, USABLE
Output	- Unclear how to organize vertical upward information flows for making local knowledge usable at higher levels	- Establishing efficient vertical upward information flows by using federal agencies as knowledge translators	COORDINATE, TRANSLATE, USABLE, STRUCTURAL OPENNESS
	- CAMs need to justify MUCA towards local stakeholders and may face obstacles when trying to initiate change	- Developing social skills of CAMs for effective knowledge integration and dissemination as institutional change agents	TRANSLATE, ROLE

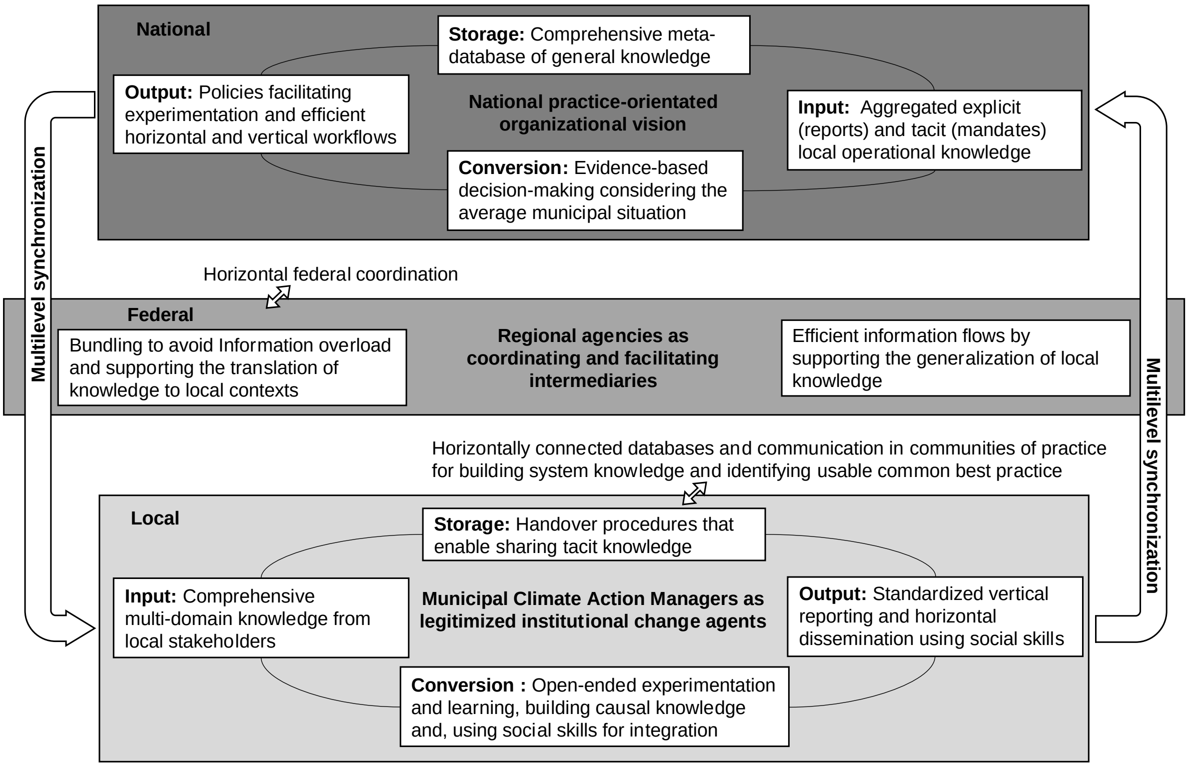


Figure 7-4 Opportunities and required conditions that facilitate knowledge processes for MUCA in the multilevel knowledge system of Germany.

7.4.1. Working environment of CAMs at local level

Challenges

The interviews show that it is challenging for CAMs to fully leverage the cross-cutting potential of climate action at the local level. Their low position in administration weakens their legitimization and results in impaired information exchange. Their environment, which resembles a "machine bureaucracy" (Lam, 2000), amplifies this effect. Formal structures shape their environment and evoke divisive thinking and the tendency towards maintaining the status quo. This leads to various "knowledge barriers" (Probst et al., 2012, p. 168).

Opportunities

A more actionable or practice-orientated "organizational vision" (Nonaka, 1994) that is "co-produced" (Jasanoff, 2010) with relevant actors would support establishing the required working environment. Beyond abstract targets, e.g., regarding emission reductions, an advanced national vision should include practice-orientated descriptions of goals and pathways that organizational units at different levels can easily adopt for operational work. This would appeal to a broad range of operational administrative staff and would, thereby, serve as a bridge in horizontal and vertical knowledge processes, e.g., between different departments. Practice orientation would also require highlighting and defining the necessary communication channels across different levels to establish seamless workflows. Therefore, policies should define additional "communication rules" (Dyer and Nobeoka, 2000) that increase the integration of CAMs in information flows and facilitate knowledge dissemination by CAMs.

For successfully establishing an advanced organizational vision with the above features, this vision needs to be updated continuously in participatory processes across vertical levels (Preisinger-Kleine, 2013; van den Heiligenberg et al., 2017). This way, administrative staff would potentially not depreciate it as abstract goals but use it as a means to achieve consensus during transition efforts (Joas et al., 2016).

7.4.2. Knowledge types and forms

Challenges

This study suggests that, in the German context, incomplete vertical alignment of knowledge processes has led to a lack of usable knowledge at the local level. A local process, parallel to national activities, is necessary for translating the orientation and methodologies provided along with high-level policies into actionable procedures for operationalizing MUCA. At the local level, this kind of process does not seem to have taken place thoroughly. Municipalities are expected to implement measures, especially of technical nature, which the national level has only sketched. Municipalities have not been equipped sufficiently with usable knowledge for defining actionable pathways. A similarly unsynchronized communication regarding the national provision of climate change information and local needs was observed, e.g., in the United Kingdom (Demeritt and Langdon, 2004). The interview results suggest that, on the one hand, the explicit knowledge provided by the national level is too abstract and focuses on techno-economic domains, while domains for initiating change, e.g., communication, are underrepresented. On the other hand, the knowledge of municipalities about their local dynamics is limited since local empirical data for assessing impacts is often fragmentary.

Opportunities

Synchronizing multilevel knowledge processes by a more personal exchange would increase the practical usability of knowledge. Already in early steps of policy-making, national knowledge processes ought to involve more structured interpersonal exchange with the local operational level by “strong ties” (Hansen, 1999). This increases the mutual understanding of current considerations and concerns (Homsy and Warner, 2013) and increases the bandwidth of information considered and disseminated for approaching local operational tasks. An option for realizing closer vertical exchange could be meeting procedures involving local mandates, e.g., from local communities of practice, who introduce local operational knowledge concisely and act as reviewers of national processes. For climate adaptation, research has already proposed institutionalized review processes at city level (Muñoz-Erickson et al., 2017). Multilevel approaches with review elements have already been successful, admittedly not frictionless, in the field of resource or ecosystem management by installing co-management arrangements (Berkes, 2009).

Another aspect that ought to receive higher emphasis is the potential of evaluations for building causal knowledge consistently for supporting a more evidence-based transition. Grounding the designs of local pathways on evidence more clearly increases the potential for success (Forrest and Wiek, 2014; Preisinger-Kleine, 2013). Several public sector studies have illustrated the importance of supporting policies and decision-making by “organised systematic empirical enquiry” (Davies et al., 2000, p. 6) using a broad spectrum of methods such as regression analysis, impact analysis, randomized experiments or, more generally, transition experiments

(Davies et al., 2000; Luederitz et al., 2017; Millard-Ball, 2012). One option to achieve such enquiry in the context of MUCA is a more detailed compulsory reporting procedure in funding schemes that asks for project data and information on local developments (see also in Section 7.4.3.4). A drawback is that this would require allocating resources for the documentation. However, improved reporting allows for establishing comprehensive connected local databases. Such a database can be used for analyzing project data via best practice management methodologies (Dani et al., 2006; Zairi and Whymark, 2000) for revealing truly usable best practice and, also, for learning from failure (Borins, 2001). Furthermore, an advanced local database enables applying mixed qualitative and quantitative analytical methods broadly for drawing (causal) inferences and creating reliable transformational knowledge.

7.4.3. Multilevel knowledge processes

7.4.3.1. Input

Challenges

The combination of incomplete information exchange and insufficient vertical coordination leads to horizontally disconnected knowledge fragments across municipalities. The limited legal basis of municipalities (Karg, 2017) hampers acquiring environmentally relevant explicit knowledge from local stakeholders, e.g., companies. Duty of disclosure such data partly exists, e.g., through the German Federal Emission Control Act, but does not cover the full range of explicit knowledge required for comprehensive climate protection. In contrast to this gap, the incomplete vertical coordination of downstream information flows towards CAMs creates “information overload” (Eppler and Mengis, 2004). The fragmentary and insufficiently coordinated input seems to be a reason for the situational step-by-step workflow often adopted by CAMs. This discontinuous workflow hampers identifying synergies between CAMs or municipalities regarding operational tasks.

Opportunities

A more precise framework for operationalizing MUCA, particularly considering the vertical and horizontal exchange, would foster leveraging existing potentials. Climate action requires advanced options for gathering data from stakeholders to build comprehensive local system knowledge. Policies, e.g., at national level, ought to introduce extended duties to disclose environmentally relevant data. At the same time, finding suitable ways to ensure data protection is crucial. The tension between data protection and provision will require increased attention in the context of climate change.

Another measure for improving information flows is strengthening the coordinating role of energy agencies as cohesive "intermediary organisation[s]" (Matschoss and Heiskanen, 2017). Bundling their outputs horizontally across the federal state level reduces information overload towards CAMs. Moreover, coordinating the municipal inputs to these agencies helps to detect synergies or innovations of greater relevance. These organizations can further play an important role in communicating local needs towards the national level. However, as a study on Manchester, United Kingdom, shows, such intermediaries need to understand themselves as representatives of and for the municipalities; otherwise, they just reinforce the national agenda (Hodson and Marvin, 2012).

7.4.3.2. Conversion

Challenges

The bureaucratic environment CAMs face in local administration is not only a challenge in the input process but also during knowledge conversion and creation. The administrations tend to disciplinary specialization and aim at the stability of existing structures. In this context, the integration of disciplines and innovative knowledge creation is demanding.

Opportunities

Allowing for more creative freedom and exchange in administrative rules and structures supports leveraging the available local innovation potential. CAMs require a working mode closer to an "operating adhocracy" (Lam, 2000) that values explicit knowledge but also supports developing tacit knowledge and open-ended experimentation. A case study on Malmö, Sweden, highlights that structured continuous interdepartmental communication can lead to policy innovations (Lenhart et al., 2014).

In the German context, administrative rules should be modified to support the emergence of a moderate experimental transition atmosphere. In the first step, not all municipalities can establish wide "epistemic networks" (Dobson, 2019) or comprehensive "transition arenas" (Loorbach, 2010) that support different working modes and institutional change. Therefore, starting with moderate steps creates preconditions for more comprehensive approaches. Administrative procedures ought to incorporate more elements allowing for flexible project development and, e.g., through additional communication rules and opportunities, a gentle integration of less innovation orientated organizational units or disciplinary thinking stakeholders. A study on 100 European cities showed that, for instance, involving rather traditional public sector organizations can be beneficial for experimental approaches (Dignum et al., 2020). Furthermore, fostering social ties and informal communication significantly supports innovative approaches (Pelling et al., 2008). This has been discussed, e.g., for climate action in Durban, South Africa (Leck and Roberts, 2015).

Facilitating communication triggers (re-)adjusting or transcending organizational and disciplinary boundaries as well as the relations between the involved perspectives and interests. Such a communicative basis facilitates empathic multilogues, increases the willingness to invest efforts in open-ended learning processes, and can lead to a fruitful collaboration in networks.

7.4.3.3. Storage

Challenges

Since several CAMs have limited-time contracts, local transformational knowledge that has already proven its value in operational work is volatile. Although CAMs partly document best practice examples, obstacles for the documentation process are missing coordination and standardization across municipalities. This leads to the unstructured storage of explicit knowledge and complicates targeted and efficient searching for best practice examples. Various examples are also documented at higher organizational levels, e.g., on national platforms. However, they serve to establish a positive public image rather than for providing usable knowledge for broad application. Beyond these deficiencies, the current modes of storing explicit knowledge hamper creating causal knowledge, which would support building reliable transformational knowledge (see also Section 7.4.2).

Opportunities

Improved structuring of the storage of operational knowledge supports the continuity of operational transformational knowledge and the efficiency of the transition process by accelerating collective learning processes. A step into this direction would be advancing the project database provided in the national meta-platform for climate action (BMU, 2018b). For ensuring “usability” (Lemos et al., 2012), the database needs to incorporate operational project experience from municipalities considering the local contexts and influencing factors beyond basic project descriptions. For the case of the United Kingdom, one study also argued that more direct communication between the local level and the national level would increase the usability of nationally issued climate change information (Demeritt and Langdon, 2004).

A recommendation that applies but is not limited to Germany is to store the best common practice examples in the sense of actionable solutions to MUCA created from projects under average conditions. This is different from storing, e.g., best practice emerging from prestigious projects based on special funding. Furthermore, CAMs highlighted that a usable database should entail information on contact persons as the basis to initiate sharing tacit knowledge on impediments and solutions. This kind of advanced empirical basis regarding local solutions should be incorporated into high-level decision-making for enabling conditions that create solutions to everyday operational problems. Setting up a comprehensive database might not be possible in the short-term. An initial compromise would be to consider, ahead of time, how to realize suitable handover modes allowing for a personal exchange between different generations of CAMs.

The proposed approach of establishing a cross-municipal database and exchange of experience is challenged by the fact that transferring local knowledge between municipalities is a sensitive and not always feasible process (Williams, 2017). However, connecting isolated local knowledge processes through collectively storing knowledge is an opportunity for triggering comprehensive learning processes that accelerate local transition processes as a whole.

7.4.3.4. Output

Challenges

It is not clear yet, how knowledge processes at the national level can integrate local knowledge in a better way. The output of CAMs is not standardized. Their vertical information output is weakly structured and often of limited usability at the national level. Therefore, at the national level, awareness tends to be higher for non-representative prestigious examples involving, e.g., the use of new technologies, than for realistic pictures on municipal developments. In this situation, several innovative approaches for advancing MUCA beyond using innovative technologies remain within local networks as tacit knowledge and do not reach a wider audience.

Regarding CAMs' output towards other administrative units and local actors, their low position requires them to use various "social skills" (Fligstein, 1997) for justifying MUCA and initiating institutional change. Other studies, e.g., in Scandinavia, also addressed such difficulties in disseminating transition knowledge in hierarchical contexts (Hauge et al., 2019; Lenhart et al., 2014). For overcoming such barriers, CAMs use "issue re-labelling" (Heinelt and Lamping, 2015) as one of the key strategies. This means taking different perspectives, e.g., of the economic departments, and highlighting advantages of MUCA from these perspectives without emphasizing MUCA but, e.g., economic advantages.

Opportunities

Incorporating a higher amount of local operational knowledge at the national level by advanced multilevel coordination allows for designing policy frameworks towards more effectiveness and innovativeness at the local level. A study on national adaptation plans of 13 countries also points out the need for similar bottom-up approaches (Alves et al., 2020). For the climate change adaptation context in Norway, a study showed, in specific, that representatives of the national level can benefit from the direct personal exchange with the local level (Hauge et al., 2019). In addition to sharing local tacit knowledge through a vertical exchange (see Opportunities in Section *4.2*), vertical upward information flows need to be efficient. CAMs need to document their experience and innovations usable form for the national level, e.g., how to activate stakeholders from different fields. Intermediary regional agencies should then support the necessary knowledge translation (Matschoss and Heiskanen, 2017).

Apart from the above-mentioned strategic aspects of vertical knowledge output, the administrative system ought to support the operational role of CAMs as institutional "change agents" (Battilana et al., 2009) or "boundary spanners" (Goodrich et al., 2020) more clearly. Strengthening the set of social skills that can foster knowledge integration (McGuire, 2006) requires more systematic support for the communicative competences of CAMs. This kind of support increases the efficiency of routine operation and knowledge creation processes in general. In a few of the studied cases, CAMs have successfully applied such skills and developed MUCA in a way that local stakeholders acknowledge the advantages of MUCA beyond merely reducing emissions. In these cases, CAMs could adapt their role towards more service-orientation and shift efforts from challenging the old institutional logic towards mainstreaming the new logic (Battilana et al., 2009). This indicates the beginning of a potential institutional change and that MUCA can be part of an integrated transition process more broadly.

7.5. CONCLUSIONS AND RECOMMENDATIONS

This study combines design principles for knowledge systems and insights into the local operational level of MUCA in Germany based on 14 interviews. This section concludes, first, by summarizing the challenges encountered in the cases studied and, second, by highlighting general opportunities and recommendations for policy-making. Furthermore, the final section highlights limitations of this study and future research needs.

This study shows that many organizational units for knowledge management are available for MUCA in the context of the German energy transition but that their dynamic interactions need to be enhanced. The bureaucratic working mode of German administration is often opposed to the flexibility required for advanced MUCA. This also impedes integrating a sustainability orientation in local administrations more generally (Kirst and Lang, 2019). Furthermore, the vague organizational vision regarding the operationalization of MUCA has partly led to an incomplete synchronization of local and national knowledge processes. Therefore, local needs are only partially fulfilled and the national level has only fragmentary knowledge about the local operational conditions. In this context, CAMs have the potential to act as institutional “change agents” (Battilana et al., 2009), who carry and create valuable operational knowledge. However, their cross-departmental integration in administrative workflows is limited. Therefore, they cannot fully leverage the available innovation potential, e.g., of interdepartmental collaboration. Another critical issue is the volatility of operational knowledge since it concentrates in individual CAMs with limited-time contracts and handover modes are not clearly defined.

For approaching the challenges described above, the knowledge system perspective of this study offers various policy recommendations. Designing and implementing structured multilevel learning processes for establishing a highly interconnected knowledge system increases the efficiency of the routine operation of MUCA and supports innovations that are usable and more transferable. A fundamental prerequisite for learning is to understand the elements and dynamics of the system in which climate action takes place. As part of a comprehensive organizational vision for MUCA, national policies should support multilevel learning processes that consider both explicit and tacit forms of knowledge. The inclusive multilevel character of these systems is pivotal since tackling climate change requires new ways of co-producing knowledge (Frantzeskaki and Rok, 2018; Jasanoff, 2010; Mach et al., 2020).

Policies should emphasize the collection of data using practicable standards, categorization schemes, and archiving rules, which can be used to build a comprehensive database of explicit knowledge. Such a database allows for applying advanced analyses for inferring causal knowledge, which can be used, e.g., for detecting common or even failed patterns of action versus successful innovative patterns (David and Gross, 2019; Derwort et al., 2019). In turn, the resulting analytical conclusions directly enhance the operational work. For successfully steering transition processes in MUCA, it is crucial to generate and store system knowledge that is not abstract but instead taps into the broad empirical basis of local knowledge from different stakeholders. Establishing open and consistent exchange of causal system knowledge, developed from the local context across horizontal and vertical levels, is required if we want this knowledge to become the basis for analyses and decision-making at the different levels.

Further, policies ought to promote institutional arrangements facilitating collaboration that support the sharing of operational tacit knowledge, e.g., within local communities of practice or public administration. Encouraging the exchange of tacit knowledge requires fostering personal exchange, also in informal settings (Nonaka and Konno, 1998; Pelling et al., 2008). In addition, policies should facilitate the exchange between staff from the local operational level and the national decision-making level. Such an exchange raises awareness for operational conditions at upper organizational levels and, thereby, increases attention to issues of feasibility when developing targets and designing transition pathways. For an efficient exchange of both explicit and tacit knowledge, it is crucial to coordinate and, where possible, bundle knowledge processes both horizontally and vertically. In this way, the multilevel learning processes benefit from data and human experience and generate actionable transformational knowledge.

In a transition context, policies should support the creation of innovative transformational knowledge. In practice, establishing supportive working environments enables the creative potential (Shalley and Gilson, 2004; Yang and Maxwell, 2011) of administrative staff that needs to engage in open-ended learning or experimentation. To a certain extent, policies can justify the need for and benefits of experimentation (Caniglia et al., 2017; Luederitz et al., 2017). They ought to support knowledge integrators such as CAMs in leveraging the potential of collaboration for innovation. A few of the municipalities studied here managed to integrate

MUCA into municipal life successfully and enabled a more service-orientated role of CAMs. This was possible because knowledge integration during MUCA achieved conceivable benefits for various municipal stakeholders. Motivated by such examples, a new official task of administrations could be dynamically creating innovative transformational knowledge and providing transition services.

In summary, for supporting effective responses to climate change and sustainability transitions in general, national policies can help to establish efficient multilevel knowledge systems by (i) supporting the generation of causal system knowledge that relies on local knowledge for effective decision-making, (ii) establishing efficient multilevel exchanges and integration of explicit and tacit knowledge for implementation, and (iii) allowing for flexibility in administrative structures to enable open-ended learning processes that leverage local innovations and create usable transformational knowledge. In this way, national policies can contribute, from the top down, to creating the conditions for and supporting the establishment of highly interconnected multilevel knowledge systems and learning processes that are rooted, from the bottom up, in local knowledge and expertise. Such orchestrated interplay of knowledge leverages the transformational potential of cities and supports integrated actions that contribute to the broader transformation towards sustainability.

7.5.1. Limitations and future studies

This section acknowledges four limitations of this study on the knowledge system of MUCA and points out research needs.

First, as pointed out in Section 7.2.1.1, the number of cases and geographical coverage limit the representativeness of this study. To a certain extent, it can still indicate some general patterns of MUCA in Germany due to the various commonalities regarding the conditions for MUCA in German municipalities (Kern et al., 2005). Furthermore, this study focuses on the average municipal situation. Future studies might conduct more comparative studies, e.g., between forerunner municipalities and the municipalities with average or even poor performance regarding MUCA for better understanding municipal dynamics. The goal of this research direction would be to develop a comprehensive roadmap of diverse municipal transition pathways with a high resolution of individual transition states. All kinds of municipalities could then link these generic states to their current own states and use the roadmap as a guide for accelerating their sustainability transitions.

Second, the knowledge management literature is the main basis of the compilation of design principles in Section 7.2.2.5, which is, thus, focused on organizational and managerial aspects. This is only one of the many possible perspectives for analyzing knowledge systems (Muñoz-Erickson et al., 2017). With reference to one of the "knowledge system analysis" (Muñoz-Erickson et al., 2017) frameworks recently proposed, the present study focuses on "functions" and "complexities" (Muñoz-Erickson et al., 2017) of knowledge systems by applying a multilevel knowledge management approach. In future work, it would be useful to compare this study with works applying complementary perspectives that look, for instance, more at epistemic aspects (Dobson, 2019; Frantzeskaki and Rok, 2018). Beyond the need to integrate different perspectives on knowledge systems and the nature of knowledge itself, a rewarding task of future research will be to understand which frameworks or perspectives are best suited to facilitate sustainability transitions in a given context. This requires transdisciplinary research projects that have applied or will apply different frameworks and provide insights into knowledge processes in practice. Accompanying meta-studies could analyze the different project settings from a second order perspective in order to gain valuable insights into the interaction of practice with different frameworks or theories.

Third, there are various other factors and contexts to knowledge systems that have not been considered explicitly such as available resources (Hegger et al., 2012; Nonaka, 1994) or the political and economic context (Feagan et al., 2019; Jasanoff, 2010). Future research might reveal the influence of these factors and contexts on the configuration and dynamics of knowledge systems in order to clarify limitations of applying a mere knowledge system perspective.

Fourth, the interview-based methodology also has its limits. Interviews are situational events influenced by various factors such as age, gender, or professional background (Qu and Dumay, 2011; Steinar and Brinkmann, 2009, pp. 123–124). The professional background of the interviewer, i.e., environmental engineering, is related to the one of most CAMs interviewed. This might have influenced the "follow-up" or "probing" questions (Steinar and Brinkmann, 2009, p. 135). Interviewers with different backgrounds might have posed other questions. Furthermore, the interviews focused on how to make MUCA more efficient from the perspective of CAMs. Interviewees might have downplayed potential personal deficiencies.

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7.7. DATA STATEMENT

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared.

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APPENDICES

Appendix A - Population statistics of Lower Saxony

Table A.1: Population Statistics – Lower Saxony and regional centers

State / City	Population in 2016
Federal State of Lower Saxony (total)	7.990.991
Hannover	536.055
Braunschweig	248.528
Oldenburg	168.301
Osnabrück	164.622
Wolfsburg	124.247
Göttingen	119.182
Salzgitter	104.441
Hildesheim	101.789
Delmenhorst	77.546
Wilhelmshaven	76.001
Lüneburg	75.333
Celle	69.225
Hameln	57.497
Lingen (Ems)	54.465
Langenhagen	54.457
Nordhorn	53.579
Emden	49.977
Sum of population of regional centers	2.135.245
Sum without Hannover	1.599.190
Sum without Hannover in percent of population of Lower Saxony	20%

Source: Federal Statistical Office of Lower Saxony, https://www1.nls.niedersachsen.de/statistik/, Accessed 12 November 2019

Appendix B – Interview Guideline

Table B.1: Set of initial questions asked during the interviews

Role and professional experience	
Professional experience and current position	Describe your education and professional background. Describe your current position and tasks.
System, Target Transformation Knowledge	
Target Knowledge	How clear is your picture about the target state of the municipality in the individual sectors industry / commerce, trade and services / mobility / private households / education? Is there something like a vision that goes beyond target states in form of CO2 reduction targets? How detailed is it concerning the structures in the individual sectors?
System Knowledge	How is your knowledge situation regarding the current state in these sectors?
Transformation Knowledge	How is your knowledge situation regarding the required actions to approach the target state?
Local information sources	
Missing (transformation) knowledge	Regarding the pathway, what is the knowledge that you are missing? At which points do you have difficulties to proceed and what knowledge would you need?
Information sources	Do you generally have all the contact persons among the local actors? Do you encounter difficulties in approaching them?
Quality of information sources	Concerning the quality of information exchange with these stakeholders, what could be improved?
Information sources in general	
Information sources	Considering all societal levels, what are you most important sources of information and knowledge for the successful climate action?
Sources for legitimization	Do you have any sources available aiding you in your legitimization in the municipality?
Best Practice databases	Which role do Best Practice databases and project examples play for you?
Improvement of Best Practice	How could the use or reporting of Best Practice examples be improved?
Specific information sources	
	You have already mentioned some of the following actors as information sources. Could you please describe more in detail which role the following actors play for you?
Difu as source	The Difu (national service centre for municipal climate action) at the national level?
KEAN as source	The KEAN (Lower Saxonian energy agency) at the federal state level?
Science as source	How does science contribute to your operational work? -You might think of science concretely as universities or research institutes but also as science in a general sense.

Knowledge conversion	
Examples of creative projects	Describe two to three examples or projects of your work, in which you used creativity to create own solution strategies or innovation. If available, one of the examples should be from an industry or economy context.
Definition and emergence of creativity	What was the creative or innovative moment in these projects? How did it evolve?
Synergy	When you approach new projects, to what extent do you consider aspects of synergy and transfer from the outset?
Storage	
In general	How do you store your knowledge and make it so to speak available forever?
Tacit	What is the knowledge that remains stored in your mind? How easy or difficult would it be for a temporal substitute for your position to access your knowledge?
Impacts	Concerning impacts of your activities, which knowledge about impacts do you store? To what extent to you document a “before and after” perspective?
Lessons learnt	To what extent do you document your “lessons learnt”, i.e “what works and what does not work”?
Causal knowledge	To what extent do you use statistical models?
Output	
Boundaries	To whom and how do you disseminate your knowledge including formal and informal ways? Particularly consider how you disseminate knowledge outside of your municipality.
Quality	Have you received feedback to the knowledge you disseminated?
Openness	Which opportunities do you have to communicate grievances, e.g., internally within local administrations and to external units?
General situation	
Negative aspects	From your perspective, which institutions at which level could improve the framework conditions for municipal climate action?
Positive aspects	In your position, that is in many situations not directly empowered for decision making, how are you successful anyway to bring forward the implementation of local climate action? What are your success strategies?
Assessment of situation	In summary, how would you assess the knowledge situation concerning local climate action in your municipality, e.g., in comparison to other municipalities?
Sustainable climate action	
Integration	What would have to be done to make local climate action more sustainable? Consider the degree of integration of the various relevant knowledge domains in particular.

Appendix C - Education and Background of CAMs

Table C.1: Overview of the education and professional background of CAMs interviewed

Category	Feature	Number of interviewees
Education	University degree	12
	Degree for the higher administrative service	2
Discipline	Engineering or technical background	1/3
	Mixed background involving geography, spatial planning, environmental and resource management	2/3
Years of working experience	Less than 3	2
	Between 3 and 7	8
	More than 7	6

Appendix D - Codes and exemplary interview statements

The following tables provide the codes, their ID labels, and the code frequencies that emerged from the interviews and, in addition, exemplary statements from the interviews. Frequencies appear in the following formats: (i) The percentage of cases that a code applies to appears as C-percentage. For example, 7 cases were counted that a code applies to / total of 14 cases = C-50; (ii) Given a certain code with sub-codes, the frequency of citations that a sub-code applies to in relation to the frequency of all sub-codes, on average over all municipalities, appears as F-percentage. For example, if code X had 2 sub-codes, in one case X-1 was mentioned 3 times, X-2 was mentioned 6 times, the resulting total mentions would be 9; in a second case X-1 was mentioned 5 times, X-2 was mentioned 10 times and the resulting total mentions would be 15. The average frequency of sub-code X1 for the two cases would be (3 / 9 + 5 / 15) / 2 = F-33, and for sub-code X-2 it would be (6 / 9 + 10 / 15) / 2 = F-67; (iii) Some codes were created from mixed statements from all interviews; these aggregated codes only partially apply to each municipality and, therefore, appear as M without a number.

Table D.1: Results regarding the role and power position of CAMs

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
RWE1	CAMs are generalists and deal with many different knowledge domains. They call for more integrative thinking in decision-making.	“Climate action management is not green – it is all colors.” „Achieving long-term effects is one of the most difficult challenges. I see the urgency to focus on the long-term effects of the projects that we initiate.” “Acting sustainably means to bring together the diverse perspectives and approaches to achieve a higher efficiency, instead of letting them run in parallel.”	C-93
RWE2	They initiate and keep alive projects that involve various topics and stakeholder networks.	„We are the motivator or project pusher and try to bring on board the relevant institutions.” „We have to keep several balls in the air, which is often difficult considering the numerous projects that run in parallel.”	C-86

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
RWE3	CAMs have faced uncertainty concerning legitimization in their direct working environment.	„Eventually, you are working for a voluntary service when you are working for municipal climate action. This is the point somehow, since climate protection is not always well-respected in the administration." "It is always a good idea to obtain confirmation or acknowledgement from externals and not only from internals, since administration is not necessarily happy that we are there."	C-79
RWE4	Almost all CAMs are responsible for climate action as single person without direct colleagues working for climate protection. About a quarter have limited-time contracts.	-	
	Limited time contract (NKI funding)	-	C-29
	Unlimited contract	-	C-71
	Single person without team	-	C-71
RWE5	Position of CAMs at lower level of administration.	-	
	Position within specialist department of administration	-	C-79
	Advisory unit for specialist department of administration	-	C-7
	Advisory unit or agency for top level of administration	-	C-14

Table D.2: Results regarding system knowledge

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
SYS1	Availability of descriptive knowledge particularly in form of sectoral CO2 accounting	-	C-100
SYS2	Use of European Energy Award process for monitoring	-	C-21
SYS3	Carbon footprints considered controversial due to missing or impracticable standards for municipal emission accounting, missing or incomprehensive data, or mistrust in the data.	"Apart from the initial accounting, we have not prepared an interim accounting, because we face difficulties to draw the right boundaries. A renewed accounting might have created numbers that would make the credibility appear questionable. […This] might ruin the work that we have already achieved." "[Apart from CO_2 accounting,] there is a lack of suitable systemic indicators. As in the case of the ecological footprint, this is linked to the problem of defining the right system boundaries."	C-71
SYS4	State-of-the-art knowledge from the domain of technology is available as own embodied knowledge, from internal specialist departments, or external experts in particular.	"Technical knowledge is not really a problem. We have our specialists for buildings, traffic, etc. Of course, there is backlog in single cases, but in general this is not a problem."	C-100
SYS5	Electric mobility is a new technological topic associated with uncertainty due to missing overall transition pathway and insufficient multilevel alignment regarding provision of useable knowledge.	"Politics demands us to act, although a lot of knowledge is missing, […which] still has to be transferred into the administrative body. […] And there are many companies who want a slice of the cake, […] and praise their products […] by saying 'look, we have all these bonus schemes and subsidy programs, now please just buy our electric cars.' […] I finally have to get an overall picture and feel uncertain in this situation."	C-36

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
SYS6	Detailed knowledge in the domain of technology sometimes required to start communication with stakeholders through naming potential options that are usually not part of municipal climate action literature but, e.g., process engineering literature.	"As long as I haven't talked to experts from the field of this specific production sector I don't know which options exist and cannot contact the individual companies by saying: You don't make us of this option, but it is still possible." (statement by an interviewee from a municipality with an advanced status of climate action)	C-7
SYS7	Unstructured approaches or ad-hoc information exchange prevailed concerning building causal or procedural knowledge about potential target groups for campaigns	Only one interviewee mentioned detailed studies on values and symbols of target groups.	C-93
SYS8	Descriptive and relational knowledge for the identification of suitable contact persons is available	"Identifying contact persons is usually no problem."	C-79

Table D.3: Results regarding target knowledge

ID	Code		Frequency
TRG1	Rough qualitative vision of target states or highly aggregated descriptive numbers concerning emission targets	The quality of the visions differed, for example, from "I have a figurative imagination how the city should change as a whole" to "I have a relatively clear personal imagination how the target state looks like concerning the sectors and key terms".	C-79
TRG2	Only municipalities with structured learning processes (see Table D.4 TRF2) have more detailed structural goals for individual sectors	"We have developed strategic goals for the city."	C-14

Table D.4: Results regarding transformation knowledge

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
TRF1	Incremental case by case way of action	„There is no manual. It is like SCRUM*: where are we, where do we want to go, what are the next steps." *SCRUM: used in industry as a manner of agile incremental product development. "It is rather an evolution than a revolution."	C-100
TRF2	Structured goal-orientated learning and adaptation process that provides confidence about the envisaged pathway although working incrementally.	„We prepare an annual work program that includes proposals of our department but also of politicians concerning the next steps. It also sheds light on ongoing measures."	C-14
TRF3	The reasons named for the step-wise approach are manifold among the interviewees. • complexity of the problem and solution strategies • missing guidance and commitment of higher institutional levels • (local) politicization of climate protection instead of rational long-term approaches • volatility of human resource capacities	• "for the German Energy Transition or the Great Transformation we basically do not have a master plan" • "if you want to eat an elephant, you need to do this a bit at a time" • Steady need for quick integration of new and innovative topics that on the one hand are not yet comprehensively prepared (see e.g. e-mobility example in Table D.5) and on the other hand appear complex towards citizens • Dependency on the economic cycle that sometimes disrupts continuous approaches • Instable legislative framework and political back and forth • "Municipal climate action is a still voluntary task, voluntary commitment doesn't work. Making municipal climate action compulsory by federal state laws has been discussed for years, however, this has not been transposed."	M

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		• Climate action sometimes gets "mangled on the local political battlefield that is often based on short-term thinking". The local discursive process does not always end in favour of climate action since other municipal concerns might opposed. • Irregular availability of resources in the education sector, so that long-term approaches are difficult to establish • Capacity of local administrative is often insufficient to fulfil the high expectations from envisioning pathways. This would lead to "working for the drawer."	
TRF4	Importance of procedural and relational knowledge for comprehensive municipal-wide communication campaigns and its use to the extent available was highlighted	"The highest priority is the dialogue with the stakeholders that has to be maintained and cultivated continuously." "In any case, it would be falling short to only focus on 'energy' for winning 'clients' and generating motivation – I feel like I am the service providers and have to win clients." „You need to know about the hobbyhorses of the people."	C-79
TRF5-7	**Required or missing knowledge for the work**		
TRF5a	Knowledge from the domain of communication and psychology to: • encounter irrational argumentation • build communication bridges and establish dialogues • consciously use one´s role	CAMs faced, e.g., • Arguments such as "We do not want that; we do not need that. We still have enough gasoline. Climate change is not real.", "If my neighbor doesn't do that, why should I?", or	F-42

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		"Ventilation systems blow out false air, I do not want that." • "Reluctance to accept advice" • "Half- or quarter-knowledge" CAMs pointed out some success factors to cope with above situation: • "You need to pick them up via everyday topics." • "Layperson are often not interested in technical details, but how individual measures affect them personally. You need to argue towards them, for example, with positive experiences of other users from the same user group at a different but still spatially close location." • "Human aspects, psychology, also matter a lot. You need to know how to approach others. This is certainly easier for a 50-year old than for a 20-year old."	
TRF5b	Descriptive and relational knowledge about sectors and individual people	This includes knowing "trendsetters", "decision-makers", "hobbyhorses", "interests", "working conditions and available capacity of people", or preferences concerning the mode of communication.	F-30
TRF6	Organizational set-ups and working processes	"Collaboration with the public utilities", "public relations work and campaigns", "collaboration with the consumer advice centre", etc.	F-20
TRF7	Technical knowledge	"In the end, technology is the really interesting part."	F-1

Table D.5: Results regarding knowledge input from information sources in general, internal sources within administration and external sources such, i.e., (local) stakeholders

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
	Information sources in general		
INP1	Knowledge sources used by CAMs rather provide knowledge from traditional domains of climate protection, especially technology, than from domains such as communication or psychology.		
	Knowledge from the domain of communication and psychology	Examples of named sources or application fields are: seminars to improve rhetoric; companies that can set-up and conduct education projects or campaigns; scientific insights in terms of methods for public relations, e.g., storytelling, marketing, etc.	F-11
	Knowledge from the domain of organizational management, e.g., in terms of organizational set-ups or working processes	Examples of named sources or application fields are: networking events with other CAMs to exchange on how projects are handled successfully; energy agencies or national service centre for climate protection for organizational drafts or frameworks to initiate campaigns or projects	F-22
	Technical knowledge and knowledge from other traditional climate protection disciplines	Named sources are, e.g.: technology institutes, individual energy experts, energy agencies, environmental NGOs, federal institutions such as the German Federal Environmental Agency or the Service Centre Municipal Climate Action	F-67
INP2	Use of energy and climate action agencies of other federal states as information source	"Considering energy agencies as information source, I prefer the ones of other federal states, especially Northrhine Westphalia."	C-43
INP3	The Internet is a good starting point for overview information at a lower degree of detail, however, the most useful information stems from personal communication.	„The Internet is always nice for identifying initial approaches, however, when it comes to the nitty-gritty, personal contacts are more important."	C-100

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
INP4	Highly relevant sources are local and partly regional internal and external networks	Named sources are, e.g.: colleagues, disciplinary experts, local institutions, CAMs from other municipalities, local associations of citizens or companies	C-86
INP5	A tacit source of high value are other climate action managers, especially those within the same federal state	Exchange happens regularly during workshops at the federal level initiated by the regional energy agency.	C-64
INP6	Higher institutional levels sometimes fail to provide useable information and stick to providing knowledge in an explicit form.	"The national platform provides a lot of material, e.g., about e-mobility. However, it is so voluminous and text-intensive that you usually do not achieve to read it. You sometimes have the feeling that they are paid for the number of words they use." "[These sources are] good, in principle, however, often too far away and abstract, they sound nice. However how do they imagine the implementation?"	C-36
INP7	Most effective and important mode of communication takes place on a personal level	"The success strategy for data acquisition are open questions and getting to know each other on a personal level." „The interpersonal relationships are the most important thing for the collaboration with stakeholders. "	C-100
	External sources		
INP8	Information flows form external are not automatically reaching CAMs, however, once effort is invested, exchange with external stakeholders works	"If information is missing, for example, concerning energy consumption behavior of households, I contact the head of the local energy supply company. During the conversation, the missing information is developed and contact persons are identified."	C-100
INP9	Acquisition of external data strongly depends on the willingness of stakeholders to share information	„What does industry do? They won't tell me about their plans. You simply try to contact the stakeholders and try to find out what they are planning."	C-43
INP10	Consciousness about experiential knowledge to retrospectively evaluate	"Setting up clear rules for acquisition and sharing of information, which means to whom	C-29

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
	communication processes and recognize the potential volatility of external communication channels and the need to establish long-term cooperation and information processes.	do you communicate what in which manner, this is finally one of the central issues." "Knowledge lives on sharing, faces, people. […] For many years, we have three annual working meetings in our regional network, this is quite a good network."	
	Internal sources		
INP11	Internal exchange strongly depends on personal contacts and sympathy	From a positive perspective one interviewee stated: "If I would use the usual rigid administrative channels, I would not achieve to acquire information in time".	C-50
INP12a	Smooth internal information exchange	"Internal information exchange works well through a continuous dialogue."	C-43
INP12b	Minor constraints in terms of missing automated integration of CAMs in information flows of other departments	„There are many departments, e.g. building construction, that perform climate action activities on their own without consulting or coordinating with us."	C-29
INP12c	Limited or blocked information flows towards climate action managers	"What I find so worrying, is that the structure is so hierarchical, the groups are side by side, but they actually avoid working together." "Especially the process of information exchange could be improved. In the end, you usually get the required information, but the process is very lengthy and time consuming."	C-29

Table D.6: Results regarding knowledge conversion

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
CN V1	The search for synergy potential in standard and innovative projects is limited to individual sectors or methods and the boundaries of individual municipalities.	„When starting a campaign in one district, we consider if we could transfer it to another, however, we are limited to our municipality and pool of knowledge. If we found a lever in such project, we try to transfer it. However, transfer is still in the back of the head and we do not directly aim to achieve it.”	C-86
CN V2	Synergies are usually not planned for a priori and rather emerge in the course of implementation.	Two positive examples of synergies: “We contracted a consulting company to develop a blueprint for emission accounting that we can easily carry on […] without being dependent on assigning follow-up orders”. “For our public relations concept […] we demanded an agency to create an overall concept that includes general methods that we can use to address the public in general, but also specific target groups.”	C-64
CN V3	Creative solutions involve, e.g., cross-combinations of or collaboration between: • disciplines • departments • sectors • technologies • forms of communication • time horizons • (re-)drawing boundaries of areas • (re-)interpretation of benefits and impediments • flexible (re-)weighing of agenda	Findings on the left side may be derived from projects, that are deemed creative by the CAMs: • IT and open data for visualizing an interactive energy map, • intelligent heat recovery by solely using waste heat of servers for building heating • educative climate bicycle route on the basis of regional cooperation • collaboration with the traditional drilling industry for climate use of ground heat in district heat networks • Integrating climate protection aspects subordinately into a food festival • making house building companies understand to use the perspective of	M

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		climate action as future marketing added value instead of an impediment	
CNV4	Creative solutions require, e.g.: • empathy • networks • common language • multilogues • intrinsic motors • open-ended learning	"Empathize with the issue" on the basis of sound knowledge; adopt "networked procedures" with the stakeholders in "structured processes"; find a common "language" to enter open "controversial discussions", that are less dialogues but multilogues, that require a continuous "motor" to keep them alive against "sceptics" and "uncertainty" when breaking new ground and against the aversion to group learning processes with potential "dead ends".	M

Table D.7: Results regarding storage of knowledge in general and storage of experiential knowledge

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
STR1	Storage of knowledge is a bottleneck. Apart from time constraints, a reason for this is the missing encoding of climate action knowledge.	"This might be my weak spot and again depends on the available resources, because systematization and storage of knowledge requires effort. I admit that I do not store all operational knowledge, so that it would be accessible to anyone. Of course, I store a lot at our central storage; but, other than that is difficult to achieve and hold on to in practice." "When a colleague is on vacation, you realize that digital storing and filing is done in totally different ways. That is to say, we are still missing the big key for this issue."	C-79
STR2a	Operational knowledge, especially relational and descriptive knowledge about stakeholders, remains embodied knowledge	Storage of knowledge in individual minds, e.g., about "people", "networks", "lines of argumentation", "working procedures", "knowledge landscape."	F-68

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		Statement highlighting the tacit nature of operational knowledge: "If you imagine a handover of the position, this would be very difficult if you would not talk a lot to each other and work together for a certain time."	
STR2b		Storage in form of "interim reports", "activity reports", "guidelines", "flyers", "protocols", etc.	F-36
STR3	Practical lessons learnt remain embodied knowledge and are not documented or discussed internally to get the chance of becoming collective knowledge (in part, they are exchanged between CAMs on workshops at the federal level – see Table D.5 INP5)	„I have not experienced documenting lessons learnt in the administration, at most, issues for me personally."	C-86
STR4	Impacts documented unsystematically; mainly qualitative or quantitative descriptive indicators; no approaches to build sound causal knowledge	CAMs collect descriptive numbers about traditional material measures such as installed renewable power plant capacity, or saved energy after modernization of heating in public buildings. "We do document, e.g., campaigns in terms of the number of consultations performed, however, I cannot really make statements on impacts. I am missing the tools for this purpose." "Concerning impacts, I often have to rely on my gut feeling." Some interviewees stated, that in some cases, shallow evaluations have been performed, especially concerning the triggered investments by incentive programs.	M

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		Three municipalities try to tackle the task of documenting impacts on a municipal level by participation in the European Energy Award.	
STR5	No use of inferential statistical models.	Only one municipality has used a chi-square test in one single project as secondary information.	C-100
STR6	Current forms of best practice databases are mostly used for a first inspiration only and their usefulness was seen critical	"Best Practice examples described in brochures may, at most, serve for inspiration only." "Best Practice examples do not play an important role at the moment. In some cases, there are good examples in specialist journals, however, for there is not suitable database that could support my work."	C-71
STR7	Transferability of best practice examples is often not given since they are often based on special financing or local conditions	"Best Practices are rarely transferable; this is almost demotivating."	C-50
STR8	Many project examples, e.g., examples provided by other municipalities on their website, are labelled as best practice that, however, are state-of-the-art.	"There are too many best practice examples and too few good ones."	C-36
STR9	In some cities, best practice examples may still serve as external reference points to show the potential for success of specific approaches.	"Best practice examples can serve to initiate communication and dialogue".	C-43
STR10	The most important part of best practice examples are the contact persons to find out what the project really was about.		C-57
STR11	Instead of best practice, a general practice database would be more helpful, which would be based on commented bundled descriptive,	Combining statements from several interviewees, such database would cover: • "annotations of the implementing persons"	M

ID	Code	Exemplary statements (or content summary of several statements)	Frequency

	relational, causal and procedural knowledge.	• "areas of special attention in single steps of implementation"
		• "how have cooperation partners been won and how was the issue brought to the decision phase"
		• "which mistakes have been made"
		• "what went wrong, what went well and how was the project received"
		• an efficient "filter function" on the basis of
		  ○ a sufficient set of variables for covering the "grading about the implementation status of climate action"
		  ○ quantitative structural data about the municipality to find out "who does something comparable"	

Table D.8: Results regarding knowledge output

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
OUT1	**Knowledge about success factors or constraints of local climate action rather stays local and does not easily reach higher institutional levels.**	The complex knowledge about operational climate action is mainly disseminated on a personal basis, e.g., during network meetings. There is, e.g., a punctual half-yearly exchange between CAMs at the federal state level via meetings organized by the regional climate action agency that the interviewed CAMs usually attend. "We operate out of the community into the community". Dissemination of knowledge to organizational units associated with the national level is rare. Considering all statements on knowledge output, there is a gradient from local to national level regarding the reception of knowledge outputs.	
	Tacit to the local level Tacit to the national level Explicit to the local level Explicit to the national level	*Please note: numbers for output to other levels are not shown to focus on or point out the differences between output to local and national level.*	F-45 F-13 F-73 F-13
OUT2	The major strategy for successful dissemination was "issue re-labelling" (Heinelt and Lamping, 2015), i.e., highlighting advantages generated by climate action in various fields beyond climate protection.	Advantages named to bridge to other perspectives are, for example: • Health concerning food, e.g. CO2 and nutrient balance of a burger, • Health concerning air pollution by fossil fueled vehicles • Health by more body movement during cycling	C-71

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		• Saving money by saving energy, with relatively short amortization times esp. for public property buildings • Possibilities of networking for local companies when attending an energy roundtable • Using climate friendliness of buildings and as a future selling argument for real estate companies • Using the winning of energy efficiency prizes by individual companies as an image gain in their field of business • Using car sharing or riding bicycles as a mobility mode of low area intensity • Using efficient forms of logistics as a cost saving argument for producers while producing higher comfort for citizens • Local value chain • saving of material resources is also climate action that reduces costs • climate action as a chance and motor for urban town planning • outsourcing of own vehicle fleet to mobility provider reduces internal workload	
OUT3	The second most important strategy was to be neutral and objective in discussions when bringing forward arguments.	"I try to moderate without getting personally involved and try to apply a neutral approach with open ended questions".	C-50
OUT4	Although neutral, arguments need to be based on sound descriptive and relational knowledge about target groups to be able to find the right words and tone in conversations.	"Once we take an offering, once an intimidating role depending on the specific stakeholder type we are talking to."	C-50

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
		In summary, several statements showed the importance of entering conversations with the right topics, e.g. current topics of daily life such as food, or considering the personal sympathy explicitly when talking to stakeholders.	
OUT5	Networking and finding allies is an important strategy to use advantages such as: • possibility to rely on colleagues that have generally been won for climate action with time in small steps • internal win-win situations based on mutual (immaterial) favours • neutral external argumentative reference points	"Favour for a favour in the sense of mutually putting a good word to specific stakeholders or decisions makers to support each others projects." (it was emphasized that this was not meant in a material sense for clear dissociation from corruption or bribery) "Slowly convincing colleagues to eat more vegetables than meat at lunchbreak so that, if this is successful, one may count on them to a certain extent." "You first have to share, before you can square" (own translation of the proverb like statement: "Du musst erst teilen können, bevor du multiplizieren kannst.")	C-43
OUT6	Thorough preparation of decision situations by preliminary sharing of information to build some kind of justified descriptive or factual knowledge. leads to successful rational decision-making.	"Before the council gathers for decision-making we usually initiate a preliminary information meeting with politicians and administrative staff to inform about our projects or plans." (It should be noted that not all municipalities have administrative rules that allow the direct exchange between politicians and administration.)	C-36
OUT7	Once decisions were made in favour of climate action, public perception of the administrative climate action unit needs to be pushed to a positive	"We are perceived as an authority. The question is how we can reach the citizens, e.g., by a climate action centre, that is publicly not perceived as authority but as neutral contact unit or partner with	C-21

ID	Code	Exemplary statements (or content summary of several statements)	Frequency
	direction towards a service unit with an offering role	opening hours apart from typical administrative opening hours […]. Of course, this is a question of available staff, but we try to develop towards a service unit."	

CHAPTER 8

SYNTHESIS AND CONCLUSIONS: TOWARDS VIABLE COMMUNICATION SYSTEMS SUPPORTING A GREAT TRANSFORMATION

8. SYNTHESIS AND CONCLUSIONS: TOWARDS VIABLE COMMUNICATION SYSTEMS SUPPORTING A GREAT TRANSFORMATION

From a systemic communication perspective, the three case studies conducted for this thesis investigate local action and international research in the context of transitioning towards a sustainable energy system and, thereby, can highlight the relation between practice and science. Using the terminology of the Viable System Model the thesis provides insights into the relation between the global intelligence function and the local implementation function. Analytically, this thesis applies a cybernetic perspective and focuses on information exchange via language in the form of spoken words or written documents (see Chapter 4).

The findings of the individual studies contribute to answering the research questions in Chapter 1 and 4. The studies demonstrate how systemic principles can guide empirical analyses and how text mining can serve for reflecting paradigms in texts from a sustainability perspective. They further contribute to understanding which conditions foster or hamper the establishment of integrated knowledge systems for societal transitions.

This final chapter derives general conclusions from a systemic perspective based on the most relevant findings of the individual studies. Section 8.1 synthesizes the findings of Case Studies 1 to 3. Focusing on overarching interpretations, it demonstrates how systemic approaches may serve for diagnosing or reflecting communication and organization in the current energy system. Section 8.2 uses these generalized insights and implications for deriving general policy recommendations and starting points for solutions to support sustainability transitions. Section 8.3 focuses on the societal subsystem of science that plays a unique role in transitions and provides recommendations for further research.

It should be noted that the following conclusions and recommendations underly the limitations that are discussed in detail in the three Case Studies 1 to 3. The main issue that might arise in this regard is the representativeness of the case studies. Communication and organization in the energy system comprise significantly more elements than municipal climate action or scientific journal articles. Acknowledging these limitations, the studies still provide useful indications on selected transition activities in relevant fields. The conclusions derived from these insights would still hold even if their representativeness might turn out low. Only their weighting in the context of recommendations from other fields of research might have to be discussed in the ongoing scientific discourse.

8.1. SYNTHESIS OF FINDINGS FROM A SYSTEMIC PERSPECTIVE

Case Studies 1 to 3 highlight that international research on sustainable energy and municipal climate action in Germany provide promising contributions to a transformation towards sustainability. Case Study 2 emphasizes the intensive research efforts for establishing a highly efficient renewable energy system, especially via materials science. Case Studies 1 and 3 highlight the motivation of various local administrations and their innovation potential in the context of the German Energy Transition.

However, research and action do not fully reflect the complexity of society and still support a growth paradigm. Case Studies 1 and 2 show that research and local action are engaging actively with the diversity of energy technologies but are lagging in dealing with the socio-epistemic system. Using German municipalities as an example, Case Studies 1 and 3 highlight the challenges of achieving coherent local action for sustainability and bottom-up organizational learning due to incomplete or uncoordinated multilevel knowledge exchange.

At the same time, the case studies also point out opportunities for supporting the required coherent multilevel learning processes based on local knowledge. They show that these processes might be enhanced by strengthening the coordinating role of intermediary organizational units or establishing closer interactions between the local operational units and the national (or even global) level.

The following Tables 8-1 and 8-2 generalize the context-specific findings of Case Studies 1 to 3 and highlight their implications from a systemic perspective. The basis of the tables is the notion of the current energy system as a recursive multilevel system according to the Viable System Model. The research design in Chapter 4, especially Figure 4-2, illustrates this perspective. Table 8-1 focuses on international science as a proxy for the global intelligence function, whereas Table 8-2 focuses on municipal climate action as a proxy for the local implementation function. Both tables focus on the most relevant patterns, although they could discuss even more interactions across levels, functions, or subsystems.

Table 8-2 further relates the intelligence and the implementation function to each other. Thereby, it responds to the need to understand a system’s focus on the “here and now” and the “future and then” (Beer, 1979) for achieving viability (see Chapters 2 and 4).

Table 8-1: Findings on the ***global intelligence function*** *(Case Study 2)*

No.	Results	Implications
	Sustainability:	
F1	- Consistency and efficiency receive considerable attention, sufficiency comparably less.	- A green growth paradigm prevails. The resulting strategies and actions will require thorough review since supporting growth might compromise ecological limits.
F2	- There is high awareness for inter-generational but comparably less for intra-generational issues.	- As it is characteristic of the intelligence function according to the VSM, science focuses on the future. For establishing a balanced system, the policy and cohesion function will have to pay close attention to intra-generational issues in the present.
	Human-Environment System Components	
F3	- Priority is given to technological aspects, especially, improving processes and materials for advanced energy supply. - The stage of resource extraction seems to be secondary. - Also, environmental or social issues such as psychology, behavior, or media receive comparably less attention.	- The intelligence function focuses on the material-biophysical part of the human system. The consideration of the problematic and operational environment is incomplete. - It pays comparably low attention to the socio-epistemic system, the environment system, and interactions of these systems with the material-biophysical system. - The discourse focuses on energy flows. It views material and information flows only as flows to be built around energy flows for serving the latter. - Matter, energy, and information will have to be considered as an integrated triplet. - Holistic transformation approaches will require a more comprehensive understanding of the human system that considers the above aspects.
	Subsystems, systemic functions, and interactions	
F5	- The consideration of subsystems is unbalanced, e.g., the heavy industry receives low attention. - Economic and political issues receive decreasing attention.	- The discourse only partially reflects the complexity of society. This leads to incomplete self-reference capability and incomplete information flows to the policy function. - The connection of the intelligence function to subsystems with key roles for achieving cohesion is limited. - Science and societal subsystems, especially politics and industry, need to be reconnected.
F6	- There is a tendency to focus on local issues and urbanization, less on global issues.	- The intelligence function focuses on issues of the implementation function at lower levels of recursion, less on coordination, cohesion, or policy at higher levels.

No.	Results	Implications
		- The capability of the cohesion function needs to be strengthened to avoid leakage effects, which could compromise global ecological limits. - Stronger cohesion will further avoid diverging local developments but, instead, foster mutual learning.
F7	- Digitalization primarily serves for balancing and optimizing (decentral) energy generation and demand systems at a technological level. Potentials in other fields receive low attention.	- To a certain extent, digitalization supports cohesion and coordination in the material-biophysical system. - Digital technologies are not used intensively for cohesion in the socio-epistemic system, although they could support knowledge systems and cohesion therein. - Potentials of consumer information systems or of digital feedback systems for reflecting behavior and societal communication might be exploited further.
F8	- The discourse has various diverging threads regarding future technological pathways, e.g., batteries vs. fuel cells, or hydrogen vs. biofuels	- The intelligence function offers various incoherent future pathways and, thereby, creates complexity compromising unequivocal goal formation by the policy function. - For informing the policy function effectively, the intelligence function needs to relate different future scenarios to each other and illustrate the meaning of different pathways for society more clearly.

*Table 8-2: Findings on the **local implementation function** (Case Studies 1 & 3) in Germany and its **relation** to the global **intelligence** function (Case Study 2)*

No.	Results	Implications
	Sustainability:	
F9	- The same results and implications apply as in Table 8-1 – F1 (low attention to sufficiency).	
		Relation to the intelligence function: - *The local implementation function and the global intelligence function follow the same paradigm. They have a certain coupling. The intelligence function has a precursory, or, at least, a reinforcing role for paradigms applied in implementation, e.g., in local climate action.*
	Human-Environment System Components:	
F10	- Energy system stages other than generation and end-use receive low attention, e.g., markets, distribution, or resource extraction (similar result as in Table 8-1 – F3).	- Similar implications as in Table 8-1 – F3 apply here concerning the incomplete consideration of the problematic and operational environment and the isolated perspectives on matter, energy, and information.
		Relation to the intelligence function: - *The practice to draw rather narrow system boundaries or to apply incomplete perspectives on the matter, energy and information triplet seems to be transferred from the intelligence to the implementation function.* - *Focusing on energy seems more plausible for the local implementation than for the global intelligence function. This is because, to a certain extent, national policies prescribe the scope of municipal climate action and limit it to energy or carbon emissions.* - *Local implementation is carried out under the assumption that the whole system is coordinated in a reasonable way to avoid, e.g., rebound or leakage effects. This assumption might not hold considering the insights on limited cohesion in the intelligence function (see Table 8-1 - F6).*
F11	- Communication measures receive comparably low attention. However, to a certain extent, municipalities start to recognize approaches	- There is increasing awareness of the importance of the socio-epistemic system. However, large-scale structured measures addressing this system are not yet applied.

No.	Results	Implications
	considering the psychological aspects regarding consumers.	
		<u>*Relation to the intelligence function:*</u> - *Through operational activities, the implementation function is inevitably confronted with humans and their individual experiences. It might, therefore, have a higher awareness of the socio-epistemic system.* - *The global intelligence function might learn from local implementation in a transition context about the socio-epistemic system. For instance, psychological approaches that work in specific local contexts might be generalized for transferring them to other contexts.*
	<u>Subsystems, systemic functions, and interactions:</u>	
F12	- There is comparably low attention to the economy and industry (similar result as in Table 8-1 – F5).	- Similar implications apply as in Table 8-1 – F5 regarding limited self-reference capability. - The implementation function should communicate its limitations to other functions regarding its possibilities to capture the operational environment for establishing a comprehensive system description. The policy function should then, for instance, set up rules to improve local self-reference capability. <u>*Relation to the intelligence function:*</u> - *The economy seems to be the subsystem that is most difficult to integrate for the implementation and the intelligence function.* - *The implementation function achieves a comparably closer interaction with the industry.* - *The potential of the local implementation level for increasing the self-reference capability concerning the economy subsystem should be exploited further.*
F13	- Local data and knowledge often stay local, especially regarding non-technological innovations. - Higher levels provide limited multilevel support to local administrations for establishing effective action networks, e.g., via coordination by climate action	- The self-reference at the cohesion, intelligence, and policy function is incomplete considering the incomplete insights provided by the implementation function about its operational activities. Thus, solutions or rules issued by the policy function only partially meet the requirements of the implementation function. - The implementation function coincides with structural boundaries, although a viable system requires a functional multilevel responsibility and dynamic interactions.

No.	Results	Implications
	agencies or provision of a clear organizational vision.	- The interface between the cohesion and implementation function will have to be improved, especially regarding the capacity of the cohesion function. Relation to the intelligence function: - *The intelligence function already focuses on local implementation (see Table 8-1 – F6) and can support the self-reference capability of the implementation function.* - *However, neither the implementation nor intelligence function is interacting intensively with the policy function.* - *(Re-)coupling the local implementation and intelligence function to the high-level policy function is required, e.g., by strengthening cohesion capacity and bridging communication modes.*
F14	- The bureaucratic working mode of administration is often opposed to the flexibility required for advanced climate action, e.g., for open-ended experimentation.	- In problem-solving processes, the implementation function is limited regarding the reflexivity on own operational activities. It sticks to traditional practices. - For achieving innovative adaptations, exploratory communication spaces outside of hierarchical structures will be required. Relation to the intelligence function: - *The local implementation function is institutionalized, but the local intelligence function is not. The latter could imagine different future pathways by applying a second-order perspective on implementation. However, it can only operate in the formal structures that hamper taking this kind of perspective.* - *The local intelligence function needs to be strengthened for completing the recursive system structure. Amongst other activities, transdisciplinary approaches are needed that facilitate holistic local solutions in contrast to disciplinary solutions.*

8.2. CONCLUSIONS AND RECOMMENDATIONS

The findings of Case Study 1 to 3 strengthen the call to support the establishment of advanced knowledge systems enabling (energy) transitions as part of the Great Transformation as set out in the introductory chapter. Based on the above synthesis and the conceptual considerations in Chapters 2 and 3, this chapter derives and discusses several recommendations that might be applied in national policy-making and that go beyond those presented in the case studies. The recommendations are valid for the German context, but, to a large extent, also for other contexts, especially for industrialized societies. Table 8-3 summarizes the recommendations that the following paragraphs illustrate in more detail.

Table 8-3: Summary of (policy) recommendations

Finding	Recommendations
	Systemic holism
F3, F10, F2	Consider matter, energy, and information flows as an integrated triplet in the context of scales, structures, and time in the various subsystems
	Knowledge society
F3, F11	Focus on the socio-epistemic system, e.g., using the perspective of knowledge systems and associated design principles as proposed in Case Study 3, **Fehler! Verweisquelle konnte nicht gefunden werden.** (not reproduced here)
	Sufficiency communication
F1, F9	Emphasize sufficiency approaches, make it attractive, and find differentiated ways for communicating them
	Multilevel cohesion and innovation
F13, F14	Achieve cohesion between the local and higher levels and leverage local innovations while avoiding isolated local action
	Organizational interface design
F3, F5, F10, F12	Define the role of organizational units by the interactions they create at the interfaces with and between societal subsystems
	Local transdisciplinarity
F8, F11, F14	Support local transdisciplinary approaches integrating various subsystems, especially industry, while coordinating these approaches from a higher level for leveraging local innovation
	Digital public system
F6, F7, F13	Exploit existing digital technologies or infrastructures in the public system and recognize the value of data in the public sphere for achieving cohesion

Recalling the theory of Chapter 2, which sees human society as complex coupled societal subsystems, it should be noted that the political system is not solely responsible for or capable of implementing these recommendations. Collaborative approaches involving various subsystems, e.g., economy, law, education, media, or arts, appear to be more promising from a systemic perspective, e.g., for satisfying the five functions according to the VSM.

[SYSTEMIC HOLISM]

A very general recommendation, which, however, is a necessary condition for establishing sustainable policies, is to consider the relevant matter, energy, and information flows in the context of scales, structures, and time. Furthermore, a sufficiently broad perspective regarding the various societal subsystems needs to be adopted to reflect the complexity of society. Some brief examples illustrate the importance of such a cross-cutting perspective. The increasing use of non-renewable metals for establishing renewable energy systems increases the dissipation, i.e., the loss of metals (energy and matter) (Kümmerer, 2016; Zepf et al., 2014). Using technology metals for energy transitions in countries of the Global North may cause social or environmental problems in countries of the Global South (energy and social systems across scales) (Bazilian, 2018). Electric mobility can lead to climate change mitigation in individual cases. However, a globally equal deployment of the technology might not be possible due to resource constraints (matter and scale) (Vesborg & Jaramillo, 2012). Isolated local learning processes without prior schemes for cohesion require high posterior efforts for consolidation (information and scale) (see Case Study 3 of this thesis). Digitalization will increase the efficiency of mobility options and lead to an increase in passenger transport; it will further create a "time rebound effect" by freeing usable time during transport (information, energy, and time) (L. M. Hilty, Arnfalk et al., 2006).

Although the holistic systemic perspective promoted by this thesis leads to high complexity in the process for finding solutions, it reduces the uncertainty regarding the numerous possible future pathways and unexpected detrimental effects. Thus, it has the chance to reduce the overall complexity over time for reaching a viable system. Still, holistic approaches will inevitably lead to questions that might not be answerable since, e.g., the data or information flows to approach the question are incomplete. Therefore, knowledge gaps need to be made transparent. Instead of ignoring them by drawing narrow system boundaries, policy-making must deal with them proactively and transparently. More progressive handling of knowledge gaps might further provide more specific starting points for transdisciplinary approaches by sustainability science.

[KNOWLEDGE SOCIETY]

The historical perspective provided in the introductory chapter indicates that for dealing with resource scarcity or environmental problems, human society has usually focused on technological advancements. It seems that the current problem-solving approaches are not substantially different. However, this thesis concludes that for achieving more radical changes, current problems require different approaches located in the socio-epistemic system. Mindsets need to change, e.g., regarding the purpose of technologies and the way how they are being used or created. This change is needed before or, at least, while new technologies are being created or implemented. Otherwise, technologies reinforce the recent paradigms of society that have created our current problems, especially paradigms of growth.

When introducing new technological approaches, related issues of societal organization and communication should have a higher priority in contrast to just establishing material infrastructures. A possible approach is to use a knowledge system perspective and associated design principles as provided in Case Study 3. This supports designing communication systems that facilitate interaction between subsystems. The potential of this perspective is that it respects the human character of knowledge, e.g., in terms of roles, power positions, or barriers and accelerators for information exchange. In this context, establishing knowledge systems will have to include mechanisms for reflecting prevalent paradigms in the science subsystems, since, as Table 8-2 shows, it has a precursory role for paradigms in other subsystems.

[SUFFICIENCY COMMUNICATION]

Finding ways to communicate about the principle of sufficiency towards and in different subsystems will be particularly important. Different narratives for promoting sufficiency need to be developed. These need to be designed carefully to be successful in different subsystems. The example of smart homes may illustrate the role of how technologies are framed in communication. Digitalizing homes promises high energy saving potentials, e.g., through optimizing the on and off times of various appliances or devices. However, in this context, digitalization may lead to the contrary. When surrounding digitalization of homes by narratives that promote digitalization as a good technology per se, these narratives change the perception of what is a pleasant life and create additional needs (Darby, 2018; Strengers & Nicholls, 2017). In sum, this may increase resource consumption. Hence, the narratives created around technologies will have to be reflected to avoid rebound effects. National policies and, in consequence, municipal climate action should not promote any technology without prior scrutiny. However, they should develop reflected standpoints and disseminate them in a coordinated way, e.g., to manufacturing companies, retailers, or households.

[MULTILEVEL COHESION AND INNOVATION]

Case Studies 1 and 3 focusing on municipal climate action show clearly that the currently promoted and implemented polycentric or multilevel approaches that assign more responsibilities to the local level require improved cohesion for unfolding their full potential. To remark again (see Chapter 2 and Case Study 3), cohesion does not mean uniformity. It means understanding the various facets of implementation or operation to allow reflecting these insights against targets or expected future pathways. Cohesion enables establishing balanced systems that are operationally efficient and future-oriented.

During history, various societies had developed such a high degree of complexity that it compromised their proper management, e.g., due to the inability to connect a large number of sub-units. In such cases, simplification of the system can be a suitable strategy (Tainter, 2011). Separating the whole system into several smaller autonomous units can lead to system regeneration and higher viability on average (Tainter, 2000). A concrete example is the decay of the Roman Empire that was followed by the “Byzantine Recovery” (Tainter, 2000). However, achieving viability by simplification often comes at the cost of well-being (Tainter, 2011). Developing human capabilities (Nussbaum, 2011) may be hampered in small sub-units that are managed rigorously for achieving efficiency.

However, this historical example is not transferable to the current society. Two reasons are: (i) the environmental problems of the former times were only local or regional, and (ii) the decline of the Roman Empire was partly due to the inability to exchange messages in due time over long distances for managing the whole system (Tainter, 2000). Today, human society faces global problems resulting from globally interconnected resource systems and value chains that inevitably connect the local and the global level. Moreover, digitalization allows to exchange messages over any distance for system management rapidly. This constellation offers various potentials but also pitfalls for achieving sustainability.

[ORGANIZATIONAL INTERFACE DESIGN]

These considerations and the empirical evidence provided by the case studies show that new interactional identities regarding the role of cities and the role of regional, national, and global governments need to form. When designing new policies or setting up new organizational units, their role should, in the first step, be defined by considering and defining the interactions with other subsystems or units, instead of defining the desired primary purpose only. The actual purpose or identity-in-use of an organizational unit results from its interactions. Case Studies 1 and 3 show that local action of municipalities is relatively uncoordinated regarding vertical and horizontal interactions. Further, Case Study 1 shows that the paradigms emerging from such polycentric approaches do support sustainability, but, in sum, might fail to safeguard adherence to global ecological limits.

This situation calls for an overarching framework that connects local and global knowledge and developments. Otherwise, as indicated in Case Study 3, global strategies cannot be translated to the local implementation level properly. Still, an aggregated global perspective is necessary for detecting beneficial or detrimental large-scale patterns.

[LOCAL TRANSDISCIPLINARITY]

A promising set-up for tackling the challenges mentioned above are local transdisciplinary or co-production approaches in transition contexts (Jasanoff, 2010; Lang et al., 2012; Withycombe Keeler et al., 2018) that are mutually interconnected and interacting with a high-level coordination unit. Such high-level coordination fosters the aggregation and generalization of knowledge. This kind of approach supports local experimentation and innovation but accounts for cohesion. Science can initiate the formation of the local intelligence function and create an open communication space that can bridge the communication between different subsystems. Designing this open communication space needs to reflect all subsystems of the society and, thus, societal complexity. Thereby, it serves as a space to understand the roles of and interactions between subsystems for tailoring communication strategies that support sustainability transitions.

Further, supporting local action-oriented research that pays attention to industrial and economic stakeholders is of particular relevance for completing the capability of self-reference required to induce change. A vital precondition for the success of such approaches is that science invests enough initial effort in finding a suitable communication basis for building up sufficient disciplinary expertise. This way, industrial stakeholders might find transdisciplinary cooperation more beneficial or attractive.

An example of current promising approaches to establish innovative knowledge systems are real-world laboratories or related research approaches. In Germany, this kind of research arenas connect diverse stakeholders locally and have started to connect horizontally in various networks (Engels & Walz, 2018; KIT, 2019). However, the networks focus on operational cooperation in rather unique, closed settings (Wagner & Grunwald, 2019). Existing coordination efforts are not yet establishing multilevel structures strategically. The various real-world laboratory approaches should be developed further and extended into coordinated multilevel knowledge systems.

[DIGITAL PUBLIC SYSTEM]

The vital task of achieving cohesion that has been pointed out in several instances above may benefit from using existing digital technologies and supporting public data initiatives. Considering the potential rebound effects connected to digitalization (L. M. Hilty, Köhler et al., 2006), in the first step, a crucial issue is to focus on the potentials of existing infrastructures instead of establishing new data-intensive or resource-intensive infrastructures. A step into this direction is improving the accessibility and structure of already available data, especially local data, in an overarching data network. This allows the local level to leverage the power of aggregated local data for its interests by providing an aggregated representative picture of the local level, hence, a more comprehensive self-reference of the implementation function. Without such a picture, the cohesion function cannot balance adequately the perspectives of the implementation function against the intelligence and policy function.

Enhanced access to quantitative data by the public system improves the self-reference capability. Case Study 3 shows that municipalities are constrained in collecting quantitative data from various subsystems. Leveraging the power of data should not be left to economic stakeholders alone such as large information and communication technology companies that have recognized and are already using this potential. While respecting individual privacy, contributions to the public good will emerge from new ways of using the data that are available to the public system or increasing the public data stock by extended access rights.

Improving options for data acquisition by municipalities is a challenging long-term goal, whereas improving the structure and accessibility of public data might be a more easily attainable goal. While the German public system provides quantitative data based on proven survey methodologies, it does not document the results from less standardized methods in a structured way. For instance, there is no national public database of municipal carbon footprints and the methods or system boundaries used[10]. This lack of documentation hampers, e.g., identifying bottlenecks regarding what data is available or missing, or improving methodologies through learning processes based on comparisons. As Case Study 1 shows, the situation is even worse for qualitative data. This study required considerable effort for text data formatting. Although municipalities prepare their climate action plans for the same purpose, the plans vary significantly in structure and format. Therefore, they cannot be analyzed easily with digital methods.

There is a considerable number of relevant documents in the public system at local and other levels, including local administrations or scientific institutions, that can be analyzed to better understand the socio-epistemic system, e.g., via text mining. For this purpose, these documents should be easily accessible and should use structuring elements that facilitate digitally supported analyses. Content-driven document standards that introduce markers within documents for indicating blocks of meaning should be used to enable advanced analyses. Such standards require improved knowledge about the content meta-structure of documents.

8.2.1. Further research

From the above general recommendations, various research opportunities emerge. This thesis highlights the following in particular: (i) advancing nature-inspired systemic frameworks, (ii)

[10] The closest to this kind of database is probably the database on Sustainable Energy Action Plans organized by the European Covenant of Mayors: https://www.covenantofmayors.eu/plans-and-actions/action-plans.html. This database is a good starting point. However, the documentation regarding, e.g., the methodological approaches or success factors of promoted best practices is not sufficiently comprehensive or structured to initiate innovative analyses or deeper learning processes.

understanding the structure and creation of human knowledge, and (iii) developing text mining methodologies towards solution-oriented approaches.

[NATURE-INSPIRED SYSTEMIC FRAMEWORKS]

The idea of finding transferable similarities between systems regarding structures or processes is not new to system theory. It calls these similarities isomorphisms. Traditionally system theory has mainly sought for them to improve the general understanding of systems (van Bertalanffy, 1968, pp. 80–88). However, using isomorphism to trigger or support sustainability transitions might receive closer attention. In other words, isomorphism could be used more actively for transformational purposes. High potential for transitions lies in investigating structures and processes that achieve sufficiency, efficiency, and consistency, and in understanding the systemic interactions that lead to these achievements.

Nature or the environment system provide useful blueprints regarding viable structures, processes, or problem-solving strategies that may support, e.g., establishing nature-inspired strategy processes. Nature does not only provide useful matter and energy flows that drive human operations. Without forgetting that humans are part of nature themselves, observing the environment system from a systemic perspective might allow discovering problem-solving or organizational strategies that can be adopted by the human system. For example, the Viable System Model was created based on human physiology (Beer, 1981, pp. 89–102). This thesis and other studies demonstrate the usefulness of this model. In the technical field, another example of nature-inspired approaches is bionic or biomimetic engineering. This includes, e.g., using nature-inspired algorithms for optimization in general (Zang et al., 2010) or referring to biological mechanisms for optimizing mechanical structures or reaction design in specific fields such as process engineering (Coppens, 2012).

[UNDERSTANDING HUMAN KNOWLEDGE]

Having highlighted research on nature-inspired solutions above, knowledge systems emerge as another promising field. Having identified solution-strategies does not mean that they are integrated into the pool of human knowledge and turned into practice. This transfer requires a better understanding of the specificities of the human system regarding information processing and internal interactions. In this context, relevant aspects are, e.g., the influence of belief systems, experience, or social and organizational roles. Advancing research in this direction is the basis for translating abstracted solutions (isomorphisms) efficiently to specific contexts in order to trigger sustainability transitions. For this purpose, research should further investigate the structure of knowledge and the dynamic processes of knowledge creation. This will clarify what kind of knowledge can even be generalized or transferred between different human contexts. For example, for designing efficient multilevel knowledge systems for sustainability it is important to distinguish what kind of knowledge should and can only stay local and what kind of knowledge should and can be generalized.

[SOLUTION-ORIENTED TEXT MINING]

Beyond these more conceptual research demands, leveraging the potential of text mining in a solution-oriented way is an underexplored but promising research field. Case Studies 1 and 2 have shown how text mining can be used to analyze interactions between subsystems. This network perspective can identify collaboration potential between different subsystems or actors, e.g., companies, municipalities, or research institutions. The potential lies in finding connections between actors that do not yet exist but appear reasonable based on consistent topical pathways that connect them. Mapping the topic-actor networks to identify such pathways can be achieved by, e.g., topic modeling. This kind of approach may support leveraging innovative and effective collaboration potential. This idea has already been demonstrated in a study at conference-level to identify potential for research collaborations using the example of the Research Map published by the German Rectors' Conference (Bickel, 2019). Hence, beyond assessing texts via confirmatory approaches or examining the complex socio-epistemic system via exploratory approaches, text mining can support identifying and using boundary objects (Carlile, 2002; Star & Griesemer, 1989) for communication processes.

8.2.2. Concluding remarks

Facing sustainability problems with global impact that are rooted in local action, human society needs to establish advanced knowledge systems that have the potential to produce useful knowledge for sustainability solutions. Without neglecting the material-biophysical reality, this requires a better understanding of the socio-epistemic system, i.e., the communication system of the human system. This thesis highlights this research gap and contributes to closing it with its three case studies in the context of sustainable energy. In this regard, it demonstrates how to use a systemic sustainability perspective combined with methods of text mining and knowledge management. In general, the thesis highlights that drawing a holistic or, in other words, a comprehensive picture of the world, which embraces complexity, is mandatory for solving sustainability problems. To be able to analyze, act, or operate, humans are forced to create simplified models of the world by drawing system boundaries and by focusing on individual organizational units or social subsystems. For achieving viable systems that are capable of respecting inter- and intragenerational justice, cohesion between these units and systems needs to be achieved. Therefore, searching for sustainable solutions requires to focus on interfaces or relations between, e.g., (physical) dimensions, scales, and the communication and organization of social systems.

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