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A new approach to semantic sustainability assessment: text mining via network analysis revealing transition patterns in German municipal climate action plans

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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.

Keywords: Urban energy system, Municipal climate action plan, Text mining, Semantic network analysis, Semantic sustainability assessment, German energy transition (Energiewende)

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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 [4–6]. Regarding global energy-related CO_2 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 [8–10]. 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 [14–16] or exemplary frameworks [17–19] show that sustainability monitoring has so far mainly been based on physical data such as mass, energy, or emission balances and socioeconomic 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.[1]

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.

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 [39–41]. 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, 49–52]. 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[2]. 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 [71–73]. 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:

- 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.

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.

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" [75–77]. 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."

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 1 shows an exemplary sheet.

Table 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 5 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.

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 1), e.g., *Title of measure*, were identified manually and used to automatically split the texts into sections. These were then split into terms.

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.

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].

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 subsections 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.

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>.

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 Additional file 1: A7.

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 Additional file 1: 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.

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.

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 2. A list of all meta-categories and categories is provided in A3.

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>,

Table 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
<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

<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 3.

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 4.

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.

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

Table 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
<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
<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 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 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

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.

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 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.

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

Table 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	60	100
Number of measures in which two categories c_x and c_y co-occur	14	9	10
Normalized co-occurrence	14/70 = 0.2	9/60 = 0.15	10/100 = 0.1
Average normalized co-occurrence (ANCO)	(0.2 + 0.15 + 0.10)/3 = 0.15		

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 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 7 shows the scaled entries of the exemplary ANCOM.

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 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 8 shows the scaled value of 0.25 in the exemplary scaled ANCOM indicating that

Table 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

<SUS><cat2> appears in 25% of the set of measures in which <ENG><cat1> occurs.

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 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.

For a clear graphical arrangement, only significant links between categories of <1><SOC> and <2><ENG>

Table 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 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

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.

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 1 shows the ANO of categories of <2><ENG>. Based on the ANCOM, Fig. 2 shows the most relevant network links between categories of <2><ENG> and <1><SOC>, and Fig. 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 Additional file 1: 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 10 focuses on planned configurations of the energy system, Table 11 on roles of societal subsystems, and Table 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.

Visual presentation of results

Occurrence of categories of <2><ENG>

The ANO of categories of <2><ENG> referring to specific stages of the energy system are displayed in Fig. 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,

Table 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

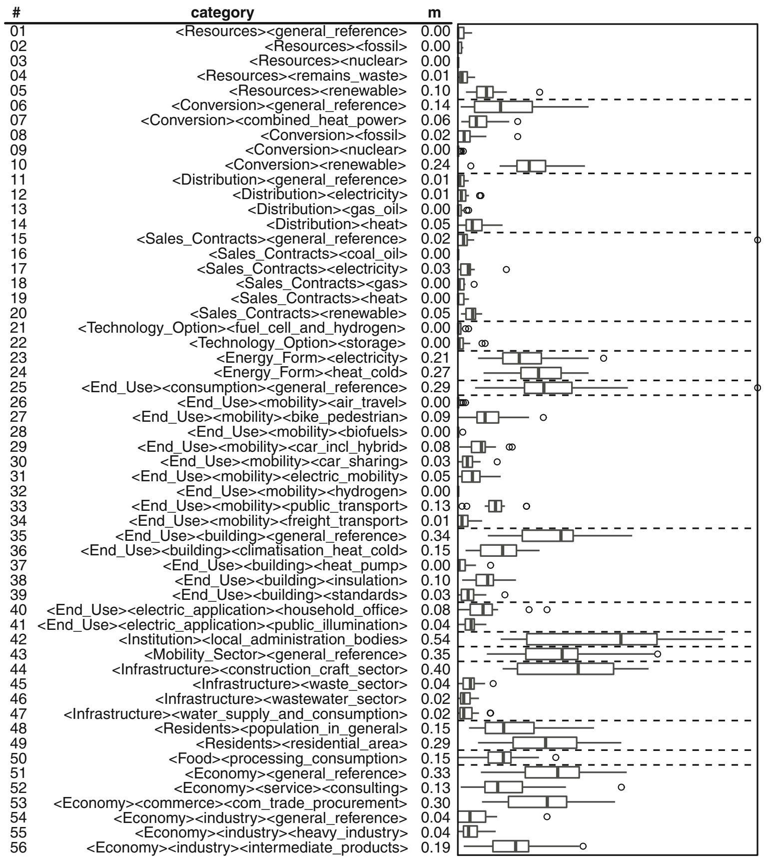

Fig. 1 Boxplot showing average normalized occurrence of categories of <2><ENG>. *Boxes* represent the mid-ranges (50% of the data), *lines in boxes* show the median, *upper and lower hinges* show the first and third quartiles, and outliers are shown as *circles* [89]. The *column m* of the table on the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

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.

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

The left axis of the co-occurrence plot in Fig. 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.

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

Figure 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.

Main results and interpretations

Energy system configuration

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

Roles of societal subsystems

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

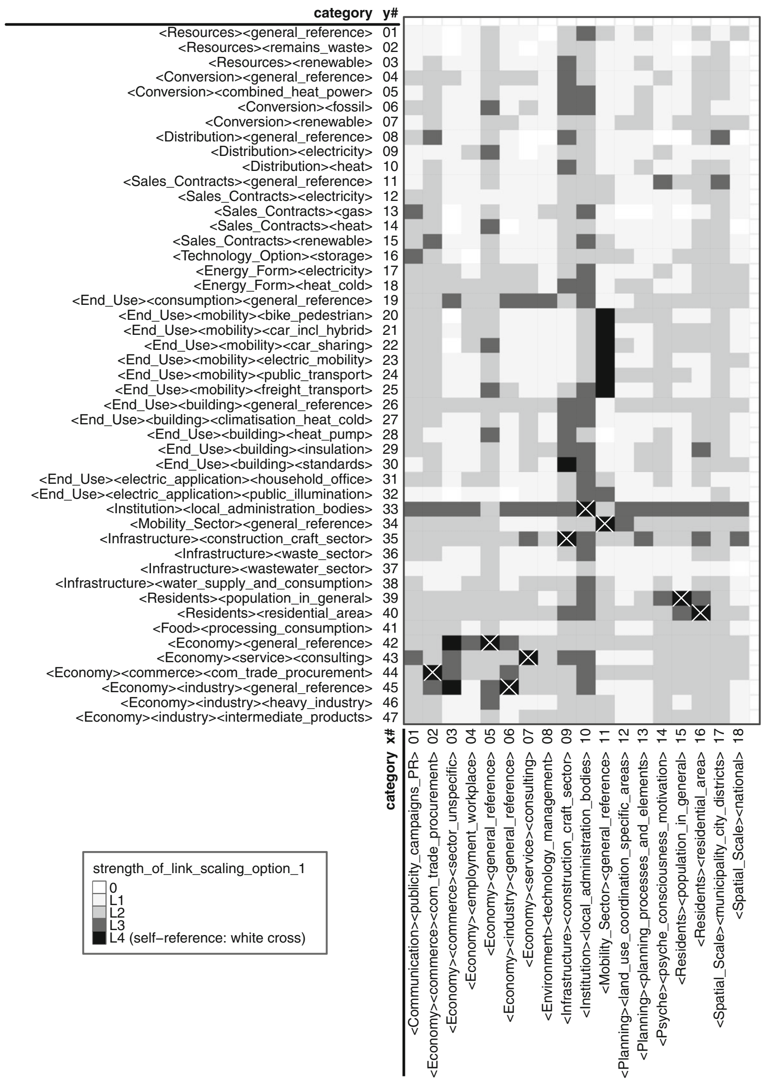

Fig. 2 Average normalized co-occurrence scaled by the first scaling option showing the strongest links of categories of <1><SOC> with categories of <2><ENG>

Preference regarding sustainability principles

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

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.

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).

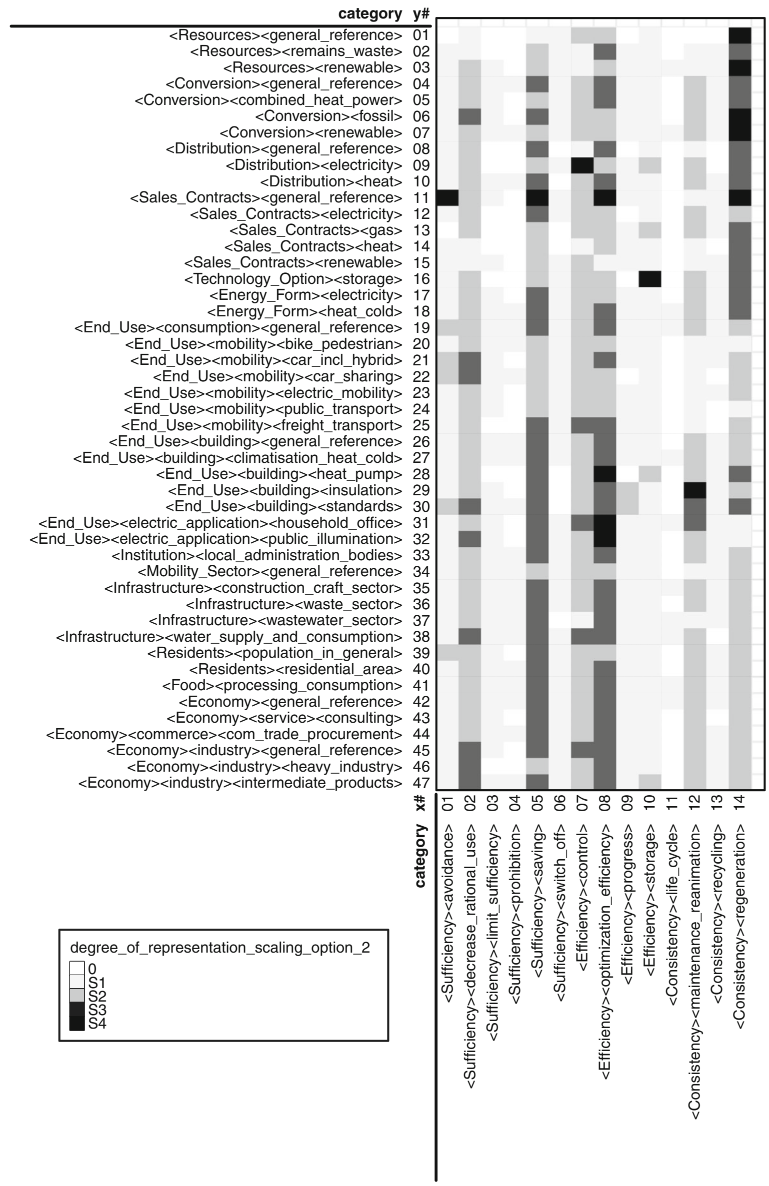

Fig. 3 Average normalized co-occurrence scaled by the second scaling option showing representation of categories of <3><SUS> within full sets of measures containing individual categories of <2><ENG>

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

Table 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 1:6, 25; 1, 11, 15, 21, 22
F2	High relevance of renewable energy power plants.		Figure 1:5, 10 Figure 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 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 1: 12; 10, 31 Figure 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 1: 36, 38; 7 Figure 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 2: *x*10*y*18/27/29, 17*y*35
F7	Gas supply contracts were the most advertised type of contracts.		Figure 2: *x*1*y*13
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 1: 27, 33, 29, 30, 31; 28, 32
F9	Common urban mobility modes were weakly linked with categories representing local actors.		Figure 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 1: 45, 46, 47 Figure 2: education not on *x* axis
F11	The industrial sector was weakly addressed.		Figure 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*

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

Table 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 1: 42 Figure 2: x11y15//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 2: x3/4/7/8/10/16/17,y33
F14	Local administrations were clearly linked with communication measures and the consulting sector.		Figure 2: x1/8/15y33
F15	Local administrations showed connections with the conventional heating sector, including rehabilitation of buildings, and district heating.		Figure 2: x11y5/6/13/18/27
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 2: x11y30, x13/14/19y33
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 2: x1/29y39/40, x15y39
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 2: x6y33, producing not on x axis; x6/11y25
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 2: x6y6/25/14/28 Figure 3: x1y45-47, x8y42
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 2: x6y9

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 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 3: x5y25-47, x8y25-47, x14y1-18
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 3: x5y1-24, x8y1-24; x2y6/21/22/30
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 x1/3/4/6
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 3: x14y1-18 Figure 2: x1-20(except 3, 11)y15 Figure 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 3: x14y27

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* 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.

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 CO_2 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.

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.

Endnotes

[1]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.

[2]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.

Additional file

Additional file 1: Appendix - A1 to A7. (ZIP 102 kb)

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)

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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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