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Development of a Process for Integrated Development and Evaluation of Energy Scenarios for Lower Saxony

Final report of the research project NEDS – Nachhaltige Energieversorgung Niedersachsen

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1. Introduction

In order to accomplish the climate change goals set by the Paris Agreement and maintain the global temperature increase below 2°C, every aspect of society needs to contribute. One area addressed in the German Sustainability Development Strategy [1], is the goal of affordable and clean energy. The Energy Sources Act (EEG) sets national targets for the power sector and stipulates that at least 80% of electricity production should come from renewable resources in the year 2050 [2]. Although renewable energy concepts are a key element of energy policy today, sole reliance on increasing the share of renewable energies is not sufficient to build a sustainable energy system [3]. Consideration of sustainability criteria, which targets more than the amount of renewable energies, is thus important in evaluating an energy system.

This final report presents the findings of the research project NEDS – Sustainable Energy Supply Lower Saxony. The main research question of the project is *how can a path towards a sustainable energy system for Lower Saxony be found, modeled, and evaluated*? To answer this question, the project was conducted from 2015 to 2019 under the collaboration of eight research institutes. At the outset of this project in 2015, Lower Saxony had an important role model function within Germany as a state with approximately 38% of its electricity coming from renewable energy sources, especially from biogas and onshore wind. Further progress is, however, necessary to reach the goals described in the state's mission statement [4] and to achieve a renewable energy supply by the year 2050, which satisfies sustainability criteria.

There have been other studies to model possible energy system configurations that can achieve the state's targets (especially in [5]), multiple system configurations and paths toward them are possible. This project used methodology developed to analyze and evaluate the configurations. For an overview of the overall project design, see Figure 1. The project team started out by qualitatively describing the energy system for the year 2015 with respect to technical, economic, social, and environmental aspects. The method of scenario planning was applied to develop future energy scenarios for the year 2050. One scenario was selected and quantified resulting in three alternative system configurations. Four reference years were selected to model and simulate the development of the energy system (2020, 2030, 2040, and 2050). In the last step, all of these system configurations in their different pathways were evaluated using multi-criteria analysis.

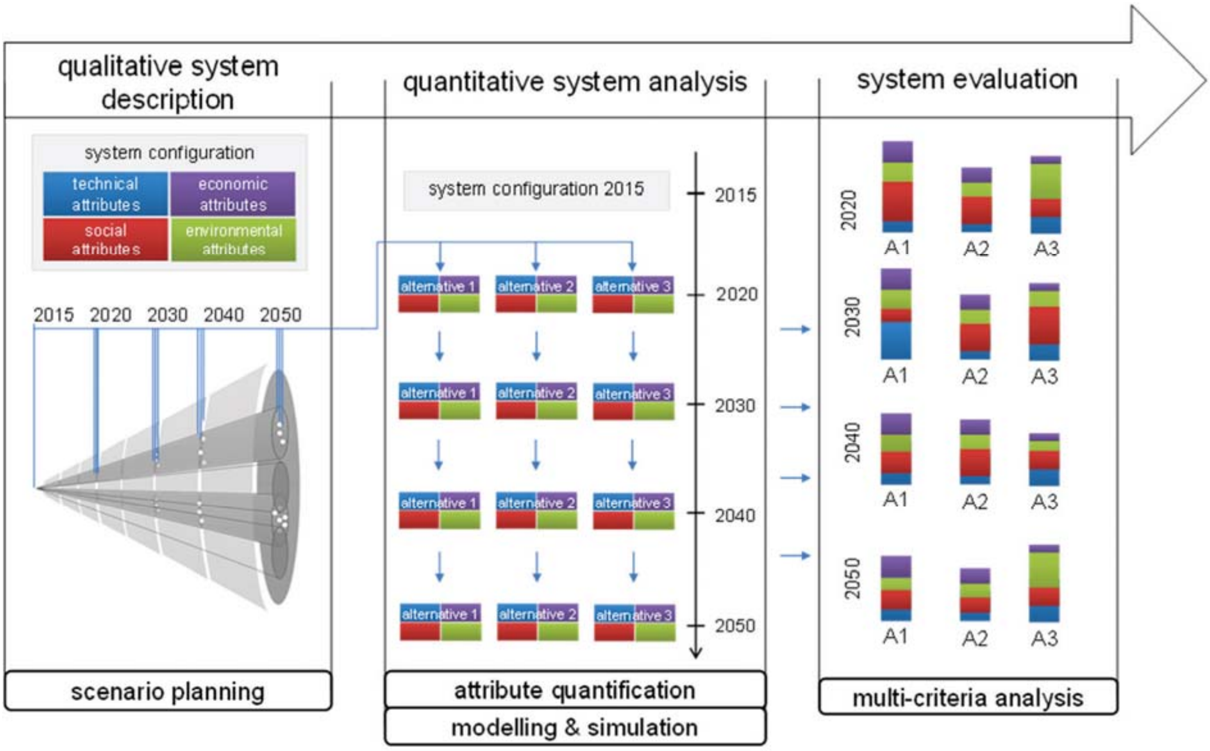

Figure 1: Project overview

In this report, we first present a brief overview of the state of literature (Section 2) before describing the project targets and deriving system boundaries for such a methodology (Section 3). A simple overview of the methodology is given (Section 4), which also encompasses how data exchange was handled in the different phases of the methodology. After that, the methodology is described in more detail. The transition of a formerly centralized electrical energy system with well controllable energy supply toward an energy system based on renewable energies has a significant impact on several areas, e.g., social or economic. The definition of evaluation criteria to assess the sustainability of the defined energy system configurations and transitions paths toward them is presented in Section 0. After that, scenarios are developed in a structured process that also allows the definition of transitions paths (Sections 6 and 8). Selected attributes of these scenarios are empirically embedded, using insights from the diffusion studies, developed for a selection of relevant innovations (Section 7).

With our interdisciplinary project consortium, we aim to analyze technical, social, environmental, and economic parameters as well as their interactions with the help of corresponding models and we focused on coupling these models. Different energy system configurations are modeled using multiple simulations and optimization models described in Sections 9. Results of the individual models are shown in Section 10. Finally, to aggregate the performance scores of the 18 criteria obtained from the simulation and optimization models, a Multi-Criteria Decision Analysis (MCDA) method is used (Section 11).

To illustrate the application of the method and support the decision process, conceivable transition paths toward a power supply based on renewable energies in Lower Saxony by 2050 were developed and examined for their sustainability and feasibility in several time steps (2020, 2030, 2040, and 2050). With the conclusion of the project, a possible transition path to a sustainable, renewable-energy-based electric power supply system for Lower Saxony was identified for a chosen scenario.

2. State of the Art Regarding Energy Scenarios for Lower Saxony

T. Witt

While many energy scenario studies examine possible future energy systems of Germany [6, 7], there actually are only few relevant energy scenario studies analyzing the transition of Lower Saxony's energy supply system toward higher shares of energy from renewable sources. To decide, which approaches and assumptions can be reused in our project, the existing studies as well as the own approach are categorized using a morphological box.

The method *morphological box* was developed by [8] in the 1960s and can be used to systematically identify all possible configurations of a certain object of interest. In the leftmost column, relevant *parameters* describing a system are collected. For example, in Figure 2, Orientation, Purpose, Type of information, etc. On the right side, the possible variations for these parameters, so-called *characteristics*, are collected. The morphological box is usually used for classification. It can also be regarded as a creativity technique, since new configurations of a system can be found by trying out different combinations of characteristics.

The morphological box for the categorization of energy scenarios has been developed at the beginning of the project [7]. Figures 2 and 3 show the categorization of four related energy scenarios concerning the energy supply system in Lower Saxony as well as the approach in this project (NEDS, marked with *). For example, regarding the scenario orientation, in [9] and [10], *predictive* scenarios are developed, while in this project (*) and [10], *explorative* scenarios are developed, and in [5] and [11], *normative* scenarios are developed. In the following, the other four studies are briefly introduced, before the new features of the approach in NEDS are highlighted.

The study *Szenarien zur Energieversorgung in Niedersachsen im Jahr 2050* (scenarios for the energy supply in Lower Saxony in the year 2050; [5]) was commissioned by the Lower Saxony Ministry for Environment, Energy and Climate Protection, which is a ministry of the federal state of Lower Saxony. Its overall goal was to provide information to develop a guideline for the sustainable development of the energy system, including power, heat, and transport, in Lower Saxony. One important premise of this study is that the whole energy demand of Lower Saxony can be provided with power and heat plants on the actual territory of Lower Saxony, so that land use competition, e.g., between photovoltaics and biogas plants, is considered. This study contains two normative scenarios: The first scenario describes an energy system with 100% renewable energy. The second scenario describes an energy system with a GHG reduction of 80%. Numerical assumptions are presented for 2012 and 2050 only, and most results are only presented for 2050. However, linear extrapolation is used to describe the development of selected key figures in the years 2020, 2030, and 2040.

(1) Scenario properties						
Orientation	Predictive [9, 10]	Explorative (*, [10])	Normative [5, 11]			
Purpose	External conditions affecting the consequences of policy actions (*)	Exploration of future conditions or environments [5, 9, 10]	Advocacy of particular courses of action [11]	Representative sample of future states		
Type of information	Mainly quantitative [5, 11, 10]	Mainly qualitative [9]	Combined (Story-and-Simulation) (*)			
The domain of results/impacts	Technical (*, [5, 9, 11, 10])	Economic (*, [5, 9, 10])	Social (*, [9])	Environ-mental (only GHG) [5, 10]	Environ-mental (*)	
Temporal scope of the scenario	Short term	Long term (*, [5, 9, 11, 10])				
Geographical scope of scenario	Local	Regional (*, [5, 9, 11, 10])	National [10]	International	Global [9]	
Economic sector	Overall economy (*)	Electricity (*, [5, 9, 11, 10])	Heat [5, 9, 11, 10]	Transport [5, 9, 11, 10]		
(2) Model properties						
Analytical approach / System perspective	Top-down (*)	Bottom-up (*, [10])	n.a. [5, 9, 11]			
The geographical scope of the model	Local (*, [10])	Regional (*, [5, 11, 10])	National [10]	Inter-national [10]	Global (*)	n.a. [9]
The temporal resolution of the model	Minutes (*)	Hours (*)	Days [5, 10]	Years (*, [11, 10])	n.a. [9]	
Number of models	One [5, 11, 10]	Multiple (*)				
Coupling of models	Soft link (*)	Hard link (*)	No link [5, 11, 10]	n.a. [9]		

Figure 2: Morphological box applied to selected energy scenarios

The study *BUND-Szenario – Energieversorgung in Niedersachsen im Jahr 2050* (BUND scenario – energy supply in Lower Saxony in the year 2050; [11] was commissioned by the Lower Saxony branch of the Bund für Umwelt- und Naturschutz Deutschland (BUND; association for environmental protection and nature conservation Germany). It is based on the scenarios and the energy system model described in [5], but sets different assumptions, for example regarding economic growth, land use of residential areas, resource consumption, and traffic volume. It is also based on the premise that the whole energy demand of Lower Saxony can be provided with power and heat plants on the actual territory of Lower Saxony. This study contains one normative scenario, which describes an energy system with 100% renewable energy. Numerical assumptions and results are described for 2050.

<table>
<tr><th colspan="11">(3) Scientific practice</th></tr>
<tr><td>Transparency of decision support</td><td colspan="5">Explicit evaluation of scenarios, e.g., with methods from (multi-criteria) decision analysis
(*)</td><td colspan="5">Implicit data-driven analysis
[5, 9, 11, 10]</td></tr>
<tr><td>The rationale for assumptions and constraints</td><td colspan="3">Provided, based on literature
(*, [5, 10])</td><td colspan="4">Provided, based on own assumptions
(*, [11])</td><td colspan="3">Not provided
[9]</td></tr>
<tr><td>Consistency of assumptions and constraints</td><td colspan="5">Demonstrated
(*, [10])</td><td colspan="5">Not demonstrated
[5, 9, 11]</td></tr>
<tr><td>Communication of uncertainties</td><td colspan="5">Critical assumptions are marked explicitly
(*, [5, 9, 10])</td><td colspan="5">Assumptions are not distinguished
[11]</td></tr>
<tr><td>Ease of model validation</td><td colspan="3">Glass box
[5]</td><td colspan="4">Grey box
(*, [5, 10])</td><td colspan="3">Black box
(*, [9, 11])</td></tr>
<tr><th colspan="11">(4) Institutional setting</th></tr>
<tr><td>Commissioner</td><td colspan="2">Public institution
(*, [5, 10])</td><td colspan="3">Private institution
[9]</td><td colspan="3">Non-governmental organization
[11]</td><td colspan="2">No commissioner</td></tr>
<tr><td>Affiliation of Commissioner</td><td>Technical</td><td colspan="3">Economic
[9]</td><td colspan="2">Social
(*, [10])</td><td colspan="3">Environ-mental
[5, 11]</td><td>No com-missioner</td></tr>
<tr><td>Involvement of stakeholders</td><td colspan="5">Stakeholders are involved
(*, [5])</td><td colspan="5">Stakeholders are either not involved or not mentioned
[9, 11, 10]</td></tr>
<tr><td colspan="11">*: Approach in NEDS</td></tr>
</table>

Figure 3: Morphological box applied to selected energy scenarios, continued

The study *Energieland Niedersachsen – Struktur, Entwicklung und Innovation in der niedersächsischen Energiewirtschaft* (Energy land Lower Saxony – structure, development, and innovation in the energy sector in Lower Saxony; [9]) was commissioned by the "Institut der Norddeutschen Wirtschaft e.V." (Institute of the North German economy). Notably, this study is not based on any particular energy system model. Therefore, most results are only presented in a qualitative way. Its goal is to provide information on the status quo of the energy sector in Lower Saxony as well as to identify future opportunities for the energy sector in Lower Saxony. This study contains one predictive (reference) scenario, which describes future potentials for the development of Lower Saxony's energy sector, e.g., in terms of the installed capacities of different renewable energy technologies or the development of the number of jobs in the energy sector. Future developments are described for different years up to 2038.

The study *Energie und Klima als Optimierungsproblem am Beispiel Niedersachsen* (Energy and climate as optimization problem applied to Lower Saxony; [10]) was commissioned by the Federal Ministry for Education, Science, Research, and Technology. Notably, this study was published in 1996 and is therefore not only the oldest of the analyzed studies but was also written well before the energy transition became a prominent topic on the political agenda in Germany. It is nonetheless included in the analysis because it is one of the few model-based studies concerning Lower Saxony's energy supply system. The goal of this study is to analyze options, which allow avoiding the use of nuclear energy and reducing CO_2-emissions in Lower Saxony, with an optimization model. This study contains three scenarios and additional sensitivity analyses, which differ in the assumed prices for energy carriers, sociodemographic and economic parameters, and assumptions concerning the use of nuclear energy. Quantitative assumptions are described for 1992, while quantitative results are presented for 2005 and 2020.

In this project, we extend upon existing studies. In particular, the integration of methods from Multi-Criteria Decision Analysis (MCDA) to evaluate transition paths and the integration of energy system models with different foci requires a new methodology for energy scenario development and evaluation. This methodology will be outlined broadly in Section 4. The multi-criteria evaluation of transition paths is described in more detail in Section 11. Another feature of this new methodology is that the consistency of assumptions and constraints is addressed with an information model, which can be used to support the data exchange in the different phases of the developed methodology. For example, when different energy system models with different temporal resolutions and system perspectives need to exchange data, the information model can be used to model the dependencies and construct a shared database for these energy system models (see Section 4.2). Furthermore, the internal consistency of the explorative scenarios is addressed in the scenario planning method (see Section 6). Finally, not only greenhouse gas emissions are considered as environmental impacts, but also other factors such as agricultural land use, by means of a Life-Cycle assessment (see Sections 9.9 and 10.5).

3. Project Framework

C. Reinhold, T. Witt

Because energy systems are very complex systems (as stated in [12]), the major question, how such a system can be transformed so that it is more sustainable in the future, can be broken down into many small research questions that need to be tackled by different disciplines [13]. Increasingly, interdisciplinary approaches, where models and methods from different disciplines complement each other, are used.

In this project, models and methods from energy technology, psychology, business administration, economics, and computer science are brought together to evaluate how sustainable energy supply can be achieved for Lower Saxony up to the year 2050. The project team comprises partners from universities located in Lower Saxony.

In Section 3.1, the project targets are described in more detail. From these project targets, the system boundaries are derived in Section 3.2.

3.1 Project Targets

C. Reinhold

The transformation of the energy supply system in Germany and especially in Lower Saxony toward a more sustainable system requires the investigation of relevant subsystems and properties that describe this system. In this field, essential instruments for decision support and scientific policy advice are the qualitative analysis of future scenarios via scenario planning, quantitative analysis of these scenarios' consequences via energy system analysis, and a subsequent multi-criteria evaluation, which helps to integrate objective model results and stakeholders' values for a holistic system evaluation. In this project, we develop a new general methodology for the development and evaluation of energy scenarios that aim to integrate scenario planning, energy system analysis, and multi-criteria analysis.

The objective of developing this methodology is, therefore, to provide an instrument for scientific policy advice, which helps to shed light on today's decision problems by providing quantitative data and allowing for sensitivity analyses, which can inform corresponding debates in the democratic system and make them more objective and transparent. The methodology does however not claim to generate binding recommendations. The energy transition affects many stakeholders because the energy system has many dependencies to economy, environment, policy, technology, and citizens. Therefore, the methodology has an additional goal to integrate this interdisciplinarity. In the first step, we develop future energy scenarios for the year 2050 as well as transition pathways marking the years 2020, 2030 and 2040. In the second step, we aim to evaluate the final system state in 2050 as well as the transition states based on a sustainability concept using a multi-criteria decision analysis approach.

In addition to the overall goal, subject-specific key questions are formulated at micro- and macro-level. For the micro-level, influencing factors on the diffusion of innovations as well as the possible necessity of behavioral adaptation for the implementation of a sustainable power supply system are examined. This requires a detailed empirical description of the behavior patterns in German households. The integration of innovations and new technologies in the residential and commercial sectors requires the investigation of the electrical behavior of buildings for each grid node in a coordinated grid system. Based on this, technical requirements are defined, which are necessary for the efficient use of smart grid technologies.

The macro-level, on the other hand, analyzes the energy system transformation and its quantitative effects on the sub-sectors of grid technology, energy economy, and national economy. To this end, the topology of the supply system and the characteristics of the generation and consumption structure are addressed. Cost-optimized expansion strategies and economic planning of the plants are essential for the transformation of the power supply system. The focus at the macroeconomic level is the evaluation of the influence of climate policy, trade policy and their interconnections on the energy sector and the economy of Lower Saxony.

Both levels are linked with each other. Statements and results from the micro-level are transferred to models of the macro-level with the use of scaling. For example, the load assumptions of a low-voltage grid are scaled and transferred to the grid extension planning for Lower Saxony's entire power grid.

Answering the key questions for future scenarios requires subject-specific simulation models to simulate the individual parts of the energy supply system. The basis for efficient simulation studies is the performance optimization of the respective simulation models. The subsequent process step is the aggregation and connecting of the simulation results with the sustainability criteria.

3.2 System Boundary

T. Witt

Because the project targets are not only to develop a methodology for development and evaluation of energy scenarios but also to apply this methodology to planning the transition of Lower Saxony's power generation system toward higher shares of energy from renewable sources, *two* system boundaries need to be distinguished:

First, the system boundary of the developed methodology and, second, the case-specific system boundary of its application to Lower Saxony.

The *system boundary of the developed methodology* is related to the so-called life cycle of energy scenarios. According to Grunwald [14], this life cycle can be distinguished into three phases. (1) Construction of energy scenarios, which may include quantitative energy system analysis, qualitative assumptions, or a mix of both; (2) evaluation of energy scenarios, which is the evaluation of an energy scenario's substance[1]; (3) impact of energy scenarios in energy policy and the energy sector, which comprises energy scenarios' consequences for decisions, the formation of opinions or structuring of public debates. In accordance with the project targets, the developed methodology for development and evaluation of energy scenarios covers only the first two phases of an energy scenario's life cycle. The generated results of the methodology can subsequently be used in the last phase of the life cycle to inform public debates. For example, as part of the project, the assumptions and results have been discussed in three public symposia with stakeholders employed in Lower Saxony's ministries, different regional associations, and the energy sector.

The *case-specific system boundary of the methodology's application* to Lower Saxony can again be divided into two parts: system boundaries of the future scenarios (see Section 6) and system boundaries of the different (energy system) models (see Section 9).

The *future scenarios* cover the power supply system of Lower Saxony, e.g., in terms of the energy mix and energy demand, and its environment, e.g., in terms of prices for primary energy carriers and political developments in the European Union. The heat and transport sectors are not covered, but assumptions for the development and growth of the overall economy are made. The temporal scope of the scenarios is 2015 through 2050, and the geographical scope of the scenarios is (mostly) Lower Saxony. For example, the energy demand of the adjoining federal states of Bremen and Hamburg is also considered, following the principle of solidarity described in [5].

Different *energy system models* cover different parts of the power generation system and have different geographical scopes. For example, the energy demand and generation of (a limited number of) households are modeled in a smart grid model. Thus, only a small section of the energy system is modeled, and this model's results

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[1] According to [14], the substance or "quality", i.e., the assumptions and methods of energy scenarios should be evaluated, which should help to select suitable energy scenarios for a decision problem. Note that a slightly different concept of evaluation is used in this project: Different alternatives are evaluated under different scenarios, which also leads to more transparent decision support. We also aim to increase the transparency of an energy scenario's construction phase with the help of an information model (see Section 4.2).

need to be aggregated before they can be used as input parameters for connected models with greater geographical scope. For detailed descriptions of each model's system boundary and the interfaces between the models, refer to the individual models' descriptions (see Section 9). Due to the varying availability of data, the temporal baseline of the models also differs. For example, while most models use input data from 2015 as their base year, the macroeconomic model uses data from 2011 as its base year, since data that is more recent was not available.

It should be noted that some of the used models and methods, e.g., the multi-criteria evaluation or empirical studies of the diffusion of innovation, require the identification of relevant stakeholders. With the object of investigation being Lower Saxony's energy supply system, different stakeholders can be investigated. However, a decision maker (or group thereof), who could implement options for Lower Saxony's future energy supply system, cannot be clearly identified, because there are simply too many actors that have different authorities over necessary resources (including energy supply companies, transmission system operators, non-energy companies, the general public, government institutions, and non-government organizations). In such a setting, we suggest that the different stakeholders can be analyzed via stakeholder analysis (see, e.g., [15] or Section 7), or that different perspectives are investigated via sensitivity analysis (see Section 5.1 for the weighting of decision-relevant criteria).

4. Development of a Methodology for the Sustainability Evaluation of Energy Scenarios

T. Witt, J. S. Schwarz

The major objective of energy policy in the European Union is to ensure a competitive, sustainable, and secure energy supply [16]. These targets are often cited in energy scenario studies for the EU and its member states. However, most energy scenario studies do not differentiate between scenarios (describing external uncertainties) and alternatives (describing options for the energy supply), and therefore do not explicitly evaluate the degree to which different alternatives actually satisfy these (multiple, usually conflicting) targets [7, 17]. Therefore, the recommendations and conclusions in these studies cannot be derived in a transparent way. To increase the transparency of the decision support, it would be useful to explicitly evaluate options in terms of these targets and thereby support today's decisions in energy policy or the energy sector.

To achieve such an evaluation, the methodology is based on the story-and-simulation (SAS) approach [18], in which the first step for developing scenarios is to develop qualitative storylines for each scenario (via scenario planning, see, e.g., [19]), which are quantified with assumptions and system models (via energy system analysis, see, e.g., [20]) afterward. Our methodology extends this SAS approach with multi-criteria analysis (see, e.g., [21]) in such a way that it leads to a number of alternatives, which can be evaluated in terms of competitiveness, sustainability, and energy security. Figure 4 illustrates the basic idea of a sustainability evaluation process.

The methodology, therefore, combines three individual processes: scenario planning, (energy) system analysis, and multi-criteria analysis. It does however not cover the last phase of the life cycle of energy scenarios (see Section 3.2), due to the nature of multi-criteria decision problems, where different stakeholders may have different opinions and priorities so that a compromise needs to be found.

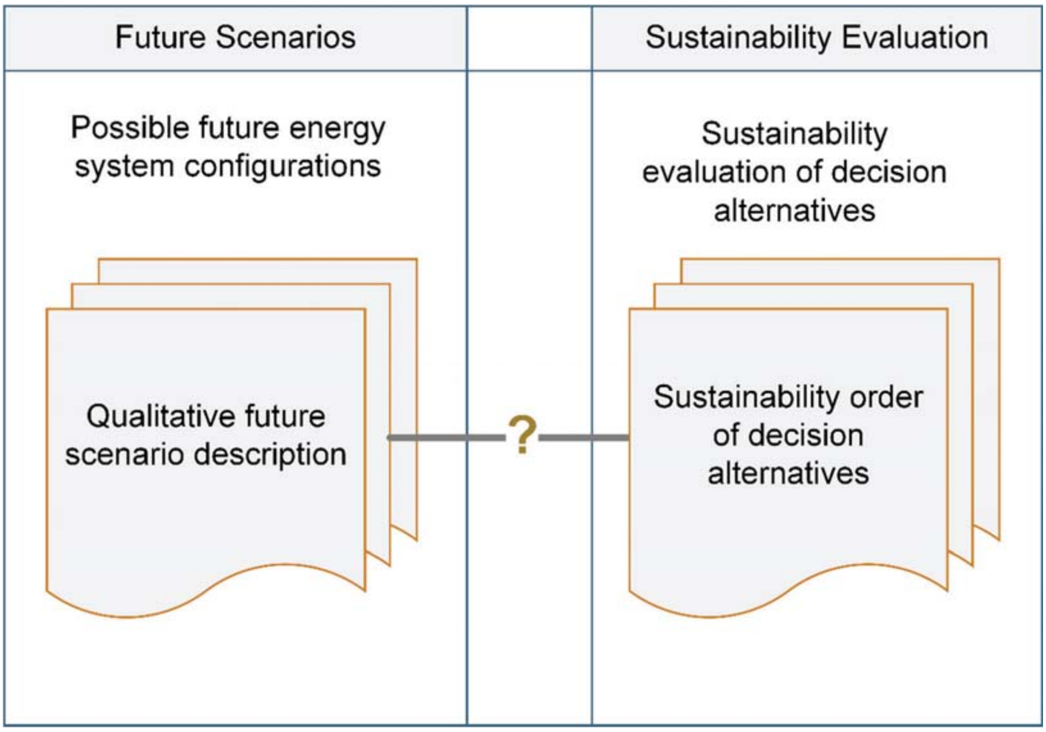

Figure 4: Methodological challenge: from qualitative future scenarios to an order of quantitatively evaluated alternatives

4.1 Process for Integrated Development and Evaluation of Energy Scenarios (PDES)

T. Witt

Two similar versions of the developed methodology have been described in [22, 17] (for a simplified version, see Figure 5; for a detailed version, see Appendix: Figure 101).[1] According to these descriptions, the methodology is divided into four subsequent phases: (1) Preparatory Steps; (2) From Story to Simulation; (3) Modeling and Simulation; (4) Sustainability Evaluation.

In the *Preparatory Steps* phase, a problem is identified and defined. The first result of this phase is a problem adequate definition of sustainability and its operationalization with concrete sustainability evaluation criteria (SEC, see Section 0). For example, in the application of the methodology to planning the transition of Lower Saxony's power generation system, not only social, economic, and environmental, but also technical criteria are used. The second result of this phase is the description of qualitative future scenarios addressing the earlier defined problem (see Section 6). For planning the transition of a complex system such as the energy supply system, different perspectives need to be integrated [13]. Therefore,

[1] Another version of the methodology, which uses the individual process of scenario planning, energy system analysis, and multi-criteria analysis as a theoretical basis, is described in [61].