Towards an Integrated Sustainability Evaluation of Energy Scenarios with Automated Information Exchange

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Keywords: Co-simulation, Energy Scenarios, Information Model, Multi-Criteria Decision Making (MCDM), Ontology, Scenario Planning, Story-and-Simulation (SAS), Sustainability Evaluation.

Abstract: To reshape energy systems towards renewable energy resources, decision makers need to decide today on how to make the transition. Energy scenarios are widely used to guide decision making in this context. While considerable effort has been put into developing energy scenarios, researchers have pointed out three requirements for energy scenarios that are not fulfilled satisfactorily yet: The development and evaluation of energy scenarios should (1) incorporate the concept of sustainability, (2) provide decision support in a transparent way and (3) be replicable for other researchers. To meet these requirements, we combine different methodological approaches: story-and-simulation (SAS) scenarios, multi-criteria decision-making (MCDM), information modeling and co-simulation. We show in this paper how the combination of these methods can lead to an integrated approach for sustainability evaluation of energy scenarios with automated information exchange. Our approach consists of a sustainability evaluation process (SEP) and an information model for modeling dependencies. The objectives are to guide decisions towards sustainable development of the energy sector and to make the scenario and decision support processes more transparent for both decision makers and researchers.

1 INTRODUCTION

The intended phase-out from nuclear and fossil power, and the transition to renewable energy resources in Germany pose new challenges. With the EU and the federal government of Germany having set targets for reducing energy demand and greenhouse gas emissions until 2030 and 2050 respectively (European Commission, 2014; Deutscher Bundestag, 2014; BMWi, 2010), decision makers in politics need to initiate and project the transition process today to achieve these targets. The goal of this transition process is to reshape the energy infrastructure and related planning and operation processes while also considering sustainable development. Thus, an approach to evaluate and compare future scenarios and corresponding transition paths regarding their sustainability characteristics is needed to provide guidance to the politically intended transition process.

Long-term energy scenarios are used to guide decision making in this context (Grunwald et al., 2016), and researchers have already put considerable effort into developing these scenarios. For example, the German database ”Forschungsradar Energiewende”[1] lists more than 920 publications on energy transition research in Germany from 2011 to 2016. This database also includes some publications on EU and worldwide levels, which are also relevant for the German debate, e.g. the World Energy Outlook (International Energy Agency, 2016). Based on these energy scenarios, different transition paths can be distinguished for the energy transition. If decision makers make use of energy scenarios to decide upon strategies, how the set targets of the energy transition can be achieved, the development and evaluation of energy scenarios should meet some basic requirements (see section 2 for more details):

- A concept of sustainability should be defined and operationalized with relevant dimensions in the evaluation process.

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[1] http://www.forschungsradar.de/studiendatenbank.html

Schwarz, J., Witt, T., Nieße, A., Geldermann, J., Lehnhoff, S. and Sonnenschein, M.
Towards an Integrated Sustainability Evaluation of Energy Scenarios with Automated Information Exchange.
DOI: 10.5220/0006302101880199
In *Proceedings of the 6th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2017)*, pages 188-199
ISBN: 978-989-758-241-7

- The decision support process should be transparent to allow decision makers to rely on the results.
- The scenario development and decision support processes should be replicable to allow repeated evaluation of energy scenarios.

In the article at hand, we will show an integrated approach for sustainability evaluation of energy scenarios with automated information exchange meeting these requirements. Our approach is based on the sustainability evaluation process (SEP) developed in the research project NEDS (Blank et al., 2016). The SEP combines qualitative future scenarios with quantitative simulation and multi-criteria decision-making. To cope with the requirements regarding replicability, we introduce an information model to support the automation of information exchange in the SEP.

The remainder of this article is structured as follows: In section 2, we elaborate on the requirements for energy scenarios. In section 3, we define the term ”energy scenario”, review related methodologies for their development and also review approaches for integrating energy scenarios with methods from decision analysis research. We furthermore describe the applicability of information modeling in the context of energy scenarios. In section 4, we combine the reviewed methodologies in our conceptual solution to set up the SEP as an integrated process with continuous tool support. After that, we give details on this solution regarding the SEP in section 5, and regarding the information model supporting the SEP in section 6. In section 7, we show how the three above-mentioned requirements are met by our solution and discuss open questions and future work.

2 REQUIREMENTS FOR ENERGY SCENARIOS

As stated in the introduction, the development and evaluation of energy scenarios should satisfy three basic requirements: They should include a definition and operationalization for sustainability, provide decision support in a transparent way and be replicable for other researchers. In this section, we elaborate on these requirements in more detail and point out that many energy scenarios do not satisfactorily fulfill them.

2.1 Sustainability Definition and Operationalization

Traditionally, a triangle of objectives including security of supply, economic viability and environmental compatibility is used to guide decision making in the energy sector. For example, in Germany these objectives are stated in the ”Energiewirtschaftsgesetz” (Energy Sector Act) (Deutscher Bundestag, 2005). Meanwhile, the concept of sustainable development is increasingly used to guide decisions in multiple fields of politics. According to the triple-bottom-line interpretation of sustainability, economic prosperity, social justice, and environmental quality need to be achieved simultaneously (Elkington, 2002).

If both approaches are integrated, technical, economic, environmental, and social criteria are all relevant to operationalize sustainability for decision making in the energy sector. However, the majority of recent research on energy transitions focuses on selected aspects and consequently fails to consider all relevant aspects simultaneously - see (Keles et al., 2011; Kronenberg et al., 2012; Hughes and Strachan, 2010) for reviews of considered aspects in Germany and the UK. Therefore, these studies might not be suitable to guide political decision making towards sustainable development of the energy sector in the definition given above.

2.2 Transparency of the Decision Support Process

While many studies aim at providing decision support for political decisions to promote sustainable development of the energy system, they fail to conceptualize this as a formal decision problem by using methods from decision analysis research. For example, in their review on 24 energy scenarios in Germany, (Kronenberg et al., 2012) point out that an integrated sustainability assessment would increase the usefulness for decision support, but is missing in most of the reviewed energy scenarios. This means that the process of generating recommendations from energy scenarios, i.e. the underlying decision support process, is not transparent for decision makers (Grunwald et al., 2016). Most energy scenarios do not specify decision alternatives for decision makers and delineate them from external uncertainties. Also decision makers' preferences are not explicitly considered, so that interpreting results for a decision towards a sustainable energy system remains an implicit and manual task. This is a problem, because most energy scenarios are developed in principal-agent relationships (Grunwald et al., 2016). For example, if researchers do not explicitly communicate the uncertainties associated with scenarios, decision makers may misinterpret the results. To this end, transparency of the methods and models used in the scenario process is needed. To overcome these problems, (Grunwald et al., 2016) proposed to introduce standards for energy scenarios in terms of scientific validity, transparency and openness of the results.

2.3 Replicability

Replicability is crucial to achieve scientific validity of energy scenario studies. It allows other researchers to repeat calculations and simulations of scenarios with the same parameters to replicate the results. Therefore, all information about the scenarios should be documented and published including input data, models and assumptions (Grunwald et al., 2016). This enables researchers to take an external scenario and vary the parameters or add new models to expand the focus of the scenario. This way, replicability also allows to reuse scenarios and to compare different scenario studies. Furthermore, in combination with a transparent decision making process it allows other researchers to replicate scenarios while also considering further sustainability facets.

During scenario development, simulation and evaluation, various data is exchanged between different actors, models and software. Due to the complexity of these processes (in particular the integration of simulation models from various domains), the information exchange is to a high degree error-prone. This calls for tool-support and automation with all data flows and dependencies being well defined and documented. This documentation of energy scenarios significantly improves the replicability (Grunwald et al., 2016).

3 RELATED WORK

In this section, we introduce different methodologies, which we combine to set up an integrated sustainability evaluation process with automated information exchange: Firstly, as we focus on scenarios in the energy domain, concepts of scenarios and methods for scenario design in this domain are described. Secondly, we discuss recent work from the area of decision support and discuss the applicability of multi-criteria decision making (MCDM)[2] in an energy scenario context. Thirdly, we point out how information models are used to support simulation and evaluation processes.

3.1 Energy Scenarios

Energy scenarios are a tool to investigate possible transformations of future energy systems. (Grunwald et al., 2016, p. 9) define them as a description of "*a possible future development (or a future state) of the energy system.*" An exemplary methodology to set up these scenarios is the story-and-simulation (SAS) approach (Alcamo, 2008). While this approach stems from environmental modeling, it is increasingly used in the energy context (Weimer-Jehle et al., 2016). SAS scenarios combine qualitative stories and quantitative data for simulation studies. With this two-fold concept, SAS scenarios allow both the involvement of decision makers and technical simulation.

The variation of quantitative attributes within the SAS scenarios leads to adapted simulation model parametrization. To this end, it should be clear, why certain quantitative parameters of a simulation are varied and others are not, based on a storyline.

For the sake of transparency a well-defined process for creating these stories is necessary, which can be found e.g. in scenario planning[3]. This is an expert-based management tool, which originates from strategic planning on company level in the 1970s (van der Heijden, 1996). Based on this prior work, (Gausemeier et al., 1998) proposed the following process for the developing future scenarios:

Firstly, participating domain experts discuss factors influencing a scenario and systematically identify the most important key factors. Afterwards, they identify the key factors' projections, which are possible developments up to a certain point in time to span a broad range of possible future developments, and describe them. These different projections are checked by the experts for consistency and the results are recorded in a consistency matrix. Based on this matrix a scenario software uses cluster analysis to build projection bundles, which represent consistent combinations of projections and thus possible future scenarios. In the last step, the domain experts write storylines, i.e. textual descriptions, for all future scenarios.

3.2 Integration of Scenario Planning and MCDM

According to (Belton and Stewart, 2003, p. 2), MCDM is "*an umbrella term to describe a collection of formal approaches, which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter*". We shall

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[2] Also called multi-criteria decision aiding/analysis (MCDA).

[3] Also called scenario management.

highlight three characteristics in this definition, which show the applicability of MCDM for energy systems planning: Firstly, as stated in section 2.1, technical, social, environmental and economic aspects are relevant for energy systems planning (”*multiple criteria*”). Secondly, the decision for a future energy system affects many stakeholders with conflicting objectives. In this context, MCDM can help to structure and inform debates (”*individuals or groups*”). Thirdly, the energy system is fundamental for sustaining modern societies (”*decisions that matter*”).

Researchers have already applied MCDM extensively in sustainable energy planning, e.g. (Wang et al., 2009) and (Oberschmidt et al., 2010) provide overviews. Surprisingly, the integration with scenario planning has not been in the focus of research. (Stewart et al., 2013, p. 682) identify four concepts for scenarios, which are more or less well-suited for integrating MCDM and energy scenarios:

1. external situations affecting consequences of policy actions,
2. exploration of future conditions or environments,
3. advocacy of particular courses of action,
4. representative sample of future states.

(Kowalski et al., 2009) integrate scenario planning and MCDM and apply this to energy systems planning in Austria. However, they do not differentiate between decision alternatives and external uncertainties: They use the scenarios from scenario planning directly as decision alternatives (see also (Madlener et al., 2007)). This approach is consistent with the scenario concept ”exploration of future conditions or environments”, in the sense that the decision alternatives are defined by a range of possible outcomes. While scenarios were originally designed to deal with external uncertainties in strategic planning, (Kowalski et al., 2009) do not consider external uncertainties.

(Stewart et al., 2013) provide general guidelines for integrating MCDM and scenario planning. To that end, they point out that ”*it is essential that the scenarios reflect external driving forces (events, states) which are separated from the policies or actions under consideration*” (Stewart et al., 2013, p. 683). This implies the interpretation of scenarios as ”external situations affecting consequences of policy actions”. However, they do not provide a detailed process model for integrating MCDM and energy scenarios.

3.3 Information Modeling

In the aforementioned development, simulation, and evaluation of energy scenarios, various data flows have to be defined. For example, the simulation of energy systems includes material flows (e.g. coal or biogas for power plants), information flows (e.g. in smart grid control strategies), and electric power flows. Additionally, the behavior of users should be included to achieve valid results. Therefore, various simulation models have to be coupled to represent this complex, dynamic, sociotechnical system. This is a complex task, so automating the exchange of data is important. This is usually done by defining an information model, which is described in (Lee, 1999, p. 1) as *”a representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse.”*

According to the definition and operationalization of sustainability (see section 2.1), experts of different domains take part in the scenario development process. Therefore, the challenge is not only to model information but also to collect domain knowledge. A single term can be used in different domains with different meanings. Therefore, the terms and relationships between them should be defined. A common technology for this representation of domain knowledge are ontologies, which *”have been developed to provide a machine-processable semantics of information sources that can be communicated between different agents (software and humans)”* (Fensel, 2004, p. 3).

Information models are widespread in industry to allow interoperability, e.g. the Common Information Model (CIM) in the energy domain (Uslar et al., 2012). It contains a data model (domain ontology), various interface specifications, technology-specific instantiations of the ontologies (communication and serialization) and allows automated communication between components of smart grids.

The common processes and languages for information modeling and ontology development require the user to be experienced in their usage. To avoid this barrier for experts from different domains, who most likely do not have this expertise, there are some approaches to use concept maps for the instantiation of ontologies (Castro et al., 2006; Simon-Cuevas et al., 2009).

4 CONCEPTUAL SOLUTION

In section 2, we have defined three main requirements for the development and evaluation process of future energy scenarios: A definition and operationalization of sustainability, transparency of the decision support process to allow decision makers to rely on the results, and replicability to ensure comparability. To take into account these requirements, we propose to use SAS scenarios in combination with scenario planning for the story and integrate the following three approaches:

Firstly, to increase the transparency of the decision support process, we propose to integrate SAS scenarios with MCDM. (Stewart et al., 2013) provide an overview of approaches from the 1990s and early 2000s that already integrated MCDM and scenario planning to provide an integrated sustainability assessment. However, today only few energy scenarios build upon these approaches and differentiate between courses of action (we will call these **decision alternatives**)[4] and framework conditions (**external uncertainties**). One obstacle might be the lack of a process model integrating these two approaches. While there already exist some guidelines for constructing SAS scenarios (Alcamo, 2008; Weimer-Jehle et al., 2016), these guidelines do not integrate MCDM. In the research project NEDS, a novel process model has been introduced for the integration of MCDM and SAS scenarios for sustainability evaluation: the sustainability evaluation process (SEP) (Blank et al., 2016). We will describe some parts of this process model in more detail in section 5.

Secondly, the complexity of energy scenarios calls for tool-support and automation of the process (see also section 2.3). Therefore, an information model is proposed to structure the data flows and dependencies in the scenario process, organize the communication between experts from different domains and collect their knowledge. To allow the participation of domain experts without having them to learn new complex description languages and techniques in detail, the information model uses a mind map for the representation of knowledge. For integration in the process and the simulation, we use the modeled information to instantiate an ontology and make the information available in a machine readable format.

Thirdly, we propose to use co-simulation for the simulation part of SAS scenarios, to allow considering multiple dimensions of sustainability. Simulation is typically done in one single simulation software (e.g. Matlab). This makes it hard to integrate simulation models from different domains, because most domains use specific software and languages (Schloegl et al., 2015). An approach for solving this issue is co-simulation, which is defined in (Bastian et al., 2011) as *"an approach for the joint simulation of models developed with different tools (tool coupling) where each tool treats one part of a modular coupled problem."* A co-simulation framework with focus on the energy domain is e.g. mosaik[5] (Lehnhoff et al., 2015; Rehtanz and Guillaud, 2016). It allows coupling different simulators, provides an application programming interface (API) for different programming languages and handles the scheduling and information exchange between the simulation models during simulation.

5 SUSTAINABILITY EVALUATION PROCESS (SEP)

Having presented our general solution approach for integrating SAS scenarios and MCDM, we now concretize this in terms of a process model for the SEP. An overview is given in figure 1. It is subdivided into four parts that will be explained in the next sections. The parts do not have to be performed in sequential order, but should be done at least partly in parallel: Two different entry points are given, on the left and on the right side of figure 1.

5.1 Future Scenarios

In the first step[6], the scenario planning process (see section 3.1) is used to develop future scenarios. These are qualitative, i.e. textual, descriptions of possible futures and thus need to be transformed into quantitative assumptions, which are used in simulation models and sustainability evaluation. Therefore, the next step is the deduction and classification of **attributes** characterizing these assumptions. On the one hand, the attributes are deduced from key factors of the future scenarios. On the other hand, attributes can also be deduced from results of the sustainability evaluation phase (in form of transformation functions and sustainability evaluation criteria, which we shall explain in section 5.4).

In future scenarios, the distinction between decision alternatives and external uncertainties is blurred and therefore a classification of attributes is needed. Figure 2 provides on its left side an overview on the different types of attributes. To allow differentiating between attributes characterizing decision alternatives and external uncertainties, we introduce a system boundary. Naturally, the decision makers' sphere

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[4] In the remaining sections of this paper, definitions related to the SEP are highlighted in bold typesetting at their first occurrence.

[5] http://mosaik.offis.de

[6] For better readability we use the term "step" to describe subprocesses of the SEP.

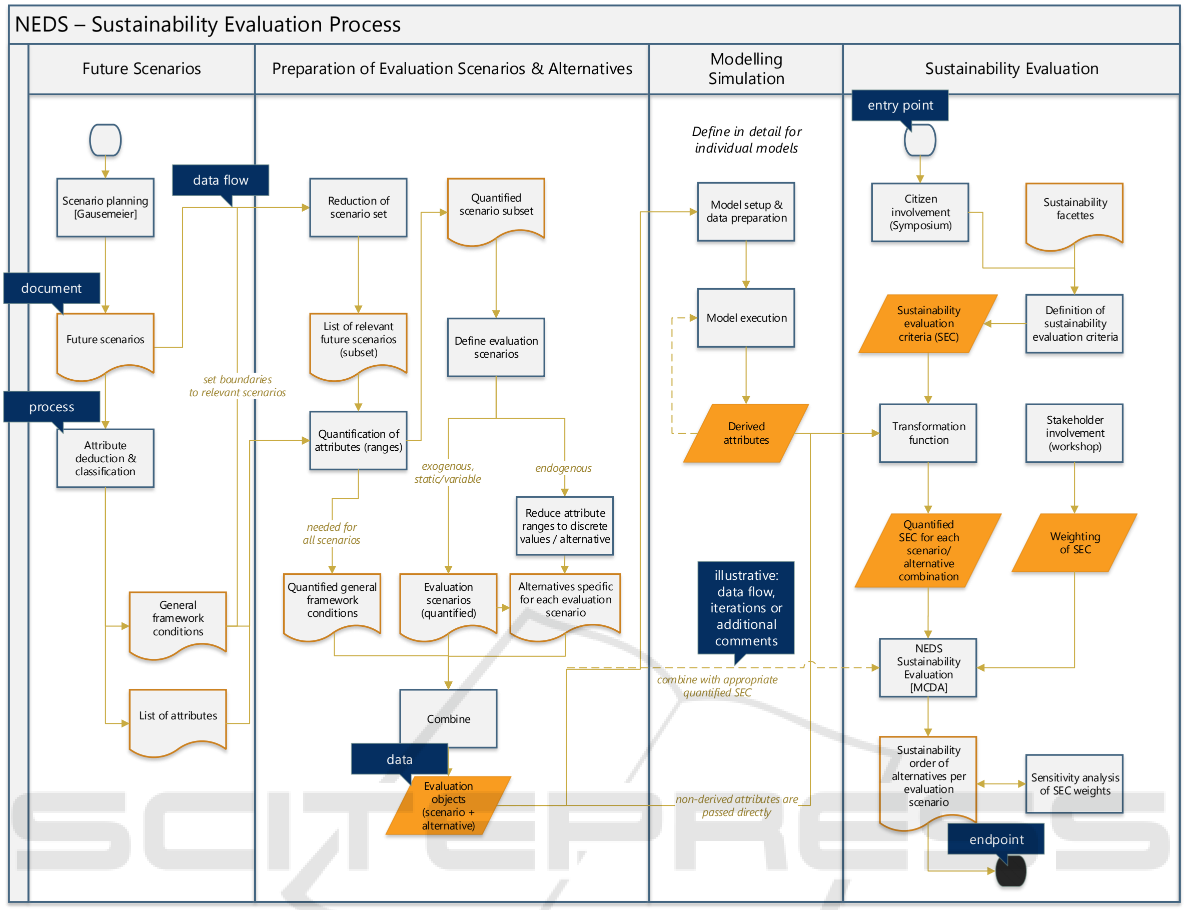

Figure 1: Sustainability evaluation process (blue legend icons give information on the semantics used within the diagram) (Blank et al., 2016).

of influence provides this system boundary: If decision makers can decide upon the values of attributes, they are classified as **endogenous attributes**. A combination of values for all endogenous attributes consequently constitutes a decision alternative. For example, political decision makers can decide, if and which renewable energy technologies are granted subsidies. Thereby, they influence their respective shares in the energy mix. In contrast, if decision makers cannot decide upon values of attributes, they reflect external uncertainties. For example, political decision makers in a federal state government cannot decide on the development of prices for crude oil. We further distinguish external uncertainties into **scenario-specific framework conditions** and **general framework conditions**. For example, prices for crude oil might be a scenario-specific framework condition, while the demographic development might be a general framework condition. The decision, whether framework conditions are interesting and therefore scenario-specific, depends on the systematic selection of key factors in the future scenarios. Since general framework conditions are not scenario-specific, they also do not have an impact on the decision between alternatives.

The results of this part of the process are textual descriptions of future scenarios, defined general framework conditions and a list of the classified attributes (see left column in figure 1).

5.2 Preparation of Evaluation Scenarios and Alternatives

In a first screening, the future scenarios are evaluated against the general framework conditions, e.g. targets for reducing greenhouse gas (GHG) emissions, which set boundaries for identifying decision alternatives. This is necessary, because the future scenarios are designed to reflect a broad range of future projections. In this step, future scenarios may be discarded, if it is obvious that they will not comply with all general framework conditions. For example, if there exists a future scenario, in which the shares of renewable energy technologies stay on today's levels and energy

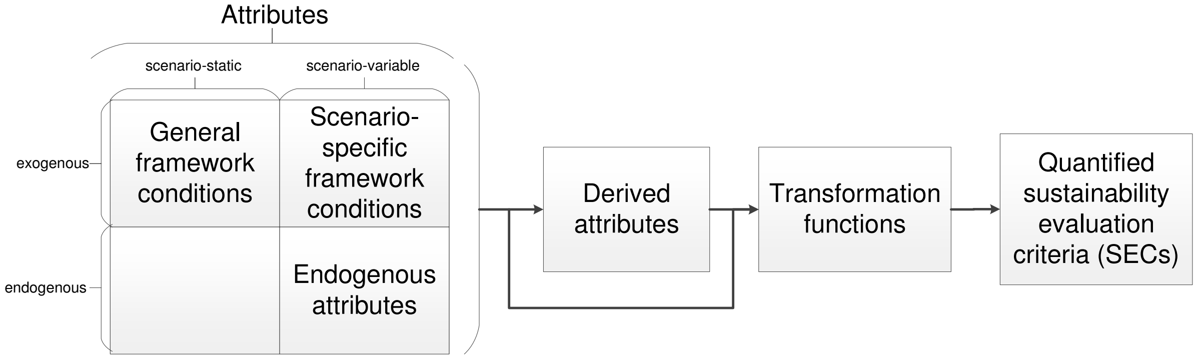

Figure 2: Overview of attribute classification in different types and the data flows of their values.

demand increases, it is quite obvious that GHG reduction targets cannot be met. However, this scenario may be used as a reference scenario, depending on the objective of the evaluation.

Quantifying the attributes for a certain point in time in the future, say the year 2030 or 2050, is the next step. This means that the different types of attributes (see section 5.1) need to be specified in such a way that a future scenario is reflected in this specification. To that end, attribute specifications can be gained e.g. from related quantitative energy scenarios in literature, i.e. scenarios that fit to the assumptions of the selected future scenarios. Using these different scenario studies, for general framework conditions a single value has to be defined, while for scenario-specific framework conditions values have to be defined for every future scenario. For the endogenous attributes, different scenario studies are used to determine ranges of possible values in every future scenario. After that, final discrete attribute values are chosen in such a way that they reflect decision alternatives. According to the SAS procedure proposed by (Alcamo, 2008), fuzzy set theory can be used for this step.

The results of this part of the process are quantified decision alternatives and quantified evaluation scenarios illustrating the associated uncertainties.

5.3 Modeling and Simulation

In the previous parts, attributes have been deduced, classified and quantified with the help of related literature. But not all relevant attributes can be quantified this way and therefore simulation is used to provide **derived attributes**. As mentioned in section 4, co-simulation is used to allow the integration of simulation models from different domains. Since modeling is done differently in every domain and this is not the focus of this paper, only a rough specification of this part is shown here. More details on this will be given in future publications.

Firstly, the different simulation models have to be set up and the input data has to be prepared, e.g. scaled to the scope of the simulation scenario. As indicated by a feedback loop in the process, models may have dependencies between each other that have to be considered. We shall explain modeling these dependencies in more detail in section 6.3. After simulation scenarios are set up, simulation can be started and the derived attributes are provided.

5.4 Sustainability Evaluation

The last part of the process is the evaluation of sustainability, which is assisted by MCDM. As a requirement for any MCDM, the researchers need to define the criteria, in terms of which the performance of alternatives is measured (Belton and Stewart, 2003). Since the criteria should reflect the different aspects of sustainability, we name them **sustainability evaluation criteria** (SECs). The values for the SECs represent the performance of a decision alternative under a given scenario in terms of these criteria for a certain year.

To guarantee that all relevant SECs are considered, we propose a two-step procedure: Firstly, related literature on MCDM in the energy context provides input for the SECs. SECs should also be gained from public participation, e.g. by using questionnaires in a public symposium (see entry point in the right column of figure 1). Secondly, the researchers should condense the collected SEC to avoid redundancies and define them.

The SECs are structured hierarchically so that the first level of the hierarchy represents the overall objective, e.g. identifying a sustainable power system. The second level represents the aspects as defined in section 2.1 (technical, economic, environmental, social). The lower levels of the hierarchy represent sub-goals, which are ultimately broken down into quantifiable SECs. For example, climate protection and biodiversity protection are sub-goals in the environmental domain, which can be broken down into greenhouse gas potential, particulate matter formation, land use etc.

With the researchers having collected and structured the SECs, the decision makers need to assign weights to reflect their preferences (Belton and Stewart, 2003). (Wang et al., 2009) provide an overview on standard procedures for the assigning weights in MCDM. While directly asking decision makers as commissioners of energy scenarios is the straightforward approach, a multi-actor MCDM involving different stakeholder groups is also possible (Steinhilber, 2015).

The next step is to define a **transformation function** for each criterion to determine the quantified SECs for each decision alternative (see the right side of figure 2). This function transforms derived and non-derived attributes into concrete values for the SECs. For example, the installed capacities of different power plants and a specified demand curve for a year, say 2050, are given as input for a simulation. Then, the schedules of these power plants in 2050 are calculated in the simulation by matching supply with demand. From these schedules, the CO_2-emissions in 2050 can be calculated for this decision alternative (installed capacities of power plants) with a transformation function (provided the CO_2-emissions for specific power plants are also known and normalized to a reference unit, e.g. [t CO_2-eq/MWh]). In this example, the demand curve could be a scenario-specific framework condition and thus altered to reflect different future scenarios.

To define the transformation functions, it is important that the criteria fit the simulation models or rather that this fit is established: In the best case, researchers can choose, expand or design simulation models in such a way that all SECs can be calculated. If this is not possible, external studies might provide input for the transformation functions. For example, studies on life-cycle assessments can provide input for the environmental criteria.

Lastly, the actual evaluation of the decision alternatives is performed by aggregating the quantified SECs of the different alternatives with the weights associated with them. To that end, different aggregation methods exist in MCDM. A suitable method in this context is PROMETHEE, since it is easily understandable and therefore also transparent for decision makers (Brans and Vincke, 1985). The result of this method is a (partial or total) ranking of the decision alternatives. This order can then be used to generate recommendations for the decision makers. Furthermore, sensitivity analysis of the SEC weights can be used to check the robustness of the results.

The results of this part of the process are a ranking of alternatives and recommendations for further action for the decision makers.

6 INFORMATION MODEL

Having presented the SEP of energy scenarios, we shall point out how an information model can help to automate the information exchange during this process. The objectives of the information model are to structure the data flows and dependencies in the described SEP, organize the communication between experts from different domains and collect their knowledge. The experts should be enabled to contribute directly to the SEP without using description languages and techniques as commonly used in information modeling. To allow participation of experts from all domains considered, an easily usable software is necessary, which is found in mind mapping tools.[7]

Our approach for fulfilling the objectives with the information model in a mind map is explained in the following sections. In section 6.1 we describe the information model's general structure and concretize this with an example in section 6.2. To allow the automated integration of the modeled information, we show its machine readable representation as an ontology in section 6.3 and explain the integration in the SEP in section 6.4.

6.1 Structure of the Information Model

The information model links future scenarios and simulation scenarios to the sustainability evaluation. While future scenarios give an overview of possible developments in the future, simulation scenarios describe the configuration of a concrete simulation, which includes the used simulation models and how they are connected and parametrized. The connections from both of these scenarios to the evaluation are implemented with transformation functions, which provide the dependencies and mathematical descriptions by mapping attributes and derived attributes onto the SECs.

The structure of the information model is depicted in figure 3. The left side represents the domains of interest for the future scenarios and simulation scenarios and consists of different levels ordered from left to right. On the first level the domains are listed. Each domain is subdivided into domain objects, which represent objects of the real world. The domain objects

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[7] We chose the mind mapping tool XMind (http://xmind.net), which can be extended with plugins and is available as open source software.

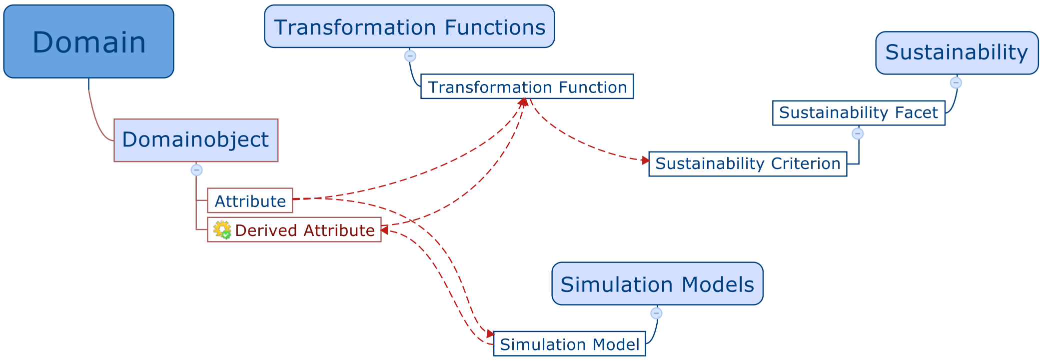

Figure 3: Structure of the information model.

consist of attributes[8] and derived attributes that describe them. Attributes have defined units and are instantiated with values in each evaluation scenario.

The derived attributes represent the results from simulations and have to be connected to the corresponding simulation model. The inputs of a simulation model are connected with incoming arrows, which show the data flows from the attributes to a simulation model. The outputs of a simulation model are connected with reversed arrows (from a simulation model to the derived attributes). Derived attributes are also marked with cogwheel icons to allow to distinguish them from other attributes.

The right side of the information model represents the evaluation part of the SEP. On the first level, the major objective is defined – in our case sustainability. The objective consists of different facets on the second level (e.g. technical, economic, environmental and social as introduced in section 2.1). Every facet is subdivided into various SECs on the third level. These SECs have to be defined by transformation functions, which may have attributes and derived attributes from the left side of the information model as input.

6.2 Example

An exemplary segment of the information model modeled in XMind is shown in figure 4. On the left side, the two domains ”information and communication technology” (ICT) and ”energy” are depicted. ”Control systems” and ”power plants” are domain objects, which are described by some attributes.

One single simulation model is included in this example representing a controller for the operational planning of power plants. This (simplified) controller uses the control strategy of the control system and the power of the power plants as inputs. The results are a schedule for all power plants and the period of use for every single power plant.

Power, specific CO_2-emissions and period of use feed the transformation function for calculating the CO_2-emissions of the whole system. In this case, the transformation is an aggregation of data, which is used to quantify the SEC CO_2-emissions on the right side of the information model.

6.3 Ontological Representation

In section 6.1, the structure of the information model in a mind map has been described. To allow the automated integration of the modeled information in the SEP it has to be made available in the form of a machine readable format. As described in section 3.3, ontologies are a frequently used technology for a machine readable representation of knowledge. Thus, we aim to allow the representation of the information model's content with an ontology. By doing so it provides a structure for reasoning the information to infer implicit knowledge and query the information with languages like e.g. SPARQL to support the development of simulation scenarios.

The capability to query data can be used to support the user in the following ways. For example, when the left and right sides of the information model have to be coupled, the user can be supported in different tasks: Firstly, querying allows to identify attributes that are missing on the left side of the information model as input for transformation functions to allow the previous defined evaluation (use it from the right to the left side). This information helps to choose the right simulation models or to include the right key factors in the scenario planning. Secondly, it allows to identify evaluation criteria that can be added on the right side of the information model to make sure that all results from future scenarios and simulation are used (use it from the left to the right side).

Additionally, the modeled information allows to examine the dependencies between simulation mod-

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[8] The term attribute in the information model includes all framework conditions and endogenous attributes described in section 5.1 and figure 2.

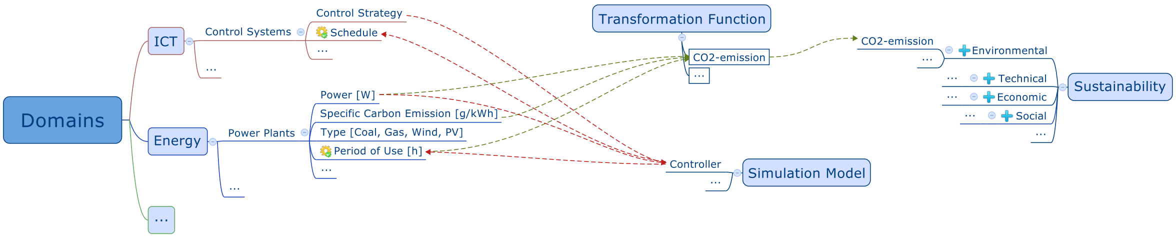

Figure 4: Example of the information model in XMind.

els. More specifically, the data flows between models can be analyzed to find mutual or cyclic dependencies to get information about the order in which the models have to be executed.

As the information model is implemented in a mind map, a transformation to an ontology is needed. To allow the ontological representation a base ontology is implemented with the general structure of the information model. Based on the modeled information in the mind map, the base ontology is instantiated with the concrete information by an extension of the mind mapping software.

6.4 Integration in the SEP

The information model is integrated in the SEP (see figure 1) and supports the following steps:

Deduction of Attributes: The results of the deduction of attributes (see section 5.1) are listed in the information model. In parallel, the SECs and transformation functions are defined in the information model (see section 5.4). As explained in the previous section, the information model is able to check the dependencies and identify missing attributes, SECs or transformation functions.

Quantification of Attributes: Having listed the attributes in the information model, experts need to quantify them, so that is it possible to use them as parameters in the simulation models and in the evaluation with the MCDM. In this step, different values are assigned to the attributes (to represent the different scenarios). The information model supports that by providing a (database) schema for the data.

Modeling and Simulation: The information model supports designing the simulation models and setting up simulation scenarios (see section 5.3). As it contains the connections of attributes and simulation models, it illustrates, which dependencies have to be considered in modeling and simulation.

Sustainability Evaluation: In the sustainability evaluation part of the SEP, the information model is directly integrated, because it contains the transformation functions, which define the derived attributes and attributes as input of the SECs. It also provides the data schema for handling the results.

7 CONCLUSIONS AND FURTHER WORK

In this article, we have shown how the SEP developed in the project NEDS (Blank et al., 2016) integrates SAS scenarios with MCDM and leads towards an integrated sustainability evaluation of energy scenarios. We have described the process and added details to different parts. Additionally, we have introduced an information model, which leads towards an automation of information exchange in the SEP. In this information model, future and simulation scenarios are linked to the sustainability evaluation via attributes, transformation functions and SECs. We shall highlight how the three requirements for the development and evaluation of energy scenarios – integrate a sustainability definition, add transparency to the decision support process and allow for replicability (see section 2) – are met by this integrated approach:

Firstly, co-simulation integrated in SAS scenarios simplifies the consideration of various sustainability facets in simulations, because it allows coupling simulation models from different modeling tools and programming languages. Thereby, not only technical or economic, but also environmental and social criteria can be considered simultaneously in energy scenarios. The information model facilitates the integration of different dimensions of sustainability by modeling the data flows between different models, software and actors in the SEP. Overall, it allows to handle the complexity of multi-domain co-simulation scenarios and supports the communication between experts from different domains.

Secondly, integrating MCDM into energy scenarios makes the decision support processes more transparent for decision makers. Integrating MCDM into energy scenarios facilitates problem structuring: The structured nature of MCDM approaches challenges decision makers to think about and make their own preferences explicit. Additionally, the proposed SEP fosters the communication of uncertainties by differentiating explicitly between decision alternatives and external uncertainties. Thereby, decision makers are presented with the impacts of their decisions in highly uncertain environments. This way, decision alternatives can be identified and evaluated.

Thirdly, the information model addresses both the transparency and replicability of the development and evaluation of energy scenarios by modeling the data flows and dependencies between different models, software and actors in the SEP. The ontological representation of information leads towards an automation of scenario definition, simulation preparation and evaluation of the results in the context of energy scenarios. This is crucial to handle the complexity of energy scenarios.

While the proposed solution satisfies the requirements for energy scenarios in theory, this is only a starting point and its applicability needs to be validated empirically. To that end, the SEP is currently applied in the project NEDS to analyze the transition of the energy system of the German federal state of Lower Saxony up to 2050. Researchers from business administration, computer science, economics, electrical engineering, and psychology work together with stakeholders to identify and evaluate future states of the energy system in Lower Saxony. Additionally, the following steps will be undertaken in NEDS:

1. **Reflection of transition paths:** To evaluate not only target years within the given future scenarios but include the transition to these in the sustainability evaluation is important for a holistic view on the problem domain. Possible methodical approaches are multi-period MCDM, e.g. by adapting the PROMETHEE method to handle multi-period decision problems.
2. **Information model usage for data management:** To allow an automation of evaluation in the SEP the direct integration of the information model in the simulation process has to be established. The definition of data in the information model will also be integrated in the data management and used for semantic analysis and information retrieval in the results.

Further work beyond the NEDS project might add handling of model induced uncertainties in the simulation process: As every simulation model is a simplification of the real world, simulation naturally introduces uncertainties, which have to be dealt with. There is some work done about quantifying uncertainties in the context of co-simulation framework mosaik (Steinbrink and Lehnhoff, 2016), which can be integrated in the SEP and the information model in future work.

ACKNOWLEDGEMENTS

The research project 'NEDS Nachhaltige Energieversorgung Niedersachsen' acknowledges the support of the Lower Saxony Ministry of Science and Culture through the 'Niederschsisches Vorab' grant programme (grant ZN3043).

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