Process for Simulation-based Sustainability Evaluation of Future Energy Scenarios

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Abstract: Political and technological decisions regarding the transformation of energy systems with respect to sustainability criteria have to follow a defined process fulfilling several requirements. In this work, we present the work foundations from the research project NEDS - Nachhaltige Energieversorgung Niedersachsen covering a process model to evaluate sustainability in future energy scenarios – the NEDS sustainability evaluation process (NEDS SEP). In the process presented, the single steps from the creation of qualitative scenarios and definition of sustainability objectives up to empirical simulation studies and finally decision support are described.

1 INTRODUCTION

In this whitepaper, we introduce the sustainability evaluation process that is currently being developed within the research project 'NEDS – Nachhaltige Energieversorgung Niedersachsen', supported by the Lower Saxony Ministry of Science and Culture through the 'Niedersächsisches Vorab' grant programme (grant ZN3043). Within this research project, research partners from five different universities and research institutes thrive for an interdisciplinary evaluation of future energy scenarios. The general goal is to define a method which helps in the decision making process needed for the transition from central fossil and nuclear energy systems to decentralized and sustainable energy systems. The regional focus is on the Federal State of Lower Saxony. Therefore the decisions to be made are defined as those options that can be chosen by the Federal State in its different political committees. This system boundary is of major importance for the defined process: If the Federal State does not have an influence on a given characteristic of the energy system, there is no decision option regarding this characteristic.

In the remainder of this paper, we will first give an introduction to the background of the depicted decision making process – including a definition of what constitutes sustainability within the presented work (Section 2) and the main methodological challenge that is addressed by the process. The solution approach and needed terms are described and defined in Section 3. After that we present the NEDS sustainability evaluation process (NEDS SEP) (Section 4). Finally we will point out needed extensions by deriving them from still open project goals (Section 5).

2 REQUIREMENTS AND METHODOLOGICAL BACKGROUND

2.1 General Requirements

The planned exit from nuclear and fossil energy and transition to decentralized renewable energy resources in Germany pose new challenges for decision makers in politics: The transition has to be planned and distinct decisions will affect many different stakeholders. With the federal government of Germany having set targets for reducing energy demand and greenhouse gas emissions until 2050 (Deutscher Bundestag, 2014), (Bundesministerium für Wirtschaft und Technologie, 2010), decision makers need to decide today on how to achieve these targets.

The effective goal of this transition process is to reshape the energy infrastructure und related planning and operation processes while considering the different aspects of sustainability. Thus, an approach to evaluate and compare future energy scenarios and possible transition paths regarding their sustainability characteristics is needed to give guidance to the politically fostered transition process.

Long-term energy scenarios are widely used to guide decision making in this context (Grunwald et al., 2016), and considerable effort has already been put into the creation of these energy scenarios. For example, the German database "Forschungsradar Energiewende"[1] already lists 895 publications on energy transition research in Germany from 2011 to 2016 (including some relevant publications on EU and worldwide levels). The overall process should be designed in such a way that decision makers are supported in the task of opting out between different possible future energy scenarios and transition paths. Under these premises, two basic requirements should be fulfilled:

- **Sustainability definition** – Define and include the relevant dimensions of sustainability in the evaluation process: The UN World Commission on Environment and Development defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This definition contains two key concepts: [...] ii) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs" (Brundtland, 1987, p. 41). Furthermore, economic and ecological considerations need to be integrated for decision making (Brundtland, 1987, p. 55). This led to the triple-bottom-line interpretation of sustainability, according to which **economic prosperity, social justice and environmental quality** need to be achieved simultaneously (Elkington, 2002). Depending on the instantiation of the process and the underlying planning task, the relevant stakeholders have to be included in the precise definition of sustainability in the given context.
- **Transparency** – Give transparency to the decision process to allow decision makers to rely on the results: While many studies aim to provide decision support for political decisions to promote sustainable development of an energy system, many of them fail to (1) integrate a sustainability assessment, and (2) conceptualize this as a formal decision problem, and (3) be transparent on methods and models used in the evaluation process. To overcome these and related problems, it has been proposed to introduce standards for energy scenarios in terms of scientific validity, transparency and openness of the results (Grunwald et al., 2016).

Against this background, the main purpose of the NEDS sustainability evaluation process is to deliver a sustainability evaluation of those parts of possible future energy system manifestations that are in the hand of the decision maker. On the left hand side of Figure 1, we can see possible future energy system manifestations. These are defined using qualitative scenario descriptions. On the right hand side, the desired output of the process is displayed: A sustainability grounded order of those parts of future energy scenarios that are to be decided by the

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

decision maker. Within NEDS, the main decision maker is the Federal State of Lower Saxony represented by its different governmental committees.

The main task within the NEDS research consortium is to define the process that leads to this result by (a) defining the different inputs needed for this process and (b) define the process steps to generate the outputs from these inputs. Part of this task is to evaluate, which actors are needed for such a sustainability evaluation, a crucial aspect when societal aspects should be part of the evaluation result as well.

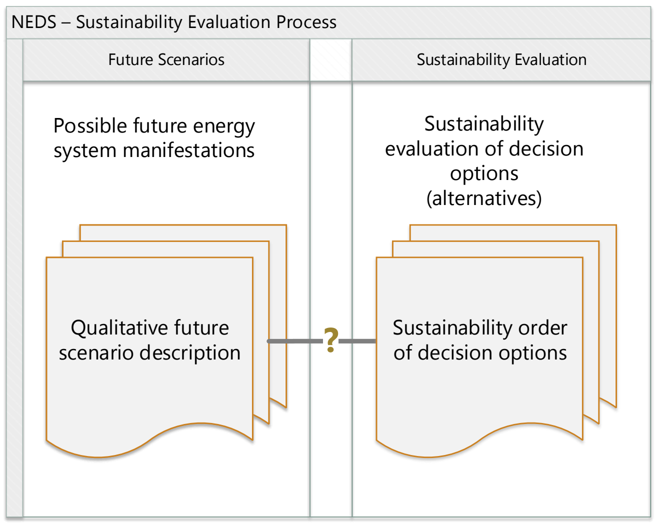

Figure 1: Methodological challenge within the research cluster NEDS.

2.2 Methodological background

It has been pointed out in the last section, that transparency of the decision support process is a core requirement to the evaluation process. To this end, multi-criteria decision management (MCDM) as a well-established decision support method has been chosen within the NEDS consortium. An overview on MCDM is given in (Belton and Stewart, 2003) and (French et al., 2011). One design characteristic of MCDM is that it is able to guide a decision maker through a decision process with conflicting objectives. With the different facets of sustainability, like economic and ecological criteria, this is clearly the case for a sustainability driven decision process.

The evaluation of future energy scenarios additionally raises the need for a transparent process on how to generate these possible future scenarios. A well-established approach to generate qualitative scenarios has been introduced with the scenario planning approach as defined in (Gausemeier et al., 1998). Whereas some work already has been presented to integrate scenario planning and MCDM (see (Stewart et al., 2013) for an overview) the integration of these methods with the goal of a sustainability driven decision process for future energy systems is still missing. Most strikingly, the differentiation between what is part of the decision process (i.e. can be influenced by the decision maker, a set of so-called alternatives) and what is out of this so-defined system boundary (framework conditions) needs precise definition within the both heavily regulated and transnational energy market and system.

With these two methodological foundations – scenario planning and MCDM – a process has to be defined that will cover the requirements as defined in Section 2.1 and thus close the gap between qualitative scenario descriptions and a quantification-driven decision support approach. In the upcoming sections, we will show how this is solved within the NEDS SEP.

3 SOLUTION APPROACH

In this Section, the general idea on how to solve the methodological challenge as presented in Figure 1 will be explained. After that we will define relevant terms needed for the definition of the detailed process.

3.1 Overview

The methodological challenge, as presented in Section 2.2, Figure 1, is to proceed from possible future energy system manifestations to a sustainability oder of decision options. This means that a qualitative description of future scenarios has to be transferred to a quantitative scenario description to allow for a simulative evaluation: Quantified attributes are needed to parametrize simulation models. Figure 2 illustrates the general solution approach. To allow the evaluation of future scenarios regarding sustainability criteria, **transformation functions**

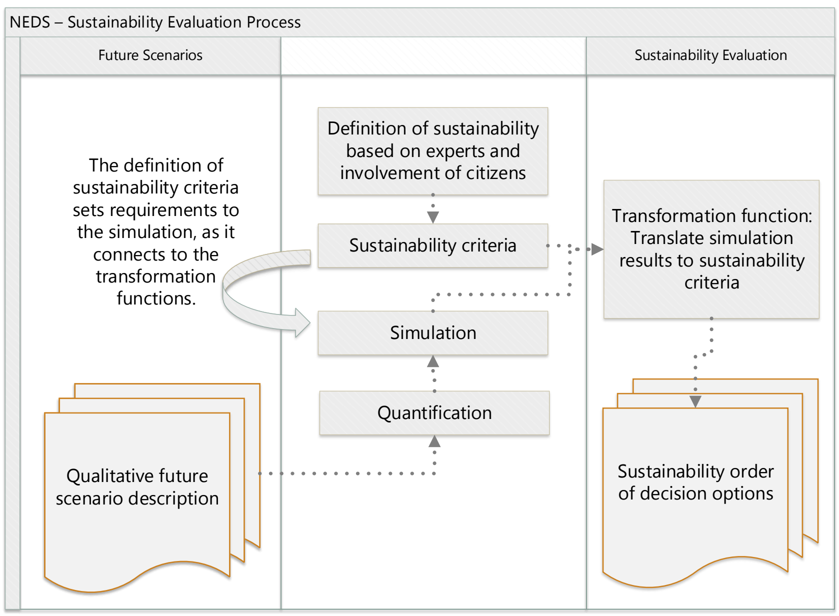

Figure 2: Schematic overview on the general solution approach.

are needed: These translate simulation results and quantified scenario descriptions to the so-called sustainability criteria. To this end, they are the crucial part of the methodological approach, as they bridge the gap between simulation driven scenario definition and sustainability driven evaluation. To define what constitutes sustainability in a given project, the involvement of the relevant stakeholders has to be guaranteed early in the process (see middle column in Figure 2). This stakeholder involvement is done to derive the relevant sustainability criteria that are needed for the evaluation part (using the transformation functions) and additionally set requirements to the simulation part: Information needed for the evaluation has to be defined as output from the simulation. Therefore, in the simulation part of the process the requirements of the sustainability notion from the relevant stakeholders meet the quantified future scenarios.

3.2 Terms and definitions

Before introducing the NEDS Sustainability Evaluation Process we will define relevant terms needed to understand the methodological approach. We will omit those terms that are specific for the core methods scenario planning and MCDM – the reader is referred to the corresponding publications (see Section 2.2). The descriptions given below are an excerpt of a glossary setup and maintained within the NEDS consortium.[2]

[2]Special terms from either scenario planning or MSDM are printed in *italics*, whereas terms defined within the NEDS consortium are printed in **bold font**.

With the SEP being a core result of the NEDS research project, the specification of the single steps will be subject to different referred publications. Therefore, in this publication the focus is to give an overall impression on how the methodological challenge as depicted in Figure 1 is addressed.

3.2.1 Scenario types

Within NEDS, we distinguish four different types of scenarios (ordered by their time of use within the SEP):

- Future scenario: A future scenario is a textual description of a possible manifestation of a defined excerpt of reality. This excerpt is defined by *key factors*. The textual description as a qualitative version of a future scenario is the starting point for the quantitative definition of the different **attribute types**. [3]
- Evaluation scenario: The classification of attributes leads to different attribute types which in part are immutable for the decision maker (**exogenous attributes**: general framework conditions and scenario-specific framework conditions). An evaluation scenario is described by these exogenous attributes.
- Alternatives: Alternatives are defined by those attributes that can be influenced by the decision maker, i.e. **endogenous attributes**. The assignment of values to a defined set of endogenous attributes defines an alternative.
- Simulation scenario: A simulation scenario is a precise description of simulation models, their parametrization, dependencies and synchronization needs.

3.2.2 Attribute types

Attributes define characteristics of energy scenarios. Whereas *key factors* (as a result of scenario planning, e.g. mix of energy resources or citizen approval of a defined energy-political orientation) define general characteristics, attributes describe the system with the most specific level of detail (e.g. oil price or PV feed-in at a given point in time). If possible, attributes are quantified by numerical values. Otherwise, a scaled definition is given. Attributes may thus give precision to the energy system, energy market, social characteristics, information technology or politics. We distinguish attributes from the phases where they are assigned values: **Scenario planning attributes** are assigned during the scenario planning process, whereas **derived attributes** either result from simulation or calculation from scenario planning attributes.

Scenario planning attributes are further classified to

- **General framework conditions**: These attributes define those characteristics of the scenario that can (a) not be influenced by the decision maker, i.e. out of the system boundary, and (b) are static within the evaluation process (example: demographic development).
- **Scenario-specific framework conditions:** These attributes define those characteristics of the scenario that can (a) not be influenced by the decision maker, i.e. out of the system boundary, and (b) are variable for different scenarios. Thus, they define uncertainties in the prognoses of future scenarios (example: oil price).
- **Endogenous attributes:** These attributes can be influenced by the decision maker. Therefore, the definition of *alternatives* as needed for MCDA, is derived from sets of endogenous attributes.

As can be seen from the examples, some attributes may be regarded as either **general framework conditions**, **scenario specific framework conditions** or **endogenous attributes**. To this end, the characterization of attributes is an important step within the NEDS SEP and sets limits to the level of detail and validity of the sustainability evaluation itself.

3.2.3 Sustainability

Sustainability as a term has gained momentum in economic and public perception, particularly in the sense of ”over-use” (DesJardins, 2016). In general, two different manifestations of sustainability are used: With the understanding of **weak sustainability** natural capital in parts can be substituted by real capital. Sustainable development in this understanding is reached if the overall capital (natural, real, human) is sustained for future generations. Accordingly, this notion of sustainability is not focused on the imperative sustainment of one capital part (e.g. natural), but on the total prosperity.

[3] See (Gausemeier et al., 1998) for details on the method and terms of scenario planning.

In the understanding of **strong sustainability** though, the complementarity of the different capital parts forbids their combined weighting. Therefore each capital part has to be sustained in the sense of strong sustainability, whereas a trade-off between them is not possible. In this notion, the protection of natural capital is of core importance in those cases where no regeneration is possible (e.g. fossil fuels). Additionally, the absorption capacity of nature may not be exhausted by using it as a sink for non-natural substances.

Within NEDS, four **sustainability facets** are in the focus: economic, ecological, social and technological sustainability.[4] When using a multi-criteria decision method like MCDM, strong sustainability can only be regarded if boundaries are defined for capital parts that may not be reduced. Though not within the focus of NEDS, these boundaries would allow to support decision processes with the notion of strong sustainability.

3.2.4 Sustainability evaluation criteria (SEC, quantified SEC)

The four **sustainability facets** are used to deduce **sustainability evaluation criteria (SEC)**: These serve as indicators for the general goal within the respective sustainability facet. To this end, SEC have to be quantifiable.

As an example, the ecological sustainability facet represents the general goal of preserving the remaining fossil fuels. To reach this goal, the energy mix has to be based on renewable energy sources. The remaining fossil fuels within the energy mix (if given) is a sustainability evaluation criterion. The evaluation of a defined scenario will lead to a quantification of a **derived attribute**.

3.2.5 Transformation function

Transformation functions build the link between simulative evaluation and sustainability evaluation using MCDM: A transformation functions takes **attributes** and **derived attributes** as input and maps them to **sustainability evaluation criteria** by defining the needed calculation function. The output of a transformation function are one or more **quantified SECs**.

4 SUSTAINABILITY EVALUATION PROCESS

Following the general approach as depicted in Figure 2, the process is defined in more detail. An overview of the resulting process is shown in Figure 3. The SEP is subdivided in four parts that show dependencies but not a strict sequential order. For the sake of clarity, we will introduce the process starting from the left side, with the creation of future scenarios (Section 4.1), notwithstanding the fact that the process starts in parallel in the rightmost column, i.e. the sustainability evaluation part (see entry points). In Section 4.2 we will describe, how evaluation scenarios are created out of the future scenarios, whereas in Section 4.3 the modeling and execution of simulations is detailed. In the most right column, the sustainability evaluation is depicted with all relevant steps (Section 4.4).

4.1 Creation of Future Scenarios

Input: none
Main task: The creation of future scenarios mainly follows the approach of scenario planning as defined in (Gausemeier et al., 1998). To allow the transition from the qualitative scenario description though, an attribute classification phase is added: Within this phase, the derived attributes are classified regarding the variability and their changeability (see Definition 3.2.2). The following steps have to be performed:

- Definition of future scenarios as defined in the scenario planning following (Gausemeier et al., 1998)
- Attribute definition
- Classification of attributes regarding general framework conditions, scenario-specific framework conditions and endogenous attributes

Required output: Qualitative description of future scenarios including a classification of the attributes relevant for the key factors.

[4]By including a technological sustainability facet we aim at evaluating the possibilities of a given infrastructure to satisfy the need for a robust and reliable system operation. More detail regarding this facet will be given in later versions of this whitepaper.

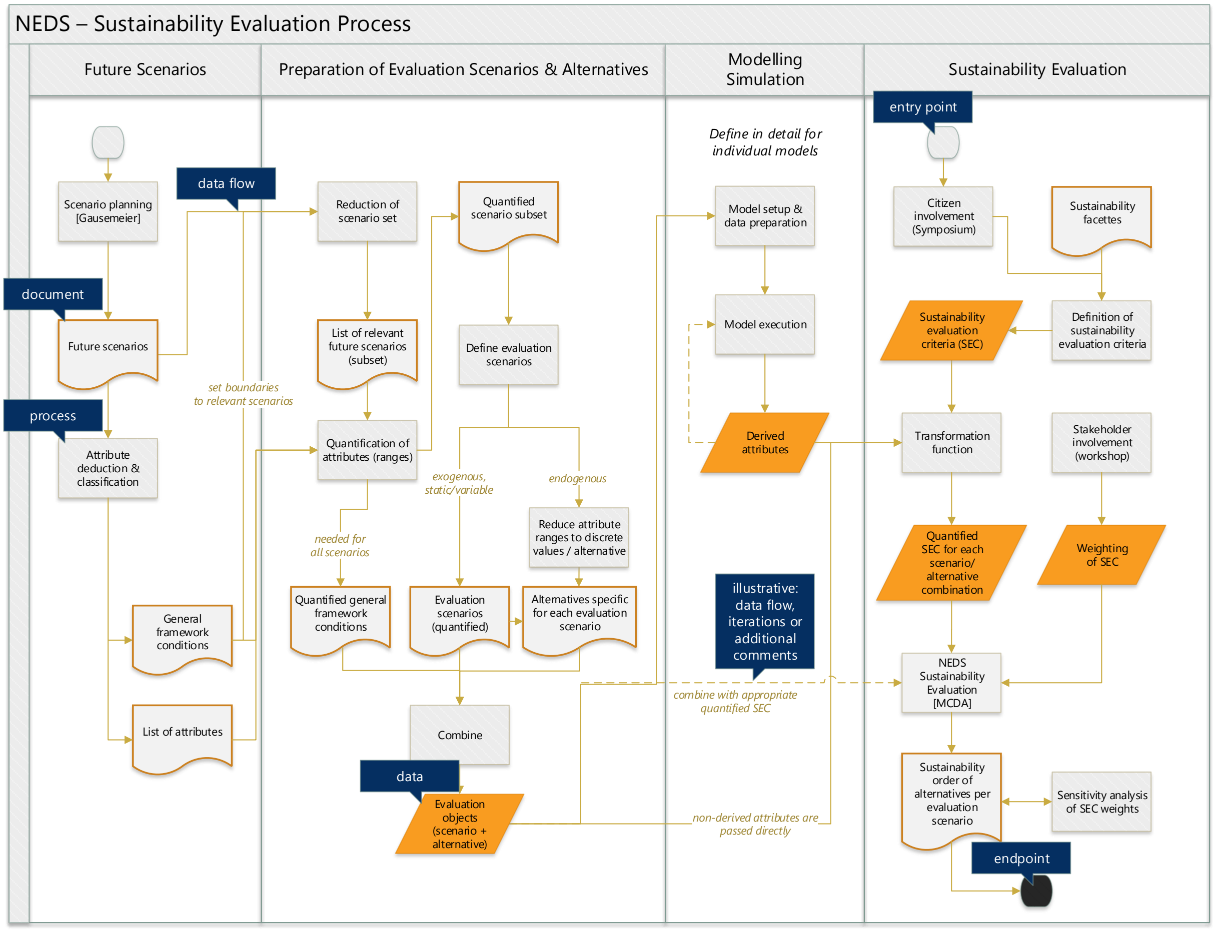

Figure 3: NEDS Sustainability Evaluation Process (blue legend icons give information on the semantics used within this process diagram).

4.2 Preparation of Evaluation Scenarios & Alternatives

Input: Future scenarios, list of attributes
Main task: Because the earlier created future scenarios are only textual description of a possible future and a simulation needs concrete values, this part describes the processing of future scenarios. This steps also contains adjustments to allow coupling of the future scenarios from scenario planning with the multiple-criteria decision analysis (MCDA), which is described in more detail in future publications.

The following steps have to be performed:

- Reduction of the relevant scenario set: Depending on the defined general framework conditions, some scenarios are no longer within the scope of the evaluation project. Consequently, these scenarios are discarded from the evaluation.
- Quantification of attributes: Define valid ranges for all variable attributes, depending in the scenario description.
- Define evaluation scenarios and alternatives: For each scenario, separate exogenous attributes (constituting the evaluation scenarios) and endogenous attributes (constituting the alternatives from the decision makers point of view).
- Reduce endogenous attributes from ranges to concrete values, thus defining different alternatives for one evaluation scenario.

Required output: Evaluation objects, each consisting of one evaluation scenario and one alternative. For each evaluation scenario, several evaluation objects exist that differ regarding the alternative. These will be subject to the sustainability ordering in the last step of the process.

4.3 Modeling & Simulation

Input: Evaluation objects
Main task: The required approach for the modeling and simulation tasks is different in every domain (e.g. user behavior, Smart Home management, transmission grid aspects), so here only a stub for the needed tasks within this process step is shown. First 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. This will be defined in more detail for every single part of simulation. Dependencies between the different models have to be reflected and are depicted by a circular reference. The interferences of the different simulation parts will be subject to future publications and versions of this whitepaper. After setup and preparation the simulations can be executed and provide the derived attributes.
Required output: Quantified derived attributes.

4.4 Sustainability Evaluation

Input: Sustainability facets (from initial project definition), derived attributes as simulation output.
Main task: The rightmost part of the process in Figure 3 is the evaluation of sustainability for which the MCDA is used. To make the evaluation possible first the sustainability evaluation criteria (SEC) have to be defined. This is done by experts based on given sustainability facets and involvement of citizens. To this end it is important to notice that the involvement of citizens to define what constitutes sustainability in the given context is an early task in the process: The transformation function is needed to couple the notion of sustainability of all relevant stakeholders with the future scenarios. Therefore, this has to be done prior to simulation, as the needed inputs for the transformation functions are output of the simulation runs – thus raising requirements to the modeling and simulation tasks. The following steps have to be performed:

- Citizen involvement to define the project's notion of sustainability.
- Deduction of sustainability evaluation criteria.
- Implementation and usage of the transformation functions.
- Weighting of the sustainability evaluation criteria.[5]
- Sustainability evaluation using MCDM.

Required output: Sustainability order of alternatives for each evaluluation scenario, possibly subject to a sensitivity analysis of the SEC weights.

5 OPEN QUESTIONS AND FUTURE WORK

In this whitepaper, we presented the NEDS sustainability evaluation process (NEDS SEP) as first draft and work in progress. With the NEDS SEP beeing used in a current project, more level of detail will be added in upcoming versions. Beside this ongoing task, some general problems still have to be solved and are not presented yet:

- Replicability: The proposed process has to support decision makers in such a way that the derived recommendations are transparent and can be regained. Modifications regarding e.g. weighting of sustainability evaluation criteria or attributes additionally raise the need for replicability. Automation of the NEDS SEP including tool support would be a valid approach to cope with this requirement.
- Integration of qualitative research parts: Parts of NEDS address more qualitative research, e.g. the level of acceptance of a given energy sufficiency program. These aspects clearly affect the evaluation results. In ongoing work, we try to define bridges to these results, e.g. by setting up a socio-technical simulation for those parts of the system that are affected by human behavior.

[5] Please note that in the notion of strong sustainability, a weighting of different aspects of sustainability (e.g. human capital and natural capital) is not valid due to the complementarity of the different capital parts. To address this, boundaries have to be defined for the different SECs in this step.

- Evaluation of transition paths: The proposed process can be used to evaluate future energy scenarios but does not give an answer to the transition towards these future manifestations. An extension of the process is needed to add this aspect.

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