Transparency in Energy Scenario Studies: Survey of Different Approaches Combining Scenario Planning, Energy System Analysis, and Multi-criteria Analysis

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Abstract: The transition of today's energy supply systems to renewable energy technologies requires planning processes that are usually supported by energy scenario studies. If scenario planning, energy system analysis, and multi-criteria analysis are combined in the design of such energy scenario studies, two possible method combinations can be identified in the literature. In this paper, these method combinations are discussed with regard to transparency and communication of uncertainties, which are basic requirements for energy scenarios. Finally, a clear specification of the intended purpose and of the method commendation is recommended to improve transparency in energy scenario studies and avoid over-interpretation by decision makers.

1 INTRODUCTION

The transition of today's nuclear and fossil-fueled energy supply systems to renewable energy technologies poses a major challenge for the 21st century. For example, the European Commission (2018) proposed a strategy to reach an economy with net-zero GHG emissions until 2050, mainly based on renewable energy technologies. To investigate how to achieve the transition to a competitive, sustainable, and secure energy supply, *energy system analysis* helps to support decision-making with quantitative data (Möst & Fichtner, 2009). The results of such system analyses are usually published in energy scenario studies. One key requirement for these studies is that they are transparent, i.e., that all necessary information which is needed to comprehend and potentially replicate the study is adequately published (Cao et al., 2016).

Given the long-term planning perspective, it is important to consider uncertainties in planning processes. *Scenario planning* has long been used to support decision making under uncertainty (Schoemaker, 1995; van der Heijden, 2009). While not strictly required in (energy) system analysis, scenario planning is often combined with system analysis to support quantitative analyses with qualitative stories. Usually, these stories are conveyed more easily than quantitative analyses and can be used to foster discussions among relevant decision makers and stakeholders (Alcamo, 2008), one objective being to support consensus among stakeholders.

As the objective of energy scenario studies is to identify suitable, sustainable energy supply systems, evaluating the suitability of future options is a core task in energy scenario studies. In quantitative techno-economic analyses such as energy scenario studies, sustainability is usually operationalized with technical, economic, social, and environmental criteria (Antunes & Henriques, 2016). The performance of a particular alternative in terms of a particular criterion is called *performance score*. However, given possible alternative system configurations, their performance scores can be at least partially conflicting; criteria are usually measured with incommensurable units; and different stakeholders may weigh them differently.

Therefore, identifying the best transition pathway towards a sustainable energy supply is challenging and calls for integration of a problem structuring

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method (Antunes & Henriques, 2016; Grunwald et al., 2016). Moreover, as strategic long-term decisions with immense investments need to be made, decisions should be well informed and transparent to increase their acceptance (Dieckhoff et al., 2014). Methods from m*ulti-criteria analysis* can be used to support decisions given this complex background (Antunes & Henriques, 2016).

Scenario planning and multi-criteria analysis can complement energy system analysis in the development and evaluation of energy scenarios (Witt et al., 2020). The objective of the method combination is to improve an energy scenario study's transparency regarding the consideration of uncertainties during scenario construction and evaluation. However, two possible method combinations can be identified in the literature. In particular, they differ in the consideration and communication of external uncertainties, leading to different levels of transparency. In this paper, these approaches are described and discussed regarding transparency.

The paper is structured as follows: In Section 2, different interpretations of the term *scenario* within the three methods are delineated. In Section 3, the two approaches for combining the methods are identified, based on the literature. In Section 4, advantages and disadvantages of the methods with regard to the different requirements for energy scenarios are discussed. Finally, the paper is concluded with a short summary and outlook.

2 THE MEANING OF "SCENARIO" IN DIFFERENT METHODS

In the following, different interpretations of the term scenario are introduced in the contexts of scenario planning, energy system analysis, and multi-criteria analysis. Because these interpretations are intertwined with the roles of decision makers and external uncertainties, both are paid special attention to.

2.1 Scenario Planning

In *scenario planning*, scenarios are consistent descriptions of future states and/or developments (Grunwald et al., 2016; van der Heijden, 2009). Those scenario planning techniques that have been developed specifically for the application in corporate planning, e.g., by Gausemeier et al. (1998) or van der Heijden (2009), additionally include the perspective of one or more decision makers. (For simplicity, the singular of the word *decision maker* is used from now on.)

In those approaches, both a decision and scenario field need to be defined. In the decision field, a decision maker has the authority over necessary resources so that she or he can decide upon the future developments, which is why Gausemeier et al. (1998) call these developments *influenceable*. For example, for a decision, which technologies should be used to provide heat and power in a bioenergy village (Lerche et al., 2017), the range of available technologies, including biogas power plants, wind energy plants, or PV systems, constitutes the decision field. In contrast, the scenario field consists of all developments that are investigated in a scenario. The scenario field can include a decision field, but does necessarily have to. Usually, non-influenceable developments, so-called external uncertainties, are also included in scenarios.

Based on the delineation of decision and scenario fields, three types of scenarios can be identified (see Figure 1): internal scenario, external scenario, and system scenario. Gausemeier et al. (1998) note that system scenarios are "easy to create but different to deal with", because they are only influenceable in parts and alternate between actions and side conditions. The choice of the type of scenario depends on the requirements and objectives of the case-specific problem.

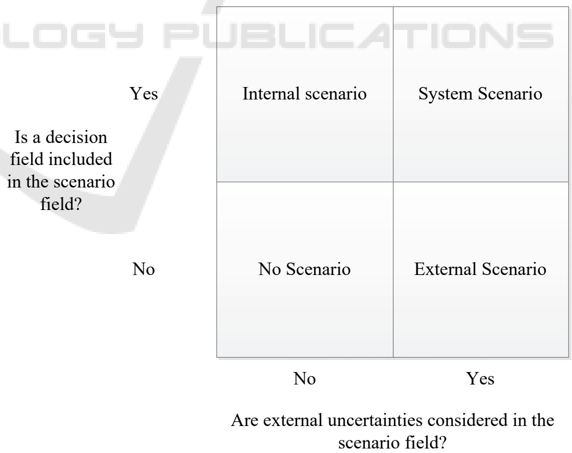

Figure 1: Scenario classification, based on Gausemeier et al. (1998).

2.2 Energy System Analysis

In *energy system analysis*, a scenario is represented by a set of assumptions (Grunwald et al., 2016; Möst & Fichtner, 2009). "Calculating a scenario" means that the model calculates results for the endogenous variables, based on the input of a set of exogenous variables – in other words, based on a scenario. From a modelling perspective, the perspective of a decision maker is irrelevant for this calculation, which is explained in the following.

Endogenous variables are also called "decision variables" of a model. This means that, e.g., an optimization model yields values that these variables need to assume to optimize the solution for a particular objective function. These variables usually correspond to factors that a decision maker can influence, but do not necessarily have to. For example, energy scenario studies usually have at least national scope, i.e., the energy system of a whole country is modeled (Witt et al., 2018). These studies typically include bottom-up or top-down optimization models minimizing system costs (Keles et al., 2011). Due to the minimization of system costs, the model determines optimal investment and unit commitment decisions *from a system perspective*. However, there is no single decision maker who can implement all these investment and unit commitment decisions, because, for example, the operation of energy supply facilities (power plants, solar panels, grid) is distributed across many different actors. Even if all actors were to act according to the same rational reasoning, information asymmetries and attempts to maximize personal gains can lead to decisions of individuals that diverge from the global optimum, i.e., system-optimal decisions.

From a mathematical point of view, it is therefore irrelevant whether (endogenous or exogenous) variables model developments, which are influenceable by a particular decision maker or not. Thus, energy system analysis can be used to model internal scenarios, external scenarios, or system scenarios. In the modeling process, the analyst needs to pay special attention to the question, which variables constitute a scenario, because this affects the implications that can be drawn for a particular decision maker.

2.3 Multi-criteria Analysis

In *multi-criteria analysis,* a scenario consists of all developments that cannot be influenced by a decision maker (Stewart et al., 2013). Such a scenario is an external scenario. The term for an option that a decision maker can implement is *alternative*, which corresponds to an internal scenario. External scenarios can be used to investigate the effects of uncertain developments on the performance scores of given alternatives. To that end, during the problem-structuring phase of multi-criteria analysis, influenceable developments, leading to a selection of alternatives, and non-influenceable developments, leading to a selection of scenarios, are identified in an iterative process (Belton & Stewart, 2003). To quantify the performance scores, different methods of consequence modeling can be applied, also including (energy) system analysis (Witt et al., 2020).

In the sense of scenario planning, assumptions regarding the future should be internally consistent (Götze, 1993; Kosow, 2015), so that the assumptions regarding alternatives and scenarios are non-contradictory. Therefore, system scenarios seem to be very suitable for developing scenarios and fitting alternatives in a common process.

3 METHOD COMBINATIONS WITH DIFFERENT SCENARIO PURPOSES

In the literature, two approaches for combining the abovementioned methods can be identified. These differ regarding the objective of the corresponding energy scenario studies: Scenarios providing general orientation and scenarios for specific decisions.

3.1 Orientation Scenarios

In this approach, the methods are combined with the objective to create and evaluate scenarios. The terms alternative and scenario are used synonymously. (This is contradictory to the approach described in Section 2.3.) Therefore, influenceable and non-influenceable developments are not separated during scenario creation and evaluation. Thus, scenario planning is applied to systematically identify possible future states or developments that are to be evaluated. For example, Madlener et al. (2007) apply scenario planning to identify a set of possible scenarios representing combinations of key factors. The consequences of these scenarios are quantified with energy system analysis and finally evaluated with multi-criteria analysis. Studies that use this concept include Bertsch & Fichtner (2016), Browne et al. (2010), Diakoulaki & Karangelis (2007), Jovanović et al. (2009), Kowalski et al. (2009), McDowall & Eames (2007), McKenna et al. (2018), Oberschmidt et al. (2010), Trutnevyte et al. (2011), and Volkart et al. (2017). An excerpt from an exemplary decision table in Bertsch & Fichtner (2016) with two criteria and three alternatives/scenarios is shown in Table 1.

Table 1: Exemplary decision table for orientation scenarios, excerpt from Bertsch & Fichtner (2016).

Scenarios (S) / Alternatives (A)	**S/A1**	**S/A2**	**S/A3**
Total expenses of electricity supply (in Billion EUR)	182	200	224
CO_2-emissions (in Million t CO_2/y)	204	201	158

On the one hand, evaluating such a decision table can help to identify a desirable alternative/scenario. Identifying an image of a desirable future corresponds to one objective of scenario planning, namely shaping the future (Götze, 1993). For example, such an analysis can be used to investigate energy policy targets related to the capacity expansion of renewable energy technologies, so that a cost-minimal expansion complying with GHG-reduction targets can be found. Based on that analysis, energy policy targets can be set accordingly.

On the other hand, this approach strongly suggests that there actually is a choice between alternatives/ scenarios. This implies that the developed scenarios are internal scenarios. Uncertain, external factors are not considered. In the context of energy system planning, a decision maker simply cannot stipulate all future developments, due to the complexity of the energy system, the long-term planning perspective, and the limit to (geographical) system boundaries. To exaggerate, a decision maker would always decide for the best-case scenario, e.g., "successful energy transition", in which all performance scores develop in the best possible way, resulting in the best evaluation of said scenario. Thus, the authors of such studies need to make clear that the developed scenarios should not be interpreted as options for choice, and thus avoid over-interpretation by a decision maker. Rather, these scenarios can provide orientation and loose guidelines, instead of options for immediate implementation. Finally, eliciting criteria weights for a multi-criteria analysis is complicated in this approach, but can be supported with stakeholder analysis (see, e.g., Steinhilber et al. (2016)).

3.2 Decision Scenarios

In this approach, the methods are combined with the objective to create and evaluate alternatives under different scenarios, in order to make robust decisions (Schwarz et al., 2019; Witt et al., 2020). As a precondition, the decision maker of a decision problem needs to be known. Based on the decision maker's decision power, scenarios and alternatives can be separated explicitly. (This corresponds to the idea described in Section 2.3).

In the first step of this approach, system scenarios are developed to ensure consistency of all assumptions (Götze, 1993; Kosow, 2015). After quantifying these assumptions, they can be used as input for model calculations. To that end, the assumptions are classified and separated. There are (1) general parameters that are constant over all scenarios and alternatives; (2) scenario-specific parameters that vary for each scenario; (3) alternative-specific parameters that vary for each alternative. The parameters are specified successively so that general parameters are quantified first. These limit the possible range for scenario- and alternative-specific parameters. After that, scenario-specific parameters are quantified, further limiting the possible range for alternatives. Finally, alternative-specific parameters are quantified for each scenario.

The parameter classification also determines the number of model runs required in an energy scenario study, because each combination of scenario and alternative needs to be calculated with the energy system model and evaluated with multi-criteria analysis (Witt et al., 2019). For example, given two scenarios and three alternatives, six model runs are needed to quantify the effects of all scenarios on all alternatives. An exemplary decision table with three criteria, three alternatives and two scenarios is shown in Table 2.

Table 2: Exemplary decision table for decision scenarios, excerpt from Witt et al. (2020).

Scenarios (S)	**S1**			**S2**		
Alternatives (A) / Criteria	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
CO_2-emissions (in kg CO_2-eq/MWh)	90.88	84.80	84.56	65.83	65.34	66.60
Agricultural Land Occupation (in m^2/MWh)	5.46	4.96	5.14	5.44	5.39	5.48
Costs of electricity production and grid expansion (in €/MWh)	69.38	68.10	67.87	34.26	27.24	27.91

By evaluating this decision table, the effects of external effects on the performance of alternatives can be investigated. For example, a loss-minimizing strategy would be to identify alternatives that perform relatively well in all scenarios (Dieckhoff et al., 2014; Götze, 1993; Porter, 1983). Notably, uncertain, external developments are made explicit in this approach. In combination with a multi-criteria analysis, in which preferences of different actors can be considered, implications and recommendations can be derived in a transparent way.

4 DISCUSSION

According to Grunwald et al. (2016), energy scenario studies need to meet three basic requirements: scientific validity, transparency, and unbiasedness. In this paper, I focus on *transparency*, because it is a cornerstone to achieve the two other requirements. Transparency can be viewed as a substitute for involvement in scenario development and evaluation. In the context of energy scenario studies, transparency means that all necessary information that is needed to comprehend and potentially replicate the study is adequately published (Cao et al., 2016). To that end, the recipient should be able to access the used models, data, and further assumptions. Grunwald et al. (2016) note that it is particularly important to point out very clearly any uncertainties in an analysis, as well as their consequences for the results and conclusions. Furthermore, conclusions should be drawn in a transparent way. Finally, addressee-specific documentation can enhance the transparency of energy scenario studies.

Some notes on transparency: First, the concept of transparency is subjective. A documentation can be transparent for some recipients, but intransparent for others, because the technical expertise and skills of the recipient are relevant for understanding complex, (model-based) energy scenario studies (Baecker, 2010). Second, an excessive, confusing supply of information is the opposite of transparency. A recipient needs to select the relevant parts from all available information. Therefore, supplying too much information can also be counter-productive if one wants to achieve a transparent documentation.

According to Grunwald et al. (2016), many energy scenario studies lack transparency and adequate communication of uncertainties. Two of their suggestions to increase transparency are: (1) development of methods to integrate diverging interests and (2) integration and increased use of methods for the systematic analysis of uncertainties.

Both method combinations (described in Sections 3.1 and 3.2) allow for the *integration of diverging interests* in the evaluation of energy scenarios. For example, different interests can be considered during scenario creation in a scenario planning process. In addition, stakeholders' interests can be made explicit in the weighting factors used in the multi-criteria evaluation.

However, regarding the *communication of uncertainties*, I argue that the presented approaches differ considerably. The approach based on orientation scenarios is suitable if no particular decision makers are involved, i.e., if no specific decision is to be supported. The objective is to identify desirable future states that are relevant for a problem and foster discussion about them. For example, the potential effects of certain energy policy measures (represented by alternatives/scenarios) can be determined and desirable or non-desirable developments can be identified (Dieckhoff et al., 2014). In general, this approach is less suitable for supporting specific decisions, because uncertainties that are relevant for specific decision makers are not identified and their effects are not modeled explicitly. This approach leaves untapped a powerful potential of scenario planning, namely sensitizing decision makers to effects of external uncertainties (Stewart et al., 2013). Special care is required by decision makers when they interpret the results.

The approach based on decision scenarios is suitable if the perspectives of specific decision makers need to be included. It allows including and analyzing the effects of external uncertainties on the performance scores of decision makers' alternatives. Thereby, an alternative can be recommended with a transparent procedure that also considers different developments of external factors (Dieckhoff et al., 2014). This approach focuses on problem structuring, so that decision makers and analysts are forced to consider, which different alternatives and uncertainties are relevant for and should be quantitatively modeled in the decision problem. Thereby, underlying assumptions that would otherwise be unspoken can be discussed, which allows decision makers and analysts to achieve a deeper understanding of the decision problem. This deeper understanding is presumed to lead to better decision-making (Götze, 1993), in addition to the quantitative results of a multi-criteria analysis of alternatives.

To improve the transparency, authors of energy scenario studies combining scenario planning, energy system analysis, and multi-criteria analysis, should therefore make very clear, which purpose their method combination fulfills: providing general orientation or providing decision support for a specific decision with known decision makers. I argue that this can limit the unintended effects of over-interpretation of energy scenario studies. While an approach based on orientation scenarios can support a discussion of possible futures and their desirability, an approach based on decision scenarios can support specific decision makers' choices between options for immediate implementation in uncertain environments.

However, an approach with decision scenarios requires more effort for decision support, because, in general, more parameter quantifications and energy system model runs are needed (Witt et al., 2019). Finally, a multi-criteria evaluation of alternatives under different scenarios proves to be challenging to be interpreted by decision makers (Durbach & Stewart, 2020; Marttunen et al., 2017). This also stresses the need to communicate clearly, which implications can or cannot be drawn from a multi-criteria analysis, based on an analysis of system scenarios and specific decision makers' preferences.

5 CONCLUSION

In this paper, two different approaches for combining scenario planning, energy system analysis, and multi-criteria analysis have been investigated, one based on orientation scenarios, the other based on decision scenarios. Their impact on the transparency and communication of uncertainties in energy scenario studies has been investigated. I argue that authors of energy scenario studies should make very clear the purpose of their method combination. This should increase not only the transparency of energy scenario studies that are based on these methods, but also increase acceptance of the implications and recommendations drawn from them by the relevant stakeholders. Increased acceptance may make it easier to implement measures to reach energy policy goals and thereby foster the transition to sustainable energy supply systems.

Commissioning institutions of energy scenarios need to clarify energy scenario studies' objectives, decision makers, stakeholders, the consideration of uncertainties and other desired features of the methodology in their tenders (Grunwald et al., 2016). Additionally, a short summary of a study's features would be helpful for transparent documentation. For example, the morphological analysis provided in Witt et al. (2018) could be extended by different methods (energy system analysis, scenario planning, multi-criteria analysis) and their corresponding scenario purposes to provide an overview of studies' key features.

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