Multi-criteria Decision Making for Energy System Evaluation

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submitted by

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For Constanze,
who is too patient,
too kind,
and too wonderful for words.
But I try anyway.

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Acknowledgements

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Contents

PUBLICATIONS INCLUDED IN THIS DISSERTATION

Paper 1: Witt, T., Stahlecker, K., Geldermann, J., 2018. Morphological analysis of energy scenarios. International Journal of Energy Sector Management 12, 525–546. DOI: 10.1108/IJESM-09-2017-0003.

Paper 2: Schwarz, J.S., Witt, T., Nieße, A., Geldermann, J., Lehnhoff, S., Sonnenschein, M., 2017. Towards an Integrated Sustainability Evaluation of Energy Scenarios with Automated Information Exchange, in: Proceedings of the 6th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS), Porto. 22.04.2017 - 24.04.2017. SCITEPRESS, Setúbal, pp. 188–199. DOI: 10.5220/0006302101880199.

Paper 3: Schwarz, J.S., Witt, T., Nieße, A., Geldermann, J., Lehnhoff, S., Sonnenschein, M., 2019. Towards an Integrated Development and Sustainability Evaluation of Energy Scenarios Assisted by Automated Information Exchange. In: Donnellan, B., Klein, C., Helfert, M., Gusikhin, O., Pascoal, A. (Eds.) Smart Cities, Green Technologies, and Intelligent Transport Systems. 6th International Conference, SMART-GREENS 2017, and Third International Conference, VEHITS 2017, Porto, Portugal, April 22-24, 2017, Revised Selected Papers. Springer Nature, Cham, pp. 3–26. DOI: 10.1007/978-3-030-02907-4_1.

Paper 4: Witt, T., Dumeier, M., Geldermann, J., 2020. Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios. Journal of Cleaner Production 242, 118414.
DOI: 10.1016/j.jclepro.2019.118414.

Paper 5: Witt, T., 2020. Transparency in Energy Scenario Studies: Survey of Different Ap-proaches Combining Scenario Planning, Energy System Analysis, and Multi-criteria Analysis, in: Proceedings of the 9th International Conference on Smart Cities and Green ICT Systems. SCITEPRESS, Setúbal, pp. 114–121. DOI: 10.5220/0009464601140121.

Paper 6: Witt, T., Dumeier, M., Geldermann, J., 2019. Multi-criteria Evaluation of the Transition of Power Generation Systems, in: Multikriterielle Optimierung und Entscheidungs-unterstützung. Tagungsband GOR Entscheidungstheorie und -praxis 2018. Springer Gabler, Wiesbaden, pp. 121–141. DOI: 10.1007/978-3-658-27041-4_9.

Paper 7: Witt, T., Klumpp, M., 2021. Multi-Period Multi-Criteria Decision Making under Uncertainty: A Renewable Energy Transition Case from Germany. Sustainability 13, 6300. DOI: 10.3390/su13116300.

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LIST OF ABBREVIATIONS

CAUSE   Criteria, Alternatives, Uncertainties, Stakeholders, Environment
DM   Decision Maker
IFORS   The International Federation of Operational Research Societies
MADM   Multi-Attribute Decision Making
MCA   Multi-Criteria Analysis
MCDM   Multi-Criteria Decision Making
MOO   Multi-Objective Optimization
OR   Operations Research
ORESTE   Organisation, Rangement Et Synthèse de données relaTionnElles
PROMETHEE   Preference Ranking and Organization METHod for Enrichment
                         Evaluations

1 INTRODUCTION

"The purpose of economics is to help decision makers make better decisions."
(Clive W.J. Granger, Nobel Prize laureate 2003)

Multi-criteria decision making (MCDM) is a field of knowledge in Operations Research (OR) that can help decision-makers make transparent and auditable decisions in a logical manner (Dias et al., 2019). It offers methods that help to choose suitable decision alternatives from the set of available alternatives, via synthesis of *objective* information – specifying the expected consequences of a decision – and *subjective* information – specifying how much any single consequence matters (Keeney, 1988; Belton and Stewart, 2003; French and Geldermann, 2005; Bouyssou et al., 2006). According to Berjawi et al. (2021), MCDM approaches can be used

(1) to open up discussions among stakeholders, decision makers (DM), and analysts by structuring complex, "wicked", decision problems (Churchman, 1967) with "Soft OR" methods (Mingers and Brocklesby, 1997; Mingers and Rosenhead, 2004), including a search for suitable alternatives as well as relevant evaluation criteria and uncertainties, and/or

(2) to close down discussions by aggregating relevant information in a logical manner and ranking the alternatives accordingly, as part of prescriptive decision theory (Brown and Vari, 1992; French, 1995a).

In the case of strategic management decision problems with long planning horizons, at least some of the information required in MCDM is usually uncertain, e.g., the set of alternatives available to a DM, alternatives' consequences, possible states of the environment, or subjective information regarding the DM's preference relations (Stewart et al., 2013; Troldborg et al., 2014). Moreover, if dynamic decision problems also require a recommendation regarding *when* to proceed with which action, explicitly modelling the temporal aspect of the decision problem becomes relevant, leading to multi-period MCDM (Yu and Chen, 2012).

One application area, where MCDM has been applied to support strategic decision-making is energy systems planning (Løken, 2007; Stewart et al., 2013; Antunes and Henriques, 2016; Kumar et al., 2017; Mardani et al., 2017). One major objective of energy

systems planning is to reach *sustainable* energy supply systems (Harjanne and Korhonen, 2019), and thus, the sustainability of such systems needs to be evaluated (Giannetti et al., 2020). In the research field of cleaner production, the sustainability objective is usually operationalized with a wide range of economic, social, environmental, and technical criteria (Antunes and Henriques, 2016). Because these criteria are usually conflicting and measured in incommensurable units, formal decision support with MCDM approaches can be helpful (Hwang et al., 1980; Stewart, 1992; Dias et al., 2019). Regarding energy policy, energy scenario studies provide orientation for decision-makers in government and industry by offering relevant quantitative information on key figures such as system costs regarding various long-term strategies in the energy sector (Keles et al., 2011; Cao et al., 2016; Weimer-Jehle et al., 2016). These energy scenario studies usually consider long-term consequences due to the long product life cycles of power plants (Grunwald, 2011; Antunes and Henriques, 2016).

According to French (2013), there are four levels of support that may be offered by decision support processes and systems:

- Level 0: Acquisition, checking and presentation of data, directly or with minimal analysis, to DMs
- Level 1: Analysis and forecasting of the current and future environment
- Level 2: Simulation and analysis of the consequences of potential strategies; determination of their feasibility and quantification of their benefits and disadvantages
- Level 3: Evaluation and ranking of alternative strategies in the face of uncertainty by balancing their respective benefits and disadvantages.

In the context of this categorization, the level of decision support provided in energy scenario studies can be described as level 2. The objective of integrating MCDM and energy systems planning is to increase the achievable level of decision support to level 3, as this would allow to include DMs' preferences and to consider uncertainties. While MCDM has already been applied to support decision-making in energy systems planning, varying forms of combining MCDM and energy systems planning hinder effective decision support. The majority of energy scenario studies thus does not incorporate MCDM techniques, but is mainly based on quantitative energy system analysis. Therefore, the objective of this dissertation is to investigate how MCDM approaches can effectively support decision-making in energy systems planning. The cumulative dissertation encompasses 7 published papers (3 journal papers, 2 conference papers, and 2 contributions to collections). Detailed information on the papers are provided in Section 4, and full texts are provided in the appendix.

Section 2 includes an elaboration of the research background regarding multi-criteria decision making and research gaps are identified. In Section 3, the research methodology is described. Section 4 summarizes the research contributions of each paper. In the final Section 5, the results of the dissertation are summarized and their implications are discussed. Finally, directions for further research are provided.

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2 THEORY FRAMEWORK

In this section, OR, MCDM, and energy system analysis are introduced and the specific challenges of dynamic MCDM and modelling of uncertainties in MCDM are described. Finally, the main research gaps regarding the integration of MCDM and energy systems planning are identified.

2.1 OPERATIONS RESEARCH

OR is "a discipline on the process of making better decision[s] through the development and the application of a wide range of problem-solving methods and techniques" (IFORS, 2020). OR emerged in the 1940s from military operations, computer science, and economics (Laengle et al., 2020). Particularly, advances in linear optimization by George B. Dantzig (summarized in Dantzig (1963)) allowed to solve optimization problems in many fields, including business and economics. Optimization approaches exist for continuous and discrete solution spaces and are particularly effective for solving "well-structured" problems (Simon and Newell, 1958), where problem structuring is only an implicit issue. This approach is also called empirical-analytic paradigm or "Hard OR" (Mingers and Brocklesby, 1997). In contrast, the interpretive paradigm or "Soft OR" makes the ill-structured nature of the problems encountered explicit (Mingers and Rosenhead, 2004).

An OR model is a conceptual representation of a real or proposed decision problem, attempting to capture all relevant problem components. Figure 1 shows the connection between a decision problem, an OR model, and its implementation. According to Ackoff (1956), it is not implied that modeling, implementation, experimentation, or validation steps are applied in a specific order, or that one step must be completed before another is begun. Contrary, there is usually a continuous interplay between all steps during the whole model development process.
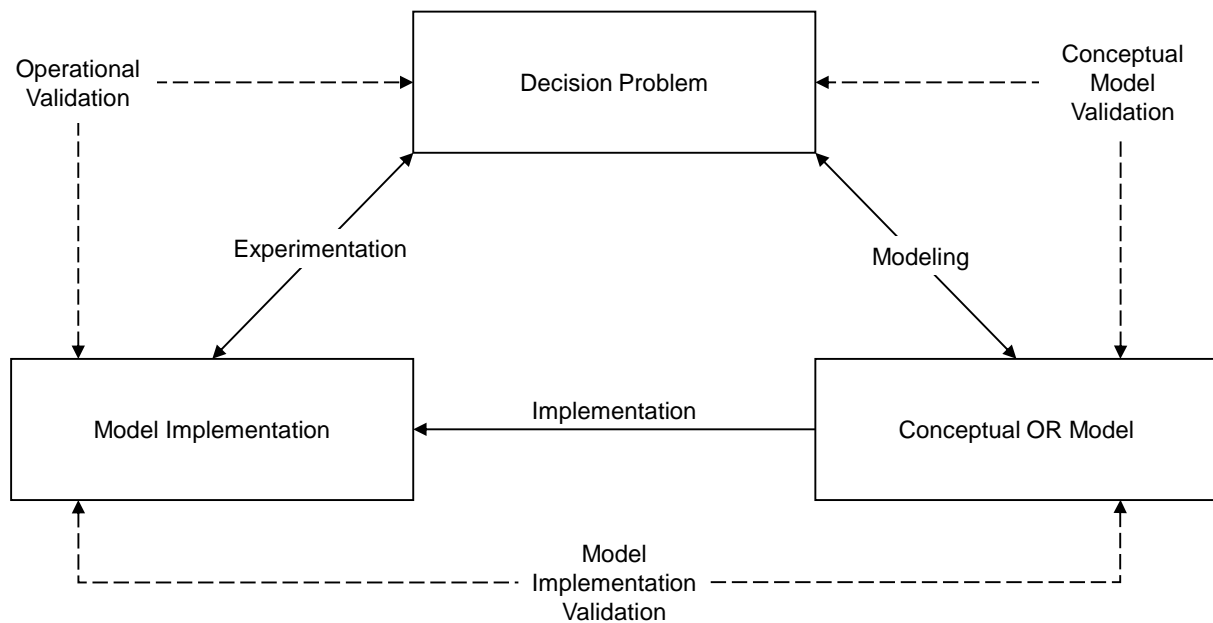
Figure 1: OR model development process (adapted from Gösling (2015))

2.2 Multi-Criteria Decision Making

MCDM is situated in the research domain of Operations Research. MCDM approaches are designed for decision problems with at least two alternatives, in which DMs need to consider at least two, usually conflicting decision criteria (French and Geldermann, 2005). In these problems, there usually is no dominant solution, so that MCDM approaches are applied to structure a decision problem (by identifying suitable alternatives, criteria, relevant uncertainties) and to sort, rank, or choose suitable alternatives based on the DMs' preferences (Belton and Stewart, 2003). Regarding these preferences however, the schools of thought of MCDM differ: the American school supposes that DMs are able to concisely articulate their preferences and assign values to decisions' consequences, while the European school considers the opposite, so that preferences need to be elicited in an interactive process (Roy and Vanderpooten, 1996). Solving a multi-criteria decision problem usually involves three stages: (1) formulating the problem, (2) evaluating the options, and (3) reviewing the decision structure (Belton and Stewart, 2003; French and Geldermann, 2005).

Regarding the problem formulation, various problem structuring methods facilitate effective structuring of a problem situation rather than "solving" it directly (Rosenhead, 2013; Marttunen et al., 2017), or as Belton and Stewart (2003, p. 35) put it: "a problem well-structured is a problem half-solved". For example, the CAUSE checklist aims to structure decision problems and includes Criteria, Alternatives, Uncertainties, Stakeholders, and the Environment of a decision problem (Belton and Stewart, 2003). All these

ingredients can be included in a decision model, which serves to formally and analytically investigate decisions' consequences and evaluate them based on the DMs' preferences (Götze and Bloech, 2002). While most MCDM approaches can determine relations of preference or indifference regarding two alternatives, some also allow for modelling incomparability (Belton and Stewart, 2003).

In decision theory, DMs are usually supposed to act rationally in the course of achieving their goals.[1] Goals can have interdependencies, i.e., two goals can be indifferent, complementary, or conflicting (Zäpfel, 1981). *Indifferent* means that achieving one goal does not have an impact on the other one, *complementary* means that achieving one goal also facilitates achieving the other one – this may be symmetric or asymmetric –, and *conflicting* means that achieving one goal hinders achieving the other one. In the context of sustainable development, typical goal dimensions are environmental, economic, and social (Elkington, 2002). In the context of energy systems planning, the energy trilemma considers affordability, environmental sustainability, and security of supply (Berjawi et al., 2021). While these dimensions usually are portrayed as conflicting, they do not necessarily have to be. However, to avoid loss of relevant information in complex decision problems, all dimensions usually need to be considered explicitly.

The alternatives (also called options, action opportunities, decision possibilities, actions, or strategies) constitute the decision field for the DMs (including sticking with the status quo) (Geldermann, 1998). The number of alternatives can be countable and discrete (approaches dealing with such situations are called *multi-attribute decision making*, MADM, or *multi-criteria analysis, MCA*) or uncountable and infinite (approaches dealing with such situations are called multi-objective optimization, MOO) (Antunes and Henriques, 2016). Deriving suitable alternatives can be supported with value focused thinking (Keeney, 1988, 1992; Siebert and Keeney, 2015). Alternatives are usually considered to be mutually exclusive, but in some decision problems, a combination of alternatives is sought. This is usually the case in multi-period decision problems, where a combination of multiple alternatives over multiple periods is evaluated (Yu and Chen, 2012).

Criteria are used to operationalize goals, which help identifying whether an alternative is suitable to achieve said goals. Criteria should be measurable, complete, independent, relevant, understandable, and non-redundant (Belton and Stewart, 2003). Criteria may be measured in incommensurable units and nominal, ordinal, or metric scales. Different MCDM approaches have been developed to deal with this diversity. For example, the

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[1] Behavioral issues are not addressed in this dissertation. Overviews of behavioral OR are provided in Kunc et al. (2016) and White et al. (2020).

ORESTE method (Organisation, Rangement Et Synthèse de données relaTionnElles) (Roubens, 1982; Pastijn and Leysen, 1989) deals with ordinally scaled criteria, while e.g., PROMETHEE (Preference Ranking and Organization METHod for Enrichment Evaluations) (Brans and Vincke, 1985; Brans and Smet, 2016) can deal with ordinal or metrically scaled criteria.

The DMs' preferences need to be considered if there is no perfect alternative – being optimal regarding all criteria – or dominating alternative – being at least as good as all other alternatives regarding all criteria and strictly better than all other alternatives regarding at least one criterion. There are inter- or intra-criteria preferences. Inter-criteria preferences regard the relative advantageousness of one criterion compared to the others (Zimmermann and Gutsche, 1991). Usually, these preferences are expressed in the form of normalized criteria weights so that the sum of all weights equals 1 or 100. For specifying intra-criteria preferences, MCDM approaches differ. For example, PROMETHEE allows expressing intra-criteria preferences with six standard types of preference functions that are based on the differences between performance scores of two alternatives (Brans and Vincke, 1985). Usually, preference parameters are subject to sensitivity analyses, which help explore the robustness of the solution regarding subjectively set parameters (Belton and Stewart, 2003).

In MCDM, uncertainty manifests in two forms: internal and external (Stewart and Durbach, 2016). *Internal* uncertainty relates to the process of problem structuring and analysis, including uncertainty about the appropriateness of a developed model for a particular real-world problem, or uncertainty about judgmental inputs required from DMs. *External* uncertainty relates to the nature of a decision problem's environment and its influence on the performance scores of a particular alternative. Approaches for modelling internal uncertainties include fuzzy set theory (Zimmermann, 2010) and rough sets (Greco et al., 2001). However, this uncertainty can inherently not be eradicated completely and should thus be resolved as much as possible during the problem structuring stage (French, 1995b; Stewart and Durbach, 2016). A promising approach for considering external uncertainties in a multi-criteria analysis is to incorporate a scenario planning technique (Schoemaker, 1995; van der Heijden, 1996; Gausemeier et al., 1998) during the problem structuring stage (Marttunen et al., 2017).

In *dynamic multi-criteria decision problems*, the previously mentioned elements of multi-criteria decision problems are allowed to change over time (Yu and Chen, 2012), including the available set of alternatives, the criteria, the consequences measured in terms of the criteria, and the preferences of DMs. Multi-period MADM approaches vary regarding their multi-period aggregation procedures, the dynamicity of preferences, and

the consideration of path dependencies, which hinder the choice of alternatives in subsequent periods, based on earlier choices (Sydow et al., 2009). For example, Kornbluth (1992) investigated the impact of future expected changes in the DMs' preferences over time on a decision at hand.

2.3 ENERGY SYSTEM ANALYSIS AND PLANNING

Energy system analysis comprises various methods that help to enhance the understanding of the operating principles of the energy system and its components. Its objective is to support decisions in energy policy and energy research with regard to technologies and infrastructures for the energy supply and energy conversion in a scientific and systematic way (Möst and Fichtner, 2009; Cao et al., 2016). The main model classes of energy system analysis are optimization models, helping to find optimal solutions – usually minimizing system costs in given constraints –, and simulation models, investigating energy systems' likely evolutions to gain insights about suitable solutions to a given problem (Schönfelder et al., 2011; Pfenninger et al., 2014).

One important current application of energy system analysis is planning the transition from energy systems relying on fossil fuels toward systems relying on energy from renewable sources, with the overall objective to tackle problems related to climate change and/or the depletion of fossil fuels. Fossil fuel reserves of different continents are predicted to become less exploitable in an economically reasonable way in the next 30–150 years (bp, 2020). On a global scale, the operation of today's energy systems is mainly dependent on fossil or nuclear fuels, but the share of renewable energy sources has been increasing steadily since the 2000s. In 2018, 86.2% of the global primary energy supply was provided by fossil or nuclear energy sources (International Energy Agency, 2020b). Although renewable and sustainable energy are not necessarily the same (Harjanne and Korhonen, 2019), the transition of energy supply systems toward energy from renewable sources is widely regarded as a key measure for reaching sustainable energy supply systems (International Energy Agency, 2019b; Blazquez et al., 2020). Energy policy frameworks across the globe often include specific targets regarding the expansion of the installed capacities of renewable energy technologies, for example:

- The European Union (EU) aims to increase the share of renewable energy to 32% by 2030, from 18.84% in 2018 (European Union, 2018; Eurostat, 2018).
- China has aimed to increase the installed capacities of hydro energy (to 340 GW) as well as wind and solar energy (to 240 GW) by 2020, from 332 GW and 226 GW, respectively, in 2016 (International Energy Agency, 2019a; National Development and Reform Commission, 2020).

- India has aimed to increase renewable capacities to 227 GW by 2020 and aims to further increase to 275 GW by 2027 (International Energy Agency, 2020a) from 84 GW in 2019.

2.4 Research Gaps

As emerged from the literature, the following research gaps can be identified:

1. Energy scenarios are usually constructed with the help of energy system analysis. However, the underlying processes of scenario construction and decision support in energy scenarios have been criticized as in-transparent, hindering effective interpretation and transfer of energy scenario studies (Cao et al., 2016; Grunwald et al., 2016; Junne et al., 2019). For improving this situation, an integrated sustainability assessment could prove useful (Kronenberg et al., 2012).

2. From a methodological perspective, a disparity regarding *how to integrate scenario planning and MCDM* can be observed in the literature: The first group of authors applies the scenario planning technique to identify alternatives for future energy systems and thus treats the terms "alternative" and "scenario" *synonymously*. This means that, in fact, "scenarios" are evaluated with MCDM. For examples from energy systems planning, see Kowalski et al. (2009), Browne et al. (2010), Ribeiro et al. (2013), Diakoulaki and Karangelis (2007), and Trutnevyte et al. (2011). The second group of authors highlights that scenarios should describe the external conditions under which alternatives need to be evaluated, therefore clearly distinguishing between "alternatives" and "scenarios" (French, 1995b; Comes et al., 2013; Stewart et al., 2013; Durbach and Stewart, 2020). The latter approach can be expected to be more useful for DMs in energy systems planning, as long-term uncertainties need to be considered in all investment decisions due to long life-cycles of power plants. An approach, which integrates MCDM, scenario planning, and energy systems analysis, in which scenarios and alternatives are distinguished, has not yet been developed and applied to an energy system planning problem. This is also acknowledged in the literature on energy scenarios. For example, Grunwald et al. (2016) call for a method which considers conflicting criteria, conflicting opinions of stakeholders, and uncertainties explicitly and transparently.

3. Effectively analyzing and communicating the uncertainties associated with certain energy futures is vital in strategic decision-making with long planning horizons (MacKerron and Scrase, 2009; Grunwald, 2011; Grunwald et al., 2016; Yue et al., 2018). Although many quantitative energy system models are readily available,

interpreting their results and specifically, the assessment and communication of uncertainties' consequences for decision-makers, can be improved.

4. While multi-period energy system models are state-of-the-art in energy system analysis (Pfenninger et al., 2014), multi-period MCDM approaches are not.[2] To support decision-making, multi-period MCDM approaches can build upon the output of multi-period energy system models. A suitable multi-period MCDM approach that allows evaluating an energy systems' evolution over time should support DMs in planning the transition towards energy from renewable sources dynamically.

In the next section, it is described how the abovementioned research gaps are addressed in this dissertation, with the overall objective to make decision-making in energy systems planning more transparent and robust.

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[2] A review of dynamic MADM approaches is included in paper 7. With multi-period MADM approaches being of very limited use in general, it can also be observed that none have been applied to energy systems planning.

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3 RESEARCH METHODOLOGY

In order to investigate how MCDM approaches can effectively support decision-making in energy systems planning, the research design encompasses a mixed research framework, which is summarized in Figure 2 and described in the following subsection 3.1. The methodology was divided into four phases (I-IV), each addressing one of the previously mentioned research gaps. In subsection 3.2, an overview of the methods used in the individual papers is provided.

3.1 CONTRIBUTION STRUCTURE

In phase I, a qualitative literature review on energy scenarios and energy systems analysis led to the development of a morphological box of energy scenarios. This box builds upon the methodological literature on developing and evaluating energy scenarios. The box comprises parameters describing the scenario properties, energy system model properties, scientific practice, and institutional settings of energy scenarios. It serves as a means of structuring the different types of energy scenario studies and helped identify research gaps regarding the integration of MCDM and energy system analysis.

In phase II followed the development of an approach, which allows the integrated development and evaluation of energy scenarios. This approach was refined through three publications: First, a prototype reference model (Wilde and Hess, 2007) was developed in the form of a data flow sheet; second, possible automations of the approach with the help of semantic web technologies and ontologies were considered; third, the approach was connected to the standard processes of scenario planning, energy system analysis, and MCDM, while using an unambiguous terminology (regarding the terms "scenario" and "alternative"). Development, refinement, and application of this approach were embedded in the research project "Nachhaltige Energieversorgung Niedersachsen (NEDS)" (sustainable energy supply Lower Saxony, Germany) (Engel, 2019), which is why the energy transition in Lower Saxony serves as an illustrative example for the approach. In its application, input from quantitative and qualitative energy system analyses from the research partners, including innovation studies (Kleinau et al., 2019), a grid expansion planning optimization model (Blaufuß and Hofmann, 2018), a smart grid optimization model (Nieße and Tröschel, 2016), a macroeconomic equilibrium model (Pothen and Hübler, 2018), and smart home energy management simulation model (Reinhold and

Engel, 2017; Reinhold et al., 2018) were integrated in the multi-criteria analysis. Input from stakeholders regarding their preferences was gathered at a public symposium embedded in the NEDS project (Wille, 2019). However, this input did not prove meaningful for the research conducted herein, which is why the project team proceeded with an equal criteria weighting followed by extensive sensitivity analysis of preference parameters. Moreover, because of time limitations in the project and the review process of the associated paper 4, we only obtained input data for the year 2050, which made it impossible to apply a multi-period evaluation with the same quality of data.

> **Research Gap 1 - Phase I:** Literature review, classification of energy scenario studies, and identification of research gaps
>> Paper 1: Morphological Analysis of Energy Scenarios

> **Research Gap 2 - Phase II:** Development of the approach for integrating MCDM, scenario planning, and energy system analysis
>> Paper 2: Towards an Integrated Sustainability Evaluation of Energy Scenarios with Automated Information Exchange
>> Paper 3: Towards an Integrated Development and Sustainability Evaluation of Energy Scenarios Assisted by Automated Information Exchange
>> Paper 4: Combining Scenario Planning, Energy System Analysis, and Multi-criteria Analysis to Develop and Evaluate Energy Scenarios

> **Research Gap 3 - Phase III:** Evaluation and comparison of new and extant approaches
>> Paper 5: Transparency in Energy Scenario Studies: Survey of Different Approaches Combining Scenario Planning, Energy System Analysis, and Multi-criteria Analysis

> **Research Gap 4 - Phase IV:** Integrating a multi-period perspective and consideration of uncertainties
>> Paper 6: Multi-criteria Evaluation of the Transition of Power Generation Systems
>> Paper 7: Multi-Period Multi-Criteria Decision Making under Uncertainty: A Renewable Energy Transition Case from Germany

Figure 2: Research framework

In phase III, the new and existing approaches for combining MCDM and scenario planning were reviewed and investigated regarding their transparency and implications for decision support and use cases for both approaches were derived.

In phase IV, the new approach was developed for and applied in a multi-period setting. This was also done in two iterations: In the first iteration, the multi-period MCDM approach was applied to the case of energy systems planning in the town of Jühnde, Lower Saxony, Germany. In the second iteration, this application was enriched with a scenario analysis, so that a multi-period MCDM approach under uncertainty was proposed and also applied to the case of energy systems planning in Jühnde.

3.2 METHOD STRUCTURE

Table 1 shows the methods that were used in the individual papers. Because the main objective of this dissertation is to investigate how MCDM can effectively support decision-making in energy systems planning, the main contributions are methodological advancements in the intersection of the fields of MCDM and energy system analysis. Therefore, the results obtained by applying the newly developed methods, e.g., results regarding the analysis of 4 energy scenario studies in paper 1, or the results of the analysis regarding the transition of Lower Saxony's energy system in paper 4, are not addressed in the following section. For the results of the individual applications of the developed methods, the interested reader is referred to the respective individual papers.

Table 1: Methods used in the individual papers

Research gap / Phase	Paper	Methods
I	1: Morphological Analysis of Energy Scenarios (Witt et al., 2018)	Literature review & morphological box
II	2: Towards an Integrated Sustainability Evaluation of Energy Scenarios with Automated Information Exchange (Schwarz et al., 2017)	Prototype model (data flow sheet)
	3: Towards an Integrated Development and Sustainability Evaluation of Energy Scenarios Assisted by Automated Information Exchange (Schwarz et al., 2019)	Prototype model (data flow sheet) & data management approach with semantic web technologies
	4: Combining Scenario Planning, Energy System Analysis, and Multi-Criteria Analysis to Develop and Evaluate Energy Scenarios (Witt et al., 2020)	Reference modelling (Wilde and Hess 2007), MCDM, energy system analysis & scenario planning
III	5: Transparency in Energy Scenario Studies: Survey of Different Approaches Combining Scenario Planning, Energy System Analysis, and Multi-criteria Analysis (Witt, 2020)	Literature review
IV	6: Multi-Criteria Evaluation of the Transition of Power Generation Systems (Witt et al., 2019)	Multi-period MCDM & energy system analysis
	7: Multi-Period Multi-Criteria Decision Making under Uncertainty: A Renewable Energy Transition Case from Germany (Witt and Klumpp, 2021)	Multi-period MCDM, energy system analysis & scenario planning

4   RESEARCH CONTRIBUTIONS

In this section, the contribution of each paper is briefly presented and discussed, focusing on the specific goals and main results. The full texts of the papers are presented in the appendix.

4.1   SUMMARY: MORPHOLOGICAL ANALYSIS OF ENERGY SCENARIOS

Energy scenarios have long been successfully used to inform decision-making in energy systems planning, with a wide range of different methodological approaches for developing and evaluating them. The purpose of paper 1 (Witt et al., 2018) is to analyze the existing approaches and classify them with a morphological box. This paper builds upon the methodological literature on developing and evaluating energy scenarios and presents a morphological box, which comprises parameters describing the scenario properties, (energy system) model properties, scientific practice, and institutional settings of energy scenarios. The newly developed morphological box is applied to four selected energy scenarios of the German energy transition. The morphological box is a suitable tool to classify current energy scenarios. The exemplary application also points toward four challenges in the current practice of energy scenario development and evaluation: increasing complexity of decision problems, transparency of the scenario development process, transparency of the decision support process, and communication of uncertainty. The morphological box of energy scenarios helps researchers soundly document and present their methodological approaches for energy scenario development and evaluation. It also facilitates the work of analysts who want to classify, interpret, and compare energy scenarios from a methodological perspective. Finally, it supports the identification of gaps between current practice and the methodological literature on energy scenarios, leading to the development of new types of energy scenarios.

    This paper substantially contributed to the further research in the subsequent phases II through IV: The challenges of increasing transparency of the scenario development and decision support process were tackled with the development of a new approach for combining MCDM with scenario planning and energy system analysis (papers 2–4). Paper 5 specifically addresses how uncertainties can be effectively analyzed and

communicated in energy scenario studies, while paper 7 provides an adequate multi-period MCDM method with an illustrative example.

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

To reshape energy systems toward renewable energy resources, DMs 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, different methodological approaches are combined in paper 2 (Schwarz et al., 2017): story-and-simulation scenarios (Alcamo, 2008), MCDM, information modeling (Lee, 1999), and co-simulation (Steinbrink et al., 2019). This paper shows how the combination of these methods can lead to an integrated approach for sustainability evaluation of energy scenarios with automated information exchange. The approach consists of a sustainability evaluation process (see Figure 3) and an information model for modeling dependencies. The objectives are to guide decisions toward sustainable development of the energy sector and to make the scenario and decision support processes more transparent for both DMs and researchers.
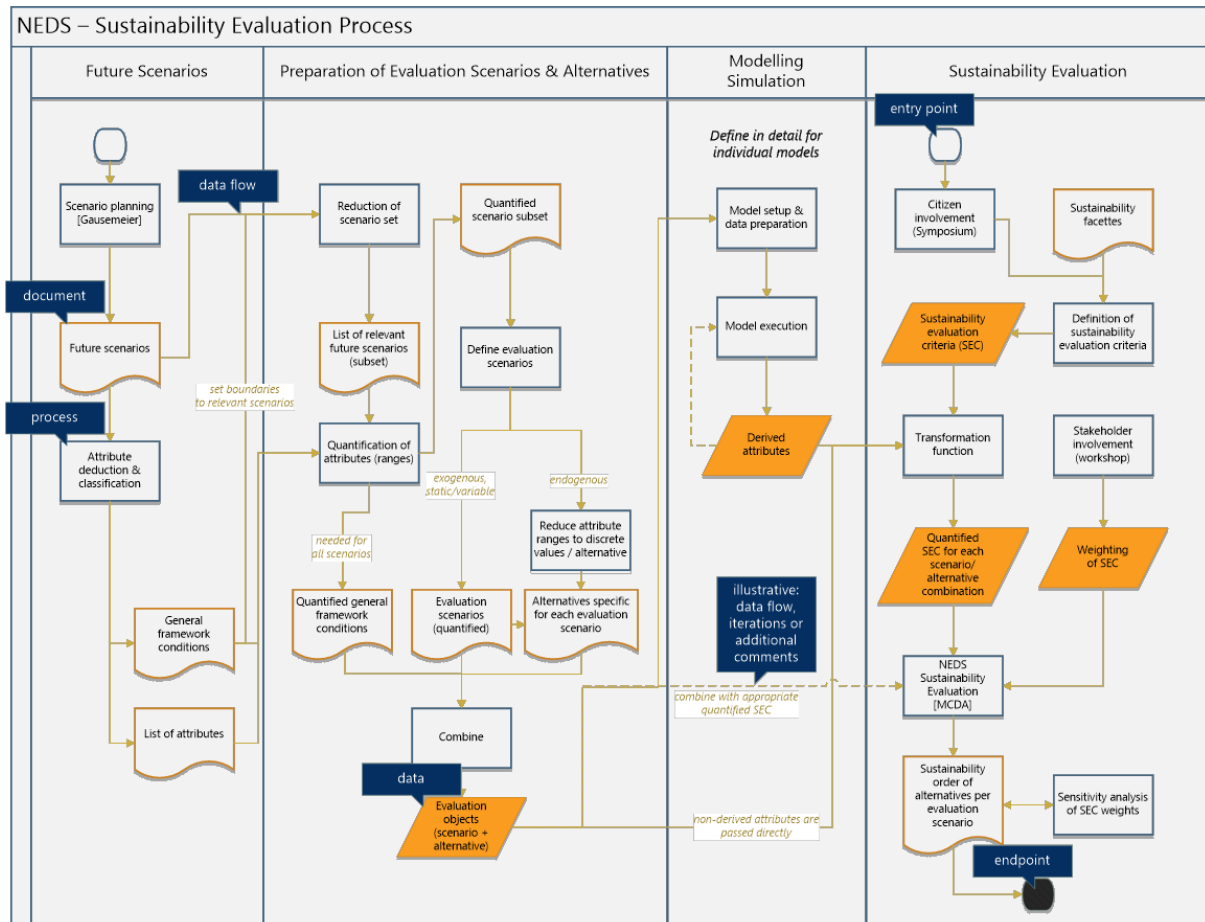
Figure 3: First iteration of the sustainability evaluation process model (Schwarz et al., 2017)

4.3 Summary: Towards an Integrated Development and Sustainability Evaluation of Energy Scenarios Assisted by Automated Information Exchange

As this paper 3 (Schwarz et al., 2019) is an extension of the previous one, there is expected overlap regarding their contents. Significant additions in paper 3 include: (1) a connection of the process to the sustainable development goals, (2) the overall conceptual solution for the scenario development and evaluation process, and (3) a table, which lists all artifacts and types of data that emerge during the development and evaluation process, also showing interdependencies between process steps and possibilities for automating the data exchange (see Table 2).

Table 2:   Description of artifacts developed during the sustainability evaluation process (S: structured, U: unstructured), (Schwarz et al., 2019) with minor editing

#	Artifact	Data	Description	Required Input	Input for
1.1	Criteria	S	Criteria, which are used to evaluate the sustainability of future energy systems with MCDM methods	–	2.2, 4.1
1.2	System boundaries	U	Temporal, spatial, and energy-sector related boundaries of the modeled energy system	–	1.3, 2.1
1.3	Qualitative scenarios	U	Qualitative future scenarios described with a storyline, detailing the interplay between key factor projections	1.2	2.2, 2.3
2.1	General framework conditions	S	Boundary conditions narrowing down valid decision alternatives	1.2	2.3
2.2	List of attributes	S	Collection of (derived and non-derived) attributes quantifying the development of qualitative key factors in numerical terms	1.1, 1.3, 4.1	2.4, 4.1
2.3	List of relevant qualitative scenarios	U	Reduced set of future scenarios, after compliance with general framework conditions is checked	1.3, 2.1	2.4
2.4	Quantified scenario assumptions	U	References and rationale for numeric values for all attributes, including general framework conditions, scenario-specific framework conditions, ranges for endogenous attributes, and final discrete decision alternatives	2.2, 2.3	2.5

Table 2:   Description of artifacts developed during the sustainability evaluation process (S: structured, U: unstructured), (Schwarz et al., 2019) with minor editing

#	Artifact	Data	Description	Required Input	Input for
2.5	Alternatives	S	Specification of alternatives for each external scenario, also including general framework conditions to provide parametrization for simulation scenarios	2.4	3.1, 4.2
3.1	Derived Attributes	S	Attributes, whose values are calculated in simulation scenarios, with simulation models of the energy system	2.5	4.2
4.1	Transformation functions	S	Functions mapping attributes and derived attributes onto criteria	1.1, 2.2	2.2, 4.2
4.2	Performance Scores	S	Attributes for the criteria describing the level of achievement of the alternatives regarding sustainability within external scenarios	1.1, 2.5, 3.1, 4.1	4.4
4.3	Weights	S	Criteria weights representing DMs' inter-criteria preferences	–	4.4
4.4	Sustainability Order of Alternatives	U	Ranking of decision alternatives and recommendations according to MCDM aggregation method, given the decision table and DMs' preferences	4.2, 4.3	–

(cont'd)

4.4 Summary: Combining Scenario Planning, Energy System Analysis, and Multi-Criteria Analysis to Develop and Evaluate Energy Scenarios

The transition from the current electricity system to a renewable electricity supply poses immense economic, technological, and policy challenges. Energy system models represent the complexity of interactions in combined processes from extraction of primary energy to the use of the final energy to supply services, goods, and processes. While these models were originally focused on energy security and costs, climate change, as the most pressing environmental concern as well as sustainability targets in general require the consideration of a broader range of decision-relevant aspects. In this context, scenario planning and multi-criteria decision-making can complement energy system analysis in the development and evaluation of energy scenarios. Therefore, in paper 4 (Witt et al., 2020), a combination of these three methods is proposed (see Figure 4) and illustrated in a case study that investigates the transition of the electricity sector in Lower Saxony, Germany, to energy from renewable sources. This method combination has resulted from connecting the process models presented in papers 2 and 3 with the standard process models of MCDM, energy system analysis, and scenario planning, and forms the basis for papers 5, 6, and 7.

The case study shows that the integration of multi-criteria analysis allows for better problem structuring by focusing on relevant alternatives, external uncertainties, and evaluation criteria. The integration of scenario planning allows for a systematic investigation of external uncertainties. Thereby, the fallacy of investigating particular assumptions for uncertain parameters, which are however not consistent with the assumptions in the scenario, can be avoided. Finally, combining the methods allows for a more balanced and objective evaluation of alternative energy systems in terms of multiple criteria, which can be used to inform discussions among stakeholders and may thus increase acceptance.
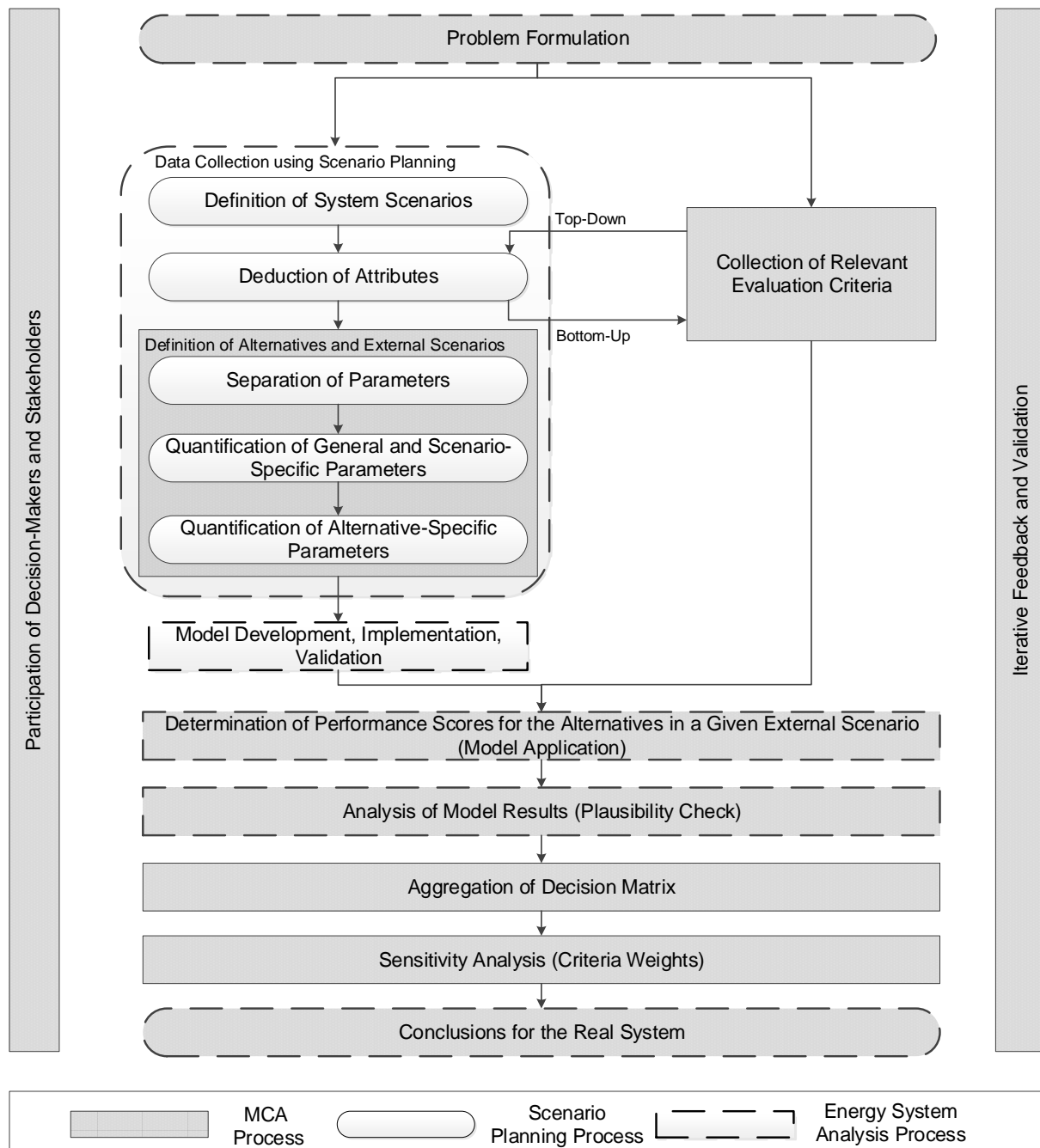
Figure 4: Framework for developing and evaluating energy scenarios as a combination of Scenario Planning, Energy System Analysis, and Multi-criteria Analysis, (Witt et al., 2019)

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

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 multicriteria analysis are combined in the design of such energy scenario studies, two possible method combinations can be identified in the literature (see second research gap in Section 2.4). In paper 5 (Witt, 2020), 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 of the method combination is recommended to improve transparency in energy scenario studies and to avoid over-interpretation of energy scenario studies' results by DMs.

This paper's results suggest that the extant approach for combining MCDM and energy system analysis should be applied if there are no specific DMs whose preferences should be considered, or no specific decision is to be supported. Rather, this method combination allows the construction of orientation scenarios, which help to identify desirable future states that are relevant for a problem, and suggests to open up a discussion about these future states (Stirling, 2008). This method combination also implies that the weighting of criteria cannot be elicited from a specific DM, but the impact of all weighting decisions should be investigated by means of sensitivity analysis (Geldermann and Rentz, 2005). Furthermore, external uncertainties cannot be considered from the perspective of a specific DM. In contrast, the new approach (developed in paper 4) allows the consideration of the perspective of specific DMs, and the objective of this method combination can be to open up or close down a discussion about relevant alternatives in a transparent and systematic way, using the preferences and considering the external uncertainties from the perspective of specific DMs. The implication for improving the transparency of energy scenario studies is that the purpose of applying a method combination of MCDM and energy system analysis should be made very clear: Is the study intended to provide general orientation or does it solve a specific decision problem with clearly defined stakeholders and DMs? This categorization is usually omitted in energy scenario studies, where MCDM and energy system analysis are combined, as most of these studies do not include the perspective of DMs, which is however a crucial component of MCDM.

4.6 Summary: Multi-Criteria Evaluation of the Transition of Power Generation Systems

Energy scenarios describe possible future states or developments of energy systems, and are often used to provide orientation for strategic decision making in the energy sector or in energy policy, e.g., for planning the energy transition towards renewable energy technologies. In this context, multiple conflicting criteria, e.g., CO_2-emissions and system costs, need to be considered. Hence, MCDM can support drawing conclusions from energy scenarios. However, as energy scenarios typically look several decades into the future, there are time-related challenges for providing adequate decision support: Today's decisions can lead to path dependencies, uncertainties associated with the input parameters and results of energy scenarios increase significantly over time, and the preferences of stakeholders may vary over time. Paper 6 (Witt et al., 2019) presents a multi-period multi-criteria approach for the evaluation of transition pathways which allows to address these challenges. The approach is based on the outranking method PROMETHEE (Brans and Vincke, 1985; Brans and Smet, 2016) and consists of a three-phase procedure: In the first phase, the relevant alternatives are identified across multiple periods and performance scores are calculated for each time-step (see Figure 5). In the second phase, the alternatives are evaluated with PROMETHEE II (Brans and Smet, 2016) in each period, and in the third phase, the evaluations of alternatives are aggregated along transition paths. As an example, the method is applied for planning the power generation system in a bio-energy village in southern Lower Saxony, Germany.
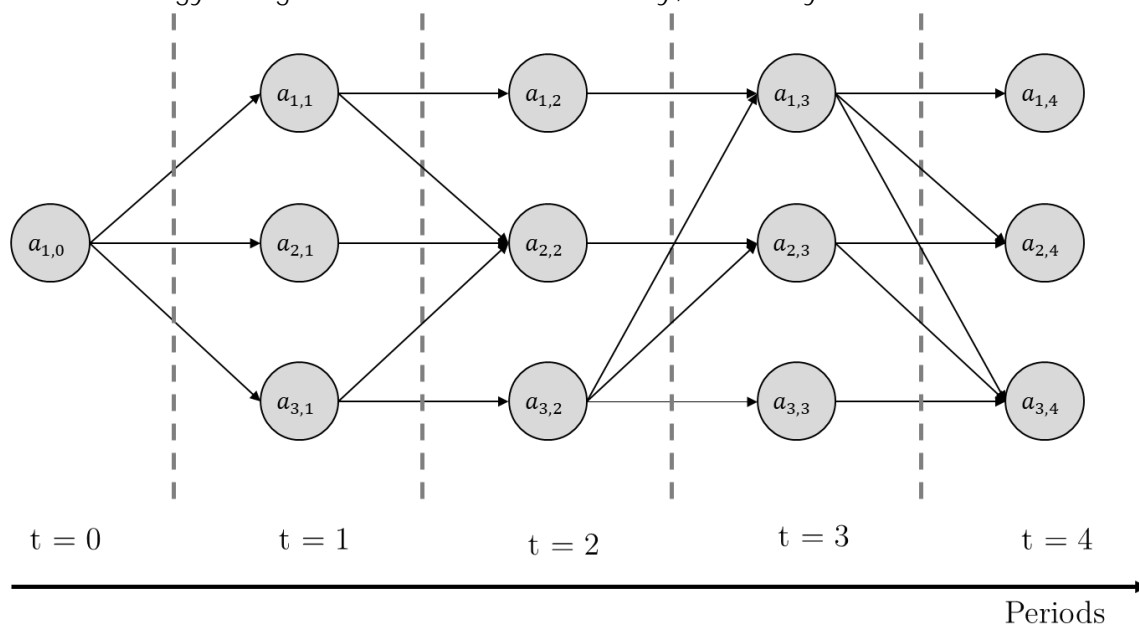

Figure 5: An exemplary directed graph to structure alternatives in multiple periods (Witt et al., 2019)

4.7 Summary: Multi-Period Multi-Criteria Decision Making under Uncertainty: A Renewable Energy Transition Case from Germany

Because of the long-term planning horizons in energy systems planning, deep uncertainties need to be considered. Based on prior multi-period MCDM approaches, including the one presented in paper 6, paper 7 (Witt and Klumpp, 2021) provides an extension of the outranking approach PROMETHEE for multi-period evaluations in deep uncertainty settings. Therefore, it extends paper 6 by an investigation of the impact of external uncertainties. In order to adequately address the consideration of uncertainties and to obtain an additional level of information, a multi-period PROMETHEE approach and scenario planning are combined. In an illustrative example, this method combination is applied to a case study from the German energy sector regarding a renewable energy transition (see Figure 6). This highlights the potential interactions of a multi-period perspective and the consideration of external scenarios in the decision-making process. Specifically, this method combination allows to evaluate the robustness of the obtained MCDM results for a number of scenarios.
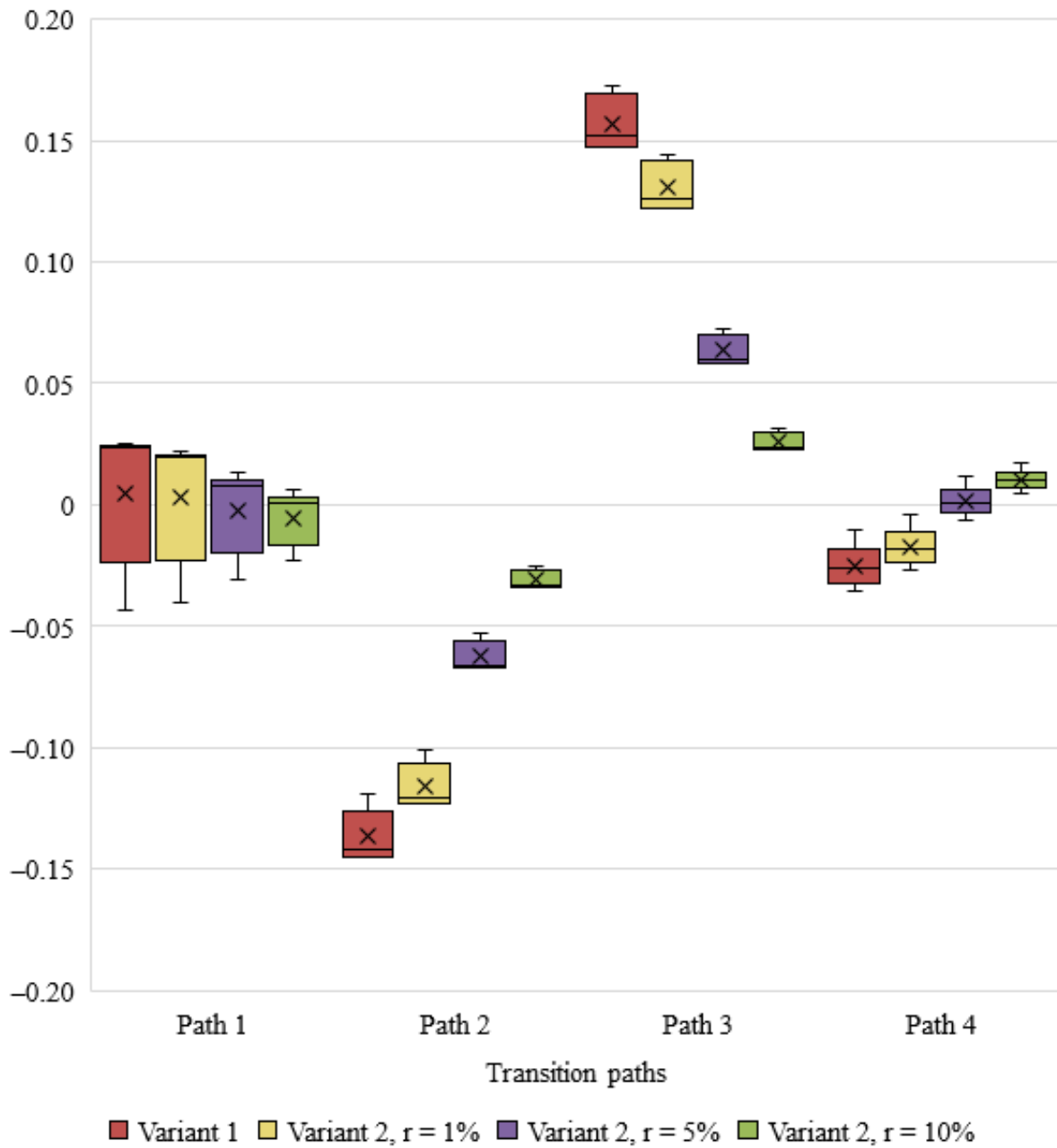
Figure 6: Exemplary results of the multi-period aggregation under uncertainty with aggregation variants 1 and 2 (r=1%, 5%, and 10%) (Witt and Klumpp, 2021)

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5 CONCLUSION

This last section sums up the results obtained, state the implications of this dissertation, and suggest potential further research developments.

5.1 SUMMARY OF RESULTS AND IMPLICATIONS

This dissertation set out to investigate how MCDM approaches can effectively support decision-making in energy systems planning. The contributions are structured in a research framework of four phases, each of which contributed to achieving this objective.

In phase I, a literature review and subsequent development of a morphological box revealed the parameters influencing the construction and interpretation of energy scenario studies (paper 1). In this phase, it became apparent that MCDM can help support decision-making in energy systems planning, if MCDM and scenario planning are combined in such a way that uncertainties are considered.

In phase II, a new process combining MCDM, energy system analysis, and scenario planning was developed and refined through three publications (papers 2–4). Starting from a prototype data flow sheet, the method combination comes in the form of a process model that is linked to the standard processes of MCDM, scenario planning, and energy system analysis. This approach allows evaluating future energy systems while also considering systemic uncertainties induced by the long planning horizon. Regarding the time of the multi-criteria evaluation, however, this approach was limited to single-period evaluations (e.g., the year 2050). It was applied to evaluate the transition of the electricity sector in Lower Saxony to energy from renewable sources.

In phase III, the newly developed approach was compared to the traditional way of integrating MCDM in energy scenario studies, with particular consideration of the implications regarding the studies' transparency and the analysis and communication of uncertainties (paper 5).

In phase IV, the newly developed approach was extended to support multi-period evaluations. However, in paper 6, no external uncertainties were considered. This was the last advancement in paper 7, where a scenario analysis was integrated. In both cases, the approaches were applied to evaluate the transition of the power system in the bioenergy town Jühnde.

According to the categorization of the levels of decision support by French (2013), also described in the Introduction, the new method combinations developed in phases II and IV could advance the field of scientific policy advice in questions of energy systems planning from decision support level 2 to level 3. With the new method combination, the decision support process (including the consideration of preferences and uncertainties) can be made more transparent and auditable. This could lead to a higher acceptance of decisions regarding energy systems planning problems. In a time when energy policy decisions will have a crucial impact on whether or not the goals of the Paris Agreement can be achieved, i.e., holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (United Nations, 2015), these energy policy decisions should be made in a very timely, transparent, and target-oriented manner.

As determined in phase III, the newly developed method combination is suitable in settings where specific DMs are facing specific decision problems, so that the spatial scale of the problem also needs to be considered (the spatial scale of scenarios and energy system models has also been investigated in the morphological box developed in paper 1). For specific investment problems with a local/project scale and a clear set of stakeholders and DMs, the newly developed method combination is immediately applicable. For larger scales and less well-defined groups of stakeholders and DMs, additional stakeholder analyses such as conducted by Steinhilber et al. (2016) may be necessary.

5.2 DIRECTIONS FOR FURTHER RESEARCH

Despite the research limitations and the related further developments tied to each paper, four directions for further research are suggested.

Regarding the developed morphological box of energy scenarios, it could be integrated with other subsequently published classification schemes of energy system models, such as the one described by Savvidis et al. (2019). This would allow for a more detailed analysis of energy system model characteristics, while still keeping the important perspective regarding the general approach to scenario construction, which is usually lacking in classifications of energy system models. Overall, this would help to bring clarity for analysts trying to navigate the abundance of energy system models (for reviews, see, e.g., Connolly et al. (2010) or Bhattacharyya and Timilsina (2010)). For DMs, this could highlight which uncertainties are included in an energy scenario study, how these are considered, and what implications and limitations follow for interpreting the study's results.

One option for the newly developed MCDM approach is to include approaches that help gain a better understanding of stakeholders' preferences (Grimble and Wellard, 1997), because long-term decision-making problems with high uncertainty, e.g., energy systems planning, often concern a high number of diverse stakeholders. For example, Steinhilber et al. (2016) integrated a stakeholder analysis in their MCDM approach and Schär and Geldermann (2021) applied a multi-actor MCDM approach. Another promising approach is group decision making (Cuoghi and Leoneti, 2019), a PROMETHEE-specific group decision-making approach is already available (Macharis et al., 1998).

Regarding the MCDM algorithm used, the included papers in this dissertation are all based on PROMETHEE. Interestingly, most multi-period approaches described in the literature are also based on PROMETHEE (see, e.g., Banamar and Smet (2018), Urli et al. (2019), and Ziemba et al. (2018)). However, other single synthesizing criterion approaches could also be used, as pointed out by Frini and Benamor (2017). Therefore, the developed PROMETHEE approach could serve as a benchmark, when similar approaches based on other MCDM algorithms are developed.

Finally, the newly developed multi-period MCDM approach can be applied to decision problems from other domains. For example, in the energy sector, the approach can not only be applied to power systems planning, but also to heat and transport questions (Savvidis et al., 2019). An application field adjunct to the energy sector would be the multi-criteria sustainability evaluation of hydrogen supply chains (Fredershausen et al., 2021), where MCDM has already been applied (see, e.g., Ren et al. (2020) and Xu et al. (2020)), uncertainties in technology evolution and its environment are high (Fazli-Khalaf et al., 2020), and long investment cycles can be expected. The newly developed multi-period MCDM approach has already been applied in waste water management (Beutler and Lienert, 2020). This sector has even longer investment cycles than the energy system, as water infrastructure is usually built and used for even longer periods. Another promising application area for multi-period MCDM approaches is sustainable forest management, as demonstrated by Frini and Ben Amor (2019).

In general, applications for multi-period MCDM approaches under uncertainty can be decision problems in domains that are of dynamic nature, have a high impact on diverse stakeholder groups, and thus need to be communicated with a high degree of transparency and auditability. One current example would be the development and evaluation of appropriate political measures to contain the Covid-19 pandemic.[3] While MCDM has been proven to be effective in nuclear disaster management (French, 1996; Geldermann

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[3] https://www.bundesregierung.de/breg-de/themen/coronavirus/coronavirus-handeln, in German, last accessed on 06.12.2021.

et al., 2009; Papamichail and French, 2013), however, is has to be kept in mind that a multi-period MCDM approach based on elaborate system modelling and preference elicitation can be very time-consuming due to its interactive and iterative nature. In this regard, the integration of behavioral OR approaches, such as the distinction between societal system 1 and system 2 thinking as proposed by Argyris and French (2017) could prove useful in accelerating the application of multi-period MCDM approaches for urgent decisions.

The advanced methodology in the intersection of MCDM, system analysis and scenario planning can help to make complex decision-making for complex management and policy decisions, where scientific inputs in terms of consequences of decisions (provided by scientific analysis) and value judgements (elicited from DMs) need to be considered, more transparent and auditable. Overall, the hope is that in the face of these complex decision problems, the developed combination of MCDM, system analysis and scenario planning can actually help DMs make better upcoming decisions.

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