Using Energy Supply Scenarios in an Interdisciplinary Research Process

Barbara S. Zaunbrecher[1(✉)], Thomas Bexten[2], Jan Martin Specht[3], Manfred Wirsum[2], Reinhard Madlener[3], and Martina Ziefle[1]

[1] Chair for Communication Science, RWTH Aachen University, Campus Boulevard 57, 52074 Aachen, Germany
{zaunbrecher,ziefle}@comm.rwth-aachen.de

[2] Chair and Institute of Power Plant Technology, Steam and Gas Turbines, RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany
{bexten,wirsum}@ikdg.rwth-aachen.de

[3] Chair of Energy Economics and Management, Institute for Future Energy Consumer Needs and Behavior (FCN), E.ON Energy Research Center, RWTH Aachen University, Mathieustr. 10, 52074 Aachen, Germany
{mspecht,rmadlener}@eonerc.rwth-aachen.de

Abstract. The sustainable energy transition (Energiewende) is a multidisciplinary challenge. While for technical disciplines, the focus is on the development of technologies which can supply, transmit and store energy in a sustainable way, economic research focuses for example on the analyses of costs and risks of different asset portfolios. Yet another perspective is taken by the social sciences who focus on social challenges associated with the implementation of measures for realizing the Energiewende (decarbonization, high energy efficiency, high shares of renewables, nuclear phaseout), for example their acceptability. A solution for energy supply and storage which is optimized only according to one of these perspectives will, however, fail to meet other essential criteria. To develop sustainable solutions for energy supply and storage, which are technically feasible, cost-effective, and supported by local residents, interdisciplinary cooperation of researchers is thus needed. Interdisciplinary research, however, is subject to many barriers, for example the need to agree on a common analytical framework. In this paper, a process model for interdisciplinary energy research is proposed, in which specific scenarios are used to aid interdisciplinary cooperation and reciprocal integration of results. Based on a current research project, the phases of the model and the use of the scenarios in disciplinary and interdisciplinary work packages are described, as well as challenges and shortcomings of the model.

Keywords: Renewable energy · Social acceptance · Economics
Technology · Interdisciplinarity · Electricity storage

B. Donnellan et al. (Eds.): SMARTGREENS 2017/VEHITS 2017, CCIS 921, pp. 77–93, 2019.
https://doi.org/10.1007/978-3-030-02907-4_4

1 Introduction

The inherent high volatility and limited predictability of the growing number of renewable power generation capacities in Europe and especially in Germany poses various challenges for a stable operation of the electricity grid (Holttinen [24]). This is a result of the requirement for an equilibrium between power generation and consumption at any time. In order to compensate for these characteristics of renewable power generation, flexible and efficient dispatchable energy conversion and storage units are needed today and in the future (Bouffard et al. [9]). Centralized large-scale units are one option to provide this required dispatchable capacity (e.g. coal fired power plants, combined cycle power plants, pumped storage power plants). An alternative is the deployment of smaller distributed units, e.g. in a municipal context. The utilization of these units leads to a better convergence of power production and consumption profiles on a local level and hence offers the potential of enhancing the electrical autarky of municipal energy supply systems while reducing the pressure on the higher voltage levels of the electric grid.

In recent years, the economic perspective on the energy transition in Germany seems to have changed to some extent. While the focus in the last decades was mainly set on getting the diffusion of renewable energy technologies started, the resulting increase of the electricity price imposed some pressure on policy makers to limit the rise. One measure was to switch from the promotion through guaranteed feed-in tariffs to an auctioning system for wind power and large PV plants, so that only the most competitive projects are realized (EEG 2016, §2 (3)). The first auctioning round conducted in spring 2017 resulted in citizens' energy initiatives receiving 93% of all awards (BMWi [15]). How this affects the diffusion of renewable energy projects and more specifically municipal energy systems remains to be seen. One option could be that local projects will forgo the strong competition for the declining national funding but turn towards business models that allow for local financing, e.g. with the support of a municipality or additional returns for local green electricity.

While the necessity of turning away from fossil fuels towards renewables is widely acknowledged and supported by the general public (Zoellner et al. [54]), specific energy projects have raised protests by (local) residents, especially large scale technologies and associated infrastructures (e.g., wind farms, transmission lines) (Wüstenhagen et al. [47]). While in the past, slow diffusion and a lack of social acceptance also occurred, the scope, pace and organization of protest has dramatically changed (Marg et al. [38]), delaying projects and leaving residents unsatisfied with the development process (Gross [20]). The reasons why local residents oppose energy infrastructure are manifold. Among other reasons, landscape impact of the energy infrastructure plays a role for its social acceptability (Wüstenhagen et al. [47], Hirsh and Sovacool [22], Johansson and Laike [27]), and, closely connected to this issue, environmental concerns (Krewitt and Nitsch [29]). Health concerns have also been shown to affect public attitudes toward energy infrastructure, for example, fear of infrasound in the case of wind power plants, or of electromagnetic fields in the case of transmission lines (Songsore and

Buzzelli [43], Baxter et al. [3], Wiedemann et al. [44]). Besides these concerns, the social setting of the planning process has an impact on local acceptance of energy infrastructure. It has been found that trust in the involved stakeholders (Huijts et al. [25], Bronfman et al. [11]) as well as perceived fairness of the decision process (Wolsink [46], Liebe et al. [35]) can also have an influence on the perception of local energy infrastructure. From a planning perspective, the claim has been made that participatory approaches, which value and integrate the parties concerned in early stages, are more likely to gain approval with local communities (Langer et al. [32], Raven et al. [40], Schweizer et al. [42]). This requires openness from the planners' perspective towards alternative options (Schweizer et al. [42]) and the acknowledgement that there is more to energy infrastructure planning than technical requirements.

An interdisciplinary approach, in which energy supply scenarios are not only evaluated from a technical, but also from an economic and social perspective, can help to develop solutions which take into account the technical, economic and social challenges associated with the changes to the energy supply system, and thus provide holistic solutions to a complex problem. Especially the early integration of social factors in early stages of the technology development process can help to overcome some of the above mentioned barriers (Zaunbrecher and Ziefle [48]). Interdisciplinarity, in this context, is understood as "a coordinated collaboration between researchers from at least two different disciplines, which can manifest itself in a simple exchange of ideas to the point of integration of methods, concepts and theories" is referred to (Hamann et al. [21]). Especially for global challenges like climate change or energy supply, interdisciplinary approaches are called for (Wilson [45]), because these complex topics cannot be answered by one discipline alone and "do not exist independently of their sociocultural, political, economic, or even psychological context" (Brewer [10]:329). While the methodological variety of interdisciplinary approaches offers the benefit of capturing a problem more holistically, the assembling of "their partial insights into something approximating a composite whole" (Brewer [10]:330) still presents a challenge. Barriers to interdisciplinary work are, e.g. different scientific cultures, thus also different frames of references and methods, with which problems are approached (Brewer [10]). Furthermore, the problem of communication, based on a different "language" of each discipline, can hinder successful interdisciplinary collaboration (Brewer [10], Holbrook [23], Jacobs and Frickel [26]). It requires the researchers involved to translate their concepts, approaches and ideas into terms that members of other disciplines can relate to (Holbrook [23]). Institutional barriers, such as incentives, funding, and the priority given to interdisciplinary over disciplinary work present a further challenge (Brewer [10]). It was in fact found that the more institutions are involved, the less knowledge outcomes are reported, due to higher coordination costs and more effort required to sustain strong working relationships (Cummings and Kiesler [14]). Distributed team members mostly do not know each other, and therefore have weaker ties, and, consequently, less communication (ibid.). Disciplinary structures, like specialized journals or conferences further hinder interdisciplinary exchange by supporting an inner-disciplinary communication rather than interdisciplinary exchange (Jacobs and Frickel [26]). Moreover, there can be a lack of knowledge about possible contributions and opportunities for collaboration with other disciplines, due to "disciplinary assumptions about the "other" half of the system [based on] simplistic models" (Lélé and Norgaard [34]:968).

Although some of these issues might not be unique to interdisciplinary teams (Jacobs and Frickel [26]), the variety of challenges on a content and institutional level illustrates the complexity of interdisciplinary research.

In this paper, a process model for interdisciplinary research is presented, taking an energy-related project as an example, which seeks to overcome some of these challenges. It presents a specific application of an interdisciplinary research approach to questions of energy supply, and moreover, can serve as a guideline for other interdisciplinary projects in other contexts with regard to the various stages of cooperation. It is shown how in the different phases of the model, interdisciplinarity is achieved as a process from separated, multidisciplinary research to fully integrated interdisciplinary research. In particular, it is shown in detail how energy-supply scenarios were used in the process to facilitate communication and data exchange between the disciplines and how those scenarios were defined in a coordinated process between the disciplines, taking into account requirements on the one hand, and applications of the scenarios in disciplinary and interdisciplinary research on the other hand.

2 Interdisciplinary Process Model

The process model (Fig. 1) describes the research process in the research project KESS[1]. In this project, an interdisciplinary group of researchers develops energy supply scenarios for municipalities, including electricity production, transmission and storage. The energy supply scenarios are analyzed from a technical perspective by researchers from mechanical and electrical engineering, an economic perspective by researchers from energy economics, and a social perspective, by researchers from communication science and linguistics. The research process is illustrated in the following chapters by first referring to the process model which was followed and afterwards by a detailed description of the scenarios which were applied in key stages of the research process. Overall, the research model describes a continuum from an "informal communication of ideas" to "formal collaboration" (Lattuca [33]).

In the first stage, stage one, the disciplines are at the beginning of the interdisciplinary collaboration. In this stage, their collaboration is thus characterized by a multidisciplinary, not an interdisciplinary approach (Jungert [28]), as the connection is not yet established through collaboration, but -at least- through a shared research topic (energy supply for municipalities). Thus, the research style here is rather a "parallel play" (Aboelela et al. [1] than an integrated approach. During this phase, each discipline defines relevant research topics and thus lays

[1] For information on the project see http://www.comm.rwth-aachen.de/index.php?article_id=954&clang=1.

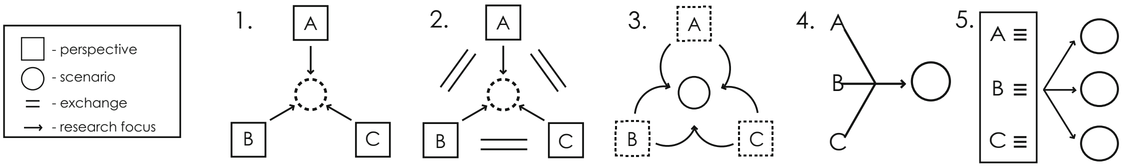

Fig. 1. Process model for Interdisciplinary Collaboration (Zaunbrecher et al. [53]).

the basis for later cooperations. The importance of this phase is underlined by the fact that disciplinarity is "considered [one of] the most important factors for successful interdisciplinary collaboration" (Hamann et al. [21]).

The research questions which are developed in this initial phase are thus also of uni-disciplinary nature, as "every component of [the] research problem calls for a different science" (Krohn [30]). Examples for uni-disciplinary research questions concern, e.g., the interconnectivity between different technical parameters from a technical perspective (Bexten et al. [5]), or the perception of single components of the system from a social perspective (Zaunbrecher et al. [52]). In order to align the results, the framing parameters of the energy supply scenario are loosely defined, e.g., which components define the energy supply system, how many inhabitants the municipality has, how large the annual electricity consumption is and how large the share of electricity produced by renewables is.

In the second stage, the multidisciplinary approach has progressed to a "multidisciplinary approach with exchange". Although all disciplines still approach the topic from their own perspective using their own methods, the process to interdisciplinarity is further progressed by an exchange between the three perspectives. This exchange includes communicating methods, approaches, terminology, ideas and requirements for further collaboration, in order to enhance mutual understanding (Armstrong and Jackson-Smith [2]). The mutual exchange can help to overcome misunderstandings between the disciplinary perspectives (Hamann et al. [21]), and, on a different note, enhance the understanding for possible contributions of the other disciplines and thus open the floor for further collaborations. It also creates the communicative basis which is needed for the negotiation of the energy supply scenarios used in later stages of the process model.

The first stage in which true interdisciplinarity is visible in the working process, in the research methodology applied, and the publications, is stage three. Central benefits of interdisciplinary collaboration can be achieved during this stage, e.g., the widening of the horizon of the researchers involved, and the innovative potential through the combination of knowledge (Hamann et al. [21]). It differs from stage two in the fact that now, research questions are formulated and approached which can no longer be solved by one discipline alone, thus requiring multiple disciplines to closely collaborate. In this stage, bilateral teams of two different disciplines approach a common research topic and align their methodological approaches. In the KESS project, which is referred to as an exemplary project, the research questions at this stage concerned socio-economic, socio-technical and techno-economic issues. For example, it was investigated how hydrogen storage was perceived by laypersons and in how far this matched the technical realities (Zaunbrecher et al. [50]). In order for the data acquired during this stage to be usable across disciplines, the framework of the research has to be more closely defined, to ensure transferability and comparability of the data. Therefore, scenarios are defined by boundary parameters which define the research context for all disciplines involved, comprising, e.g. obligatory and optional components of the system and the specific technologies involved. It is also negotiated on which level of detail the analyses will be conducted, in order to ensure the resulting data are comparable. The specific scenarios used in the exemplary project and how they were derived from the requirements of the different disciplines are presented in Sect. 3.

In stage four, mature interdisciplinarity and elaborate communication between the disciplines is achieved. The research topic is approached using a multi-method approach, combining viewpoints, methods and approaches from all perspectives. It is an advancement to stage three because instead of bilateral teams, all disciplines involved in the research project now collaborate on a single research question. These joint efforts are supported by the ever increasing trust of the partners into the potential of the collaboration in terms of working quality and scientific merit. In the KESS project, the energy scenarios (defined in stage three) are evaluated from all involved perspectives in a parallel working process, in order to achieve a multidimensional evaluation of the scenarios, in which the different properties of the scenarios (technical, social, economic) can, in a final step, be weighted against each other. For the social acceptability, the evaluation could refer to a relative preference value for each scenario which will be derived using conjoint analysis (for a similar procedure see, e.g., Zaunbrecher et al. [51]). The degree of self-sufficiency of the investigated energy supply system scenarios is one example for a core criterion from a technical point of view. Another possible candidate for a technical criterion, focusing on the ecological impact, is the total amount of CO_2 emissions during an analyzed time period. The economic assessment, in turn, tries to optimize the monetary value of a proposed scenario. The predefined scenarios function as a baseline for the level of detail for the analysis. By attributing one value per perspective to each scenario, an interdisciplinary exchange about the overall suitability of a scenario is possible. Furthermore, trade-offs between the perspectives can be discussed (e.g., in which context should a socially acceptable scenario be preferred over an economically efficient one?). According to the combined evaluation from three perspectives, the scenarios can then, as a final step, be qualitatively ranked according to suitability.

Stage five represents the transferral of the interdisciplinary evaluation of the scenarios into practice (transdisciplinarity). In this stage, the results from stage four are operationalized in a tool which allows decision makers to gain insights into different suitable energy supply scenarios according to his needs. The technical, economic and social requirements towards the energy supply can be predefined and, on this basis, possible suitable scenarios are suggested. As a prerequisite, the multidimensional evaluation from stage 4 is needed. The tool would allow decision makers to enter framework conditions according to their local requirements. The tool would then, based on the framework conditions, suggest potential energy supply scenarios, which are characterized by technical, economic and social attributes. Besides being useful for planners, such a tool could enhance understanding of laypersons of planning procedures and conditions which need to be taken into account for the planning of large infrastructure projects. Similar approaches can be found in the context of urban green space planning (Grêt-Regamey et al. [19]) or wind power planning (Cavallaro [12], Gamboa and Munda [18]).

3 Definition and Integration of Energy Scenarios

Beginning at stage 3, specific scenarios were defined in an interdisciplinary exchange to help coordinate research paths and align the depth of the analyzed data. This was considered an essential step in order to be able to compare data from the different disciplines. While the research scenario was only loosely defined in the first stages, specific scenarios were formulated for the final stages of the research process.

The scenarios used for the exemplary case presented in this paper are set up in order to represent a mid-sized municipality with a high share of volatile renewable power generation. It is assumed that there a roughly 10,000 inhabitants living within the municipality and that the associated households are the predominant consumers of power. The result of these assumptions is an annual power consumption of 20 GWh. Regarding the set up of the renewable power generation within the municipality, all scenarios follow the concept of "integral autarky". This means that the number of installed renewable power generation capacities (i.e. wind turbines and photovoltaic panels) is chosen in a way that the corresponding annual power generation is equal to the annual municipal power consumption. This approach is not comparable to full autarky of the municipality due to the inevitable temporal mismatches between volatile renewable power generation and power consumption. In order to maintain the balance between power generation and consumption, the municipality can interact with the grid. Renewable power is fed into the grid in times of excess generation while power is supplied by the grid in times of residual demand. In addition, energy storage and conversion units are integrated into the scenarios (i.e. battery storage and hydrogen storage). These units are used to store and produce electricity on a local level, thus reducing the need for grid interactions.

Regarding the renewable power generation capacities, a reference year in the region of Aachen, a mid-sized city in Western Germany, is chosen to provide data for solar irradiation and wind speeds. For solar power, installation on rooftops was assumed rather than a solar park. Furthermore, the types of components used (i.e. wind turbines, solar panels, battery storage, hydrogen storage) are technically specified for the scenarios (Bexten et al. [4]).

3.1 Disciplinary Parameters and Scenario Requirements

Apart from the reference framework described above, each perspective had specific requirements for the definition of the scenarios.

Technical: From a technical point of view, the main purpose of the scenarios is the analysis of the interaction between renewable power generation capacities, local consumers, and dispatchable energy storage and conversion units within a municipal energy supply system.

On the one hand, these investigations focus on overall system performance parameters that are influenced by the interaction between the renewable power generation portfolio and the configuration of the dispatchable energy storage and conversion units. Investigated performance parameters include the self-sufficiency of the municipal energy supply system, the power exchange with the upstream transmission grid and the total CO_2 emissions of the system. The scenarios used for these investigations have to incorporate a wide range of diverse renewable power generation portfolios in order to capture the individual characteristics of wind and solar based renewable power generation like seasonal and short-term volatility. In addition, the scenarios also have to incorporate an extensive set of energy storage and conversion unit configurations in order to highlight the individual capabilities of the investigated technologies (e.g. short-term battery storage vs. long-term hydrogen storage).

On the other hand, the scenarios are used for a detailed analysis of the dispatchable units operation regarding the degree of utilization and the flexibility requirements. These investigations require information on the time-dependent dispatch and performance of the individual system components within the scenarios. To be able to include these aspects into the scenarios, high fidelity models of the components, incorporating part-load characteristics and operational flexibility parameters, have to be integrated into the overall model of a municipal energy supply system. This approach subsequently enables the detailed time-dependent simulation of the energy supply system operation within a predefined scenario after a corresponding operational strategy is defined.

Economic: Scenarios help to estimate costs and benefits of different asset portfolios in the economic assessment. In early stages, they support decisions such as either to focus on a calculation with total values (e.g., a Net Present Value analysis) or to head for relative values such as levelized costs of electricity (LCOE). Especially for the optimization of scenarios that compare technologies with very different shares of capital and operational costs and different life expectancies, or to account for different operational strategies, LCOE are often preferable. However, a holistic economic analysis should not only account for the monetary cost benefit analysis but should also consider aspects such as portfolio optimization, investment risks and the capital structure. To preclude technically unfeasible constellations, predefined scenarios can narrow down the scope for an economic optimization, but still the scenario with the highest expected return does not necessarily have to be the best advice or preferred option for a planner. This is due to the investment risk and the fact that many, typically rather risk averse decision makers, should search for a trade-off between profitability and risk (Madlener [37]). Scenarios with a strong focus on only one source of uncertainty (e.g. "only wind plants") are often more vulnerable to external factors and errors in the assumptions, whereas the versatile scenarios (e.g. "wind power, PV and battery storage") provide more reliable estimates leading to a lower investment risk. Or, to put it differently, a scenario with reliable returns might still be preferred to a highly speculative scenario even with lower average returns.

Social: For the analysis of the social acceptability of energy scenarios, it is indispensable that the scenarios which are to be evaluated are technically feasible, in order to ensure technical relevance of the acquired results. Also, whenever users are included with the task to engage themselves with the scenarios and evaluate the social acceptability, it is mandatory that the scenarios are actually realistic. Therefore, the technical feasibility of the scenarios needs to be determined as a first step (cf. methodological considerations in Zaunbrecher et al. [49]). This included the number and combination of infrastructural elements, in this case, electricity production and storage infrastructure. Furthermore, information on the specific local impact of the technical infrastructure, for example in terms of size, was needed, in order to explore questions of local visual impact of the infrastructure (McNair et al. [39], Johansson and Laike [27], Devine-Wright and Batel [16]). Further important information included technical consequences of combinations of components, such as the degree of self-sufficiency of the municipality, determined by the type and number of PV panels, wind turbines and storage technologies. These technical consequences can serve as potential trade-offs for laypeople in their evaluation of the scenarios (e.g., more self-sufficiency means more local storage infrastructure). Despite the necessity of some technical framework conditions, it had to be taken into account that the participants in the socio-psychological studies should not be overstrained with too many technical details that are outside of their level of knowledge and not relevant for social acceptance on a broad level of scale. For example, although technically relevant, it was determined that the specific technical components, in terms of particular products with technical performance data, need not be determined in detail for the use in social-psychological analyses. This is justified by the explorative nature of the research: As literature on the social acceptability of electricity storage technologies is still scarce, the goal of the analyses within the scope of the project was to gain a general understanding of acceptance-relevant parameters of electricity storage in general, not with relation to one specific model of an electricity storage facility. In order to present systematically varying scenarios to the participants, it was also necessary to define attributes of the scenarios which could be implemented in different variations (e.g., attribute "storage" could be implemented as battery storage, hydrogen storage, no storage etc.).

3.2 Final Scenarios

The final specifications of the scenarios (Table 1) were the result of a balancing process between the three perspectives described in the previous section. The scenarios varied in the renewable power generation portfolio and the type of local storage technologies. The decision to define different shares of wind and solar based renewable power generation was mainly influenced by technical and social considerations. The shares should correspond to integer numbers of the same type of wind turbines and solar panels to make the scenario feasible from a technical point of view. At the same time, there should be substantial differences between the scenarios (e.g., not 33% vs. 35%), so that the differences are relevant to laypersons and the different technical characteristics of wind and solar based power generation are highlighted. According to these requirements, shares of around 30/70 and 50/50 were chosen. The impact of the integration of electricity storage into the scenarios was operationalized by the differentiation between battery and hydrogen storage systems. It was refrained from including different technical specifications of the battery or hydrogen storage systems, as these differentiations were considered to be too detailed information for laypersons. The combination of these two factors resulted in 12 scenarios (Table 1), which are used in subsequent stages for interdisciplinary research approaches.

Table 1. Energy supply scenarios (Zaunbrecher et al. [53]).

Scenario	Electricity mix	No. wind turbines	No. PV modules	Storage
A1	73% wind, 27% PV	3	1025	No storage
A2	73% wind, 27% PV	3	1025	Battery storage
A3	73% wind, 27% PV	3	1025	Hydrogen storage
A4	73% wind, 27% PV	3	1025	Hydrogen + battery storage
B1	49% wind, 51% PV	2	1960	No storage
B2	49% wind, 51% PV	2	1960	Battery storage
B3	49% wind, 51% PV	2	1960	Hydrogen storage
B4	49% wind, 51% PV	2	1960	Hydrogen + battery storage
C1	24% wind, 76% PV	1	2695	No storage
C2	24% wind, 76% PV	1	2695	Battery storage
C3	24% wind, 76% PV	1	2695	Hydrogen storage
C4	24% wind, 76% PV	1	2695	Hydrogen + battery storage

3.3 Integration of Scenarios in Disciplinary and Interdisciplinary Research

The scenarios defined in Table 1 were used in disciplinary and interdisciplinary research approaches.

Technical: In a first approach, the described scenarios were used as input parameters for the simulation of the municipal energy supply system operation. The subsequent analysis of the simulation results mainly focused on the impact of the different predefined dispatchable energy storage and conversion units on the self-sufficiency of the overall system and the remaining power exchange with the upstream transmission grid (Bexten et al. [6]). In addition to the analysis from a technical point of view, the main findings of this study also served as input parameters for subsequent studies focusing on the social acceptance of the scenarios. Due to the fact that the simulation results indicated a high operational flexibility requirement by the gas turbine as part of the hydrogen storage system, additional investigations were conducted. These investigations focused on options to reduce the number of start-ups and fast load changes of the gas turbine by using additional battery storage capacity (Bexten et al. [5]).

In a following step, the scenarios were used as a framework for more detailed investigations regarding the capability of individual dispatchable units to enable a more efficient integration of the volatile renewable power generation capacities into the overall energy supply system. An example for this kind of investigations is an analysis of the potential of wind farm forecast error compensation by the utilization of flexible combined heat and power units (Bexten et al. [7]).

In future studies, the scope of the scenarios and the associated simulations will be extended to the municipal heat demand and the potential to provide the required heat with dispatchable units. This allows for the conduction of a wide range of studies within the rapidly growing research field of "sector coupling". Besides a number of technical research questions that can be answered using the extended scenarios (e.g. optimal use of heat storage capacities), an additional dimension is added to the studies focusing on the social acceptance of municipal energy supply systems.

In addition to the extension of the technical scope of the scenarios, future work will also focus on a closer link between the technical and the economic aspects of the scenarios. Previous studies mainly used simplified operational strategies and predefined configurations of the renewable power generations capacities and the dispatchable energy storage and conversion units. The planned integration of economic parameters (e.g. investment costs, operational costs) and corresponding optimization algorithms will enable the determination of optimized forecast-based control strategies as well as the composition of economically optimized system configurations.

Economic: To enable potential decision makers to evaluate the trade-off between risk and value, a pre-simulator was programmed. The goal was to minimize computational time for this simulator to be able to use it live in discussions with decision makers or activists. As input to this simulator, the parameters and limitations from the technical perspective had to be taken into account. While less precise than the technical simulation, this pre-simulator allows for a quick overview of the economic viability and risks of different technical generation portfolios, which can subsequently be addressed from a social perspective. The results can help to keep risk at a socially acceptable level without losing too much of the economic value. Besides of the quick pre-simulation, the technical simulator was also taken up as base for an advanced economic simulation. Adding costs and using the Monte Carlo simulation technique to account for uncertainties, we currently investigate their impact on the value distribution. Since the acquisition of national funding became more complicated and competitive with the recently introduced auctioning scheme in Germany, a further focus was put on the evaluation of different financing schemes. Several alternatives, such as a focus on green electricity certifications or municipal funding, are discussed as an alternative, depending on the pursued energy solution. This again goes hand in hand with social acceptance, since it is unlikely that, for example, a municipality would support a project that lacks support by the residents.

Social: The scenarios were used as a basis for various socio-psychological studies in close cooperation with the researchers from technical disciplines. In a first, exploratory approach, the scenarios were used in focus groups. Focus groups are organized group discussions, which serve the purpose to gain broad insights into attitudes, experience and motives of participants regarding a specific topic (Krueger [31]). The scenarios were used as an anchor in the discussions, using a scenario builder (Fig. 2), while the participants discussed not only the single components of the scenarios, but also discussed the differences between the scenarios. The scenarios further helped to introduce participants to a the situation where they were asked to imagine the energy supply of their hometown would be renewed and different options were available, because the scenarios were sufficiently concrete. The results of this stage of research included general acceptance-relevant parameters for the single components of the energy supply system (battery and hydrogen storage, wind power and PV), as well as dimensions for trade-offs between the scenarios. In a next step, acceptance for the scenarios was quantified by means of a conjoint analysis (Luce and Tukey [36]), in which the scenarios were decomposed into their single components. Participants could then state their preferences for combinations of components (energy supply scenarios), so that the relative, quantified preference for each energy supply scenario (defined in Table 1) could be calculated. In this way, the preference for a scenario from a social point of view can, on the one hand, be integrated as a boundary parameter in technical simulations, and, on the other hand, be compared side-by-side to technical and economic evaluations of the scenarios (cf. Stage 4 of the Process model).

4 Discussion

While the interdisciplinary approach, for which a process model is proposed in this paper, has many advantages when complex topics such as energy supply are addressed, the intensive collaboration required on different levels also has its drawbacks. In order to align their research interests and to ensure comparability and the ability to integrate data from the different disciplines, the representatives of the disciplines involved have to agree on a certain level of detail of the analysis, as, in this example, was done when the scenarios were defined. From the (still) relatively broad definition of the scenarios (Table 1), it becomes obvious that the interdisciplinary approach bears the cost of disciplinary detail. From an economic, technical or social perspective alone, the scenarios would have been defined differently, with a different level of detail in certain aspects. It could thus be argued that this approach results in a lack of depth of analyses (Hamann et al. [21]). In order to counterbalance this caveat, continued disciplinary approaches, in addition to the more general, interdisciplinary analyses, are necessary. In this way, the level of detail which cannot be covered by interdisciplinary approaches can be tackled by more detailed, disciplinary approaches while at the same time providing a level of detail regarding the data which can still be used for integration with other disciplines.

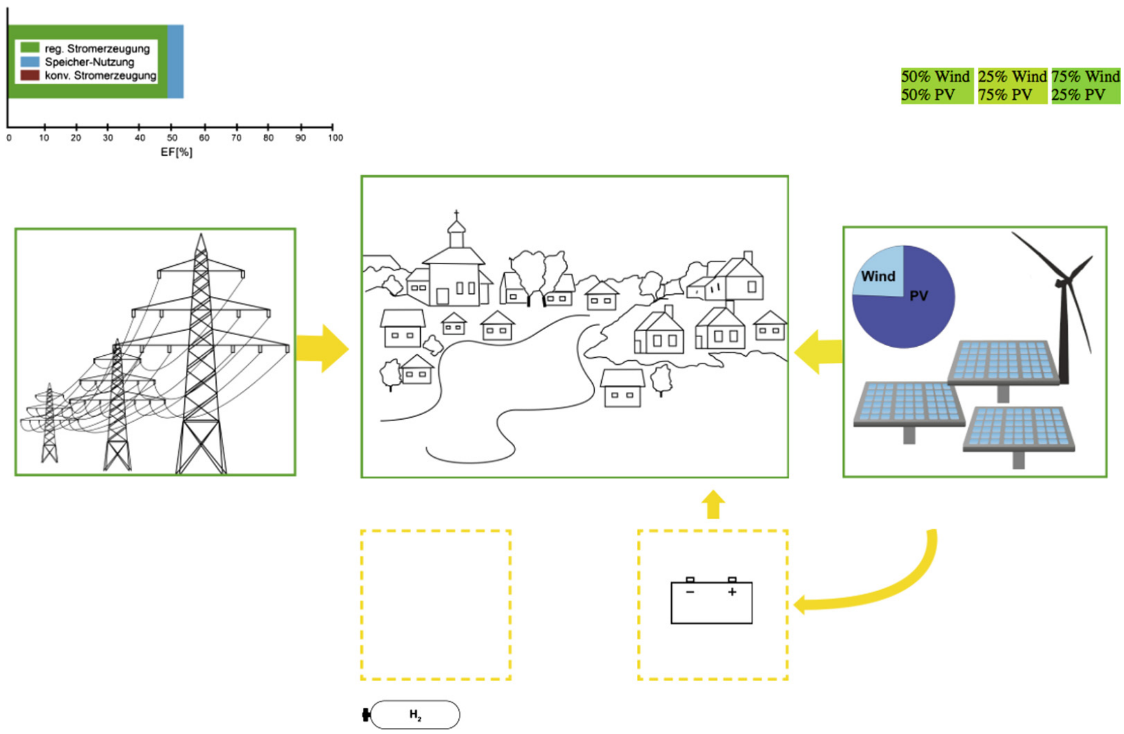

Fig. 2. Scenario builder for social acceptance studies (Zaunbrecher et al. [53]).

Regarding the transferability of the process model to other research projects, some limitations need to be mentioned. An advantage of the KESS project was the fact that all members of the research project were based at the same university, so that institutional barriers were probably lower as if different organizations had been involved (Cummings and Kiesler [13]). Moreover, while the model can provide some guidelines for interdisciplinary research projects, its application cannot guarantee the success of interdisciplinary collaborations. This might be subject to the research topic (content) of the project, the disciplines involved, or even the researchers themselves (Rhoten and Pfirman [41]).

While it is increasingly acknowledged that interdisciplinarity should be the methodological approach to address complex problems, and that it presents a core academic competence (Boddington et al. [8]), education at universities does not systematically incorporate interdisciplinarity as an inherent component of content-related questions across disciplines. It should therefore be an aim to “train future scholars and professionals to think way beyond the confines of their basic disciplines to attain the broadest perspectives so urgently needed for environmental protection.” (Brewer [10]:333). Novel modules in different faculties, in which interdisciplinary methods are interlinked with content related questions to teach multiperspective problem solving, could address this need. First evaluations of such courses have shown the potential to change students’ mindsets and promote openness towards interdisciplinary collaborations (Drezek et al. [17]).

5 Conclusions

The paper has presented an example of how interdisciplinary research in the field of energy supply can be achieved using a step-wise process model which shows how researchers from different disciplines can interact with each other to move on from multidisciplinary research, in which the disciplines are still separated from each other, to truly integrated, interdisciplinary research. Energy supply scenarios can help in this process to align research interests, and to provide a basis for mutual data integration. As an advantage of this research approach, the enabling of close cooperation as well as the communication about requirements and goals, and a common level of detail were achieved. As a disadvantage, the possible lack of detail of the analyses was identified, along with measures to counterbalance this development. While the model is generally applicable to other research projects, it should not be taken as a guarantee for successful interdisciplinary research, as this depends on multiple factors.

Acknowledgements. A previous version of this paper was presented at the 7th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS) (Zaunbrecher et al. [53]). Special thanks go to the KESS project members for the fruitful discussions which have contributed and led to this paper. Thanks also to Dr. Klaus Baier, Julian Halbey, Iana Gorokhova and Saskia Ziegler for research support. The “KESS” project conducted at RWTH Aachen University is funded by the strategic funds of the Excellence Initiative of the German federal and state governments.

References

1. Aboelela, S.W., et al.: Defining interdisciplinary research: conclusions from a critical review of the literature. Health Serv. Res. **42**(1), 329–346 (2007)
2. Armstrong, A., Jackson-Smith, D.: Forms and levels of integration: evaluation of an interdisciplinary team-building project. J. Res. Pract. **9**(1), 1–20 (2013)
3. Baxter, J., Morzaria, R., Hirsch, R.: A case-control study of support/opposition to wind turbines: perceptions of health risk, economic benefits, and community conflict. Energy Policy **61**, 931–943 (2013)
4. Bexten, T., et al.: Modellbasierte Analyse der Auslegung und des Betriebs kommunaler Energieversorgungssysteme [Model-based analysis of the design and operation of municipal energy supply systems]. In: 14th Symposion für Energieinnovation, EnInnov 2016, Graz, Austria, 10–12 February 2016 (2016)

5. Bexten, T., et al.: Einfluss betrieblicher Flexibilitätsparameter einer Gasturbine auf Auslegung und Betrieb eines dezentralen Energiever- sorgungssystems [Influence of flexibility parameters of a gasturbine on design and operation fo a municipal energy supply system]. In: Kraftwerkstechnik 2016: Strategien, Anlagentechnik und Betrieb, Saxonia, pp. 541–552 (2016)
6. Bexten, T., et al.: Impact of dispatchable energy conversion and storage units on the electrical autarky of future municipal energy supply systems. In: Proceedings of the International Renewable Energy Storage Conference, IRES, Düsseldorf, Germany (2017)
7. Bexten, T., et al.: Techno-economic study of wind farm forecast error compensation by flexible heat-driven CHP units. In: Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017, GT 2017-63555, Charlotte, NC, USA, 26–30 June 2017 (2017)
8. Boddington, A., Kermik, J., Ainsworth, T.: Interdisciplinary design in the college of arts and humanities at the university of Brighton. In: Banerjee, B., Ceri, S. (eds.) Creating Innovation Leaders. UI, pp. 239–254. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-20520-5_15
9. Bouffard, F., Ortega-Vasquez, M.: The value of operational flexibility in power systems with significant wind power generation. In: Power and Energy Society General Meeting. IEEE (2001)
10. Brewer, G.D.: The challenges of interdisciplinarity. Policy Sci. **32**(4), 327–337 (1999)
11. Bronfman, N.C., Jiménez, R.B., Arévalo, P.C., Cifuentes, L.A.: Understanding social acceptance of electricity generation sources. Energy Policy **46**, 246–252 (2012)
12. Cavallaro, F., Ciraolo, L.: A multicriteria approach to evaluate wind energy plants on an Italian island. Energy Policy **33**(2), 235–244 (2005)
13. Cummings, J.N., Kiesler, S.: Collaborative research across disciplinary and organizational boundaries. Soc. Stud. Sci. **35**(5), 703–722 (2005)
14. Cummings, J.N., Kiesler, S.: Who collaborates successfully?: prior experience reduces collaboration barriers in distributed interdisciplinary research. In: Proceedings of the 2008 ACM Conference on Computer Supported Cooperative Work, pp. 437–446. ACM (2008)
15. Federal Ministry for Economic Affairs and Energy (BMWi): State Secretary Baake: "Citizens' energy" wins first onshore wind auction, 19 May 2017. https://www.bmwi.de/Redaktion/EN/Pressemitteilungen/2017/20170519-staatssekretaer-baake-buergerernergie-gro%C3%9Fe-gewinner-der-ersten-ausschreibungsrunde-wind-an-land.html. Accessed 10 July 2017
16. Devine-Wright, P., Batel, S.: Explaining public preferences for high voltage pylon designs: an empirical study of perceived fit in a rural landscape. Land Use Policy **31**, 640–649 (2013)
17. Drezek, K.M., Olsen, D., Borrego, M.: Crossing disciplinary borders: a new approach to preparing students for interdisciplinary research. In: Proceedings of the 38th ASEE/IEEE Frontiers in Education Conference, pp. F4F1–F4F6. IEEE (2008)
18. Gamboa, G., Munda, G.: The problem of windfarm location: a social multi-criteria evaluation framework. Energy Policy **35**(3), 1564–1583 (2007)
19. Grêt-Regamey, A., Celio, E., Klein, T.M., Hayek, U.W.: Understanding ecosystem services trade-offs with interactive procedural modeling for sustainable urban planning. Landsc. Urban Plan. **109**(1), 107–116 (2013)
20. Gross, C.: Community perspectives of wind energy in Australia: the application of a justice and community fairness framework to increase social acceptance. Energy Policy **35**(5), 2727–2736 (2007)

21. Hamann, T., Schaar, A.K., Calero Valdez, A., Ziefle, M.: Strategic knowledge management for interdisciplinary teams - overcoming barriers of interdisciplinary work via an online portal approach. In: Yamamoto, S. (ed.) HIMI 2016. LNCS, vol. 9735, pp. 402–413. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-40397-7_38
22. Hirsh, R.F., Sovacool, B.K.: Wind turbines and invisible technology: unarticulated reasons for local opposition to wind energy. Technol. Cult. **54**(4), 705–734 (2013)
23. Holbrook, J.B.: What is interdisciplinary communication? Reflections on the very idea of disciplinary integration. Synthese **190**(11), 1865–1879 (2013)
24. Holttinen, H.: Impact of hourly wind power variations on the system operation in the Nordic countries. Wind Energy **8**(2), 197–218 (2005)
25. Huijts, N.M., Molin, E.J., Steg, L.: Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. Renew. Sustain. Energy Rev. **16**(1), 525–531 (2012)
26. Jacobs, J.A., Frickel, S.: Interdisciplinarity: a critical assessment. Annu. Rev. Sociol. **35**, 43–65 (2009)
27. Johansson, M., Laike, T.: Intention to respond to local wind turbines: the role of attitudes and visual perception. Wind Energy **10**(5), 435–451 (2007)
28. Jungert, M.: Was zwischen wem und warum eigentlich? Grundsätzliche Fragen der Interdisziplinarität [What between whom and why? General questions of interdisciplinarity]. In: Interdisziplinarität, Theorie, Praxis, Probleme, pp. 1–12. Wissenschaftliche Buchgesellschaft, Bamberg (2011)
29. Krewitt, W., Nitsch, J.: The potential for electricity generation from on-shore wind energy under the constraints of nature conservation: a case study for two regions in Germany. Renew. Energy **28**(10), 1645–1655 (2003)
30. Krohn, W.: Interdisciplinary cases and disciplinary knowledge. In: The Oxford Handbook of Interdisciplinarity, pp. 31–49. Oxford University Press (2010)
31. Krueger, A.: Focus Groups: A Practical Guide for Applied Research. Sage, Thousand Oaks/London/New Delhi (1994)
32. Langer, K., Decker, T., Menrad, K.: Public participation in wind energy projects located in Germany: which form of participation is the key to acceptance? Renew. Energy **112**, 63–73 (2017)
33. Lattuca, L.R.: Learning interdisciplinarity: socio-cultural perspectives on academic work. J. High. Educ. **73**(6), 711–739 (2002)
34. Lélé, S., Norgaard, R.B.: Practicing interdisciplinarity. BioScience **55**(11), 967–975 (2005)
35. Liebe, U., Bartczak, A., Meyerhoff, J.: A turbine is not only a turbine: the role of social context and fairness characteristics for the local acceptance of wind power. Energy Policy **107**, 300–308 (2017)
36. Luce, R.D., Tukey, J.W.: Simultaneous conjoint measurement: a new type of fundamental measurement. J. Math. Psychol. **1**(1), 1–27 (1964)
37. Madlener, R.: Portfolio optimization of power generation assets. In: Zheng, Q., Rebennack, S., Pardalos, P., Pereira, M., Iliadis, N. (eds.) Handbook of CO_2 in Power Systems. ENERGY, pp. 275–296. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-27431-2_12
38. Marg, S., Hermann, C., Hambauer, V., Becke, A.B.: Wenn man was für die Natur machen will, stellt man da keine Masten hin [If you want to help nature, you don't build pylons in it]. In: Die neue Macht der Bürger: Was motiviert die Protestbewegungen? BP-Gesellschaftsstudie, pp. 94–138. Rowohlt (2013)
39. McNair, B.J., Bennett, J., Hensher, D.A., Rose, J.M.: Households' willingness to pay for overhead-to-underground conversion of electricity distribution networks. Energy Policy **39**(5), 2560–2567 (2011)

40. Raven, R.P., Mourik, R.M., Feenstra, C.F.J., Heiskanen, E.: Modulating societal acceptance in new energy projects: towards a toolkit methodology for project managers. Energy **34**(5), 564–574 (2009)
41. Rhoten, D., Pfirman, S.: Women in interdisciplinary science: exploring preferences and consequences. Res. Policy **36**(1), 56–75 (2007)
42. Schweizer, P.J., et al.: Public participation for infrastructure planning in the context of the German "Energiewende". Util. Policy **43**, 206–209 (2016)
43. Songsore, E., Buzzelli, M.: Social responses to wind energy development in Ontario: the influence of health risk perceptions and associated concerns. Energy Policy **69**, 285–296 (2014)
44. Wiedemann, P.M., Boerner, F., Claus, F.: How far is how far enough? Safety perception and acceptance of extra-high-voltage power lines in Germany. J. Risk Res. **21**(4), 463–479 (2018)
45. Wilson, G.: The world has problems while universities have disciplines: universities meeting the challenge of environment through interdisciplinary partnerships. J. World Univ. Forum **2**(2), 57–62 (2009)
46. Wolsink, M.: Wind power implementation: the nature of public attitudes: equity and fairness instead of 'backyard motives'. Renew. Sustain. Energy Rev. **11**(6), 1188–1207 (2007)
47. Wüstenhagen, R., Wolsink, M., Bürer, M.J.: Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy **35**(5), 2683–2691 (2007)
48. Zaunbrecher, B.S., Ziefle, M.: Integrating acceptance-relevant factors into wind power planning: a discussion. Sustain. Cities Soc. **27**, 307–314 (2016)
49. Zaunbrecher, B., Arning, K., Falke, T., Ziefle, M.: No pipes in my backyard? Preferences for local district heating network design in Germany. Energy Res. Soc. Sci. **14**, 90–101 (2016). https://doi.org/10.1016/j.erss.2016.01.008
50. Zaunbrecher, B.S., Bexten, T., Wirsum, M., Ziefle, M.: What is stored, why, and how? Mental models, knowledge, and public acceptance of hydrogen storage. Energy Proc. **99**, 108–119 (2016)
51. Zaunbrecher, B., Linzenich, A., Ziefle, M.: A mast is a mast is a mast...? Comparison of preferences for location-scenarios of electricity pylons and wind power plants using conjoint analysis. Energy Policy **105**, 429–439 (2017). https://doi.org/10.1016/j.enpol.2017.02.043
52. Zaunbrecher, B.S., Linzenich, A., Ziefle, M.: Experts and laypeople's evaluation of electricity storage facilities: implications for communication strategies. In: Proceedings of the International Renewable Energy Storage Conference, IRES, Düsseldorf, Germany (2017)
53. Zaunbrecher, B., Bexten, T., Specht, J.M., Wirsum, M., Madlener, R., Ziefle, M.: Using scenarios for interdisciplinary energy research. A process model. In: 6th International Conference on Smart Cities and Green ICT Systems, Smartgreens 2017, pp. 293–298. SCITEPRESS - Science and Technology Publications (2017). https://doi.org/10.5220/0006355702930298
54. Zoellner, J., Schweizer-Ries, P., Wemheuer, C.: Public acceptance of renewable energies: results from case studies in Germany. Energy Policy **36**(11), 4136–4141 (2008)