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Development of Scenarios for a Multi-Model System Analysis Based on the Example of a Cellular Energy System

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Abstract: Scenario analysis combined with system and market modelling is a well-established method to evaluate technological and societal developments and their impacts on future energy pathways. This paper presents a process-oriented method for developing consistent energy scenarios using multiple energy system models. Its added value is that the developed energy scenarios are consistent in a multi-model environment and practicable for a broader target group from scientists to practitioners. The scenarios consist of comprehensive storylines and systematically defined quantitative parameters. Following a step-by-step process, a condensed set of overlapping descriptors is generated and used to define the scenarios in a consistent parameter matrix. The set of descriptors allow consistent and comparable outputs independent of model-specific characteristics. The corresponding quantitative parameters can be used by diverse energy system tools. Using multiple models, a team of researchers can explore questions from differing points of view. In an example study, we apply the method to develop scenarios in the context of a cellular energy system. This approach enables the development of scenarios that provide a consistent basis for both stakeholder discourse and multi-model system analysis.

Keywords: scenario development; multi-model analysis; cellular energy systems; energy system modelling

1. Introduction

This paper presents a generic method for developing scenarios in a multi-model research environment. The method meets two important requirements for scenario analyses. Firstly, it describes probable future developments using a storyline approach. This enables heterogeneous groups of stakeholders with different background knowledge to comprehend, discuss and evaluate the research questions. Secondly, the approach permits consistent modelling with different types of models by deriving a set of quantitative descriptors that meets the requirements of scientific analysis. The parameters are determined in accordance with the descriptors in a step-by-step process that combines a qualitative storyline with quantitative modelling. This procedure enables modellers working in a cooperative project to analyse the specific research question in a comparable and transparent way.

The proposed method can be used to develop energy scenarios in a customised and practicable way that feature qualitative, comprehensive storylines and quantitative input parameters suitable for energy system models (1). It renders multiple models capable of evaluating a research question collaboratively (2) while addressing a specific aspect of energy system research (3). We demonstrate this by applying our method to a scenario for the evaluation of cellular energy systems.

Why is scenario development important for energy system research? Scenarios are a useful tool to analyse options and conditions with high variability and uncertainty, e.g., long-term transition pathways or costly investments [1]. Regarding energy systems, the decarbonisation of today's electricity generation represents a fundamental transformation. Key elements of this energy transition include the phasing out of fossil-based energy sources, increasing energy efficiency at all levels of energy conversion, introducing decentralised renewable power plants [2] and promoting regional energy infrastructures that focus particularly on stakeholder participation [3]. In light of the many options and variables in the energy system—many of them subject to fundamental changes—it is difficult to forecast specific developments [4]. Therefore, it is necessary to identify possible pathways and alternatives [4]. Scenario development and analysis is one way of putting potential developments into context and analysing their implications. In order to analyse the various energy transition pathways and their implications, scenarios are a common and suitable tool that enables a structured debate with the involved stakeholders and institutions [5]. When doing so, not only the desired process of transition but also the desired future state is taken into account to identify supportive or obstructive path dependencies and effects due to long-lived investments [6]. Since scenarios are also used to support structured decision making [5], energy scenario debates aim at defining a range of possible alternative futures, but also at drawing the attention of stakeholders to the drivers and causalities that lead to different outcomes [7,8].

Scenario development is also a core component of energy system analysis and is considered more viable than a linear extrapolation of trends [9]. It is thus closely linked to energy system modelling [10]. Energy system models are a standard instrument used to analyse the impacts of possible evolutions of an energy system. They facilitate the understanding of pathways to a future with high levels of uncertainty and of interactions between various elements of the energy system [9,10]. Therefore, combining energy scenarios and energy system modelling allows a qualitative and quantitative interpretation of future developments of the energy system.

Developing possible quantitative and qualitative images of the future requires the systematic application of scenario techniques and methods [11]. Conducting scenario development systematically is indispensable, but time-consuming [10]. The resulting scenarios reflect a range of visions for the future, but are often abstract and unspecific, making it difficult to use them directly in energy system models. Many studies, in contrast, consider scenarios merely as a way to parameterise models [12].

Thus, there is the need for a pragmatic approach that combines clear visions of the future energy system, which are easy for all stakeholders to understand, with the use of models able to calculate quantitative pathways to different future states. Since an integrated approach using only a single model can hardly capture all the important aspects [13], it seems more suitable to use multiple models focussing on different aspects of the energy system to provide answers within a complex setting of uncertain conditions. By using multiple models, modellers can benefit from complementary aspects and from analysing differences between the models [14]. Using and comparing the results of multiple models, however, demands a common and consistent set of scenarios. The method presented here develops a scenario set using a generic approach that can be applied to different research questions regarding the energy landscape.

We apply the method to develop scenarios for evaluating concepts related to "cellular" energy systems. By applying the method, a framework scenario is created in which the claimed benefits of a cellular energy system can be analysed and weighed against its drawbacks. This allows to evaluate the following research question: To what extent are cellular energy systems suitable and favourable in different scenarios of energy system development?

Cellular energy systems are a type of decentralised energy system [15]. Decentralised energy systems (often also referred to as distributed or embedded energy systems [16,17]) are characterised by small electricity sources or storages that are relatively independent of the main electricity supply chain [18,19]. Generation is supposed to occur close to demand in order to reduce network losses compared to centralised systems [20,21]. Decentralised energy systems are associated with benefits such as avoiding greenhouse gas (GHG) emissions due to their focus on renewable energy sources (RES) [22]. Additionally, it is claimed that decentralised energy generation enhances system security and reliability due to the widespread distribution of electricity sources, which makes the electricity system less vulnerable and complex [22]. From a socioeconomic perspective, decentralised energy systems can promote the local value and job creation and increase the environmental commitment of local actors [23,24] while strengthening local identity [25]. However, decentralised energy systems also have drawbacks such as higher costs, e.g., due to reduced economies of scale [22], more storage capacity needed [26] and less efficient use of resources if suboptimal locations for RES are used to increase regional renewable electricity generation [27].

Cellular energy systems feature many characteristics of decentralised systems, such as the generation and distribution of electricity on a regional or even local level [15]. However, in cellular energy systems, there is an emphasis on organising the balancing of demand and supply autonomously on a regional level before any interaction with adjacent cells or superordinate entities [15,28]. The cellular approach can be used for different areas in the energy system: Market areas, electricity grids or the connection and control of flexibility options [29].

This paper is structured as follows. First, we provide a theoretical background on the development of different scenarios in environmental and energy system research as well as methods of scenario development (Section 2.1). Additionally, we present models used for scenarios and energy system research, looking particularly at multi-model approaches (Section 2.2). We also explain the drivers for developing the approach presented here and identify the target group for which the approach proposed here can prove to be beneficial (Section 2.3). In the section on methodology, we explain the challenges in the scenario development process and describe the steps of the method in more detail (Section 3). In Section 4, we apply our scenario development method to an analysis of cellular energy systems. The resulting scenario allows the combined and consistent multi-model analysis of cellular energy systems. Finally, the presented approach is critically reflected (Section 5), followed by concluding remarks (Section 6).

2. Background and Motivation

2.1. Scenarios and Scenario Development in Energy Research

Different images of the future state of the energy system and options derived from them shape attitudes in society, and today's political and economic decisions [5]. Conversely, today's decision-making affects future pathways [5]. Thus, developing objective and consistent scenarios is very important for decision-making in fields like environmental and climate research, but also in the field of energy system research.

As scenario planning has existed for more than 60 years, there are multiple definitions and types of scenarios [30]. In Kahn and Wiener's [31] frequently used definition, scenarios are described as "hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points". This already underlines the importance of identifying decisive factors that influence the future, as explicitly expressed in [32].

Many authors, such as [32,33], mention the concept of (alternative) "images of the future" when explaining scenarios—as opposed to extrapolating trends and making prognoses. In contrast, Rotmans et al. declare that not only the future state or "snapshot" of a system is important in scenario planning, but that the pathway (scenarios as "dynamic movies" or "sequences of images") developed to reach it and the drivers leading to a pathway are equally significant [7].

In our case, the terminology is less important. Our focus is on the approach used to develop scenarios and the conception of a method for pathways on the one hand, and on "causal processes" [31] or "identifying factors" [32] on the other hand.

There are many scenario development methodologies for qualitative scenarios that have already been reviewed by several authors [6,34–37]. The methodologies can be categorised by the type of scenario they produce. However, they all systematically follow certain steps in an interactive way.

They start by defining a goal for the scenarios then put together knowledge and identify influencing factors to create different, consistent and alternative visions of the future [34,38]. Reibnitz presents a scenario development process consisting of eight steps [11]. It begins with the definition of an objective. In the subsequent steps, the weaknesses and strengths of a field are analysed, and areas of influence are identified in order to create scenario alternatives. The method explicitly includes disruptive events and the deviation of strategies from the scenarios. Several tools are used within the method's eight steps, e.g., consistency matrices [11,34]. Godet and Roubelat [39] develop a toolbox, which combines multiple instruments (workshops, Delphi, cross-impact analysis, multi-criteria decision analysis) to construct scenarios and long-term planning strategies. The various tools aim at identifying key variables and consider trends and actors. Subsequently, tools are applied in order to create scenarios from the gathered information and to assess options [39].

As energy production is embedded in a complex network of dependencies and interactions and associated with high uncertainties and costs, it is a field in which a multitude of scenarios have been created [5]. In many of them, scenarios are developed using computational modelling as a core element. Table 1 shows selected scenarios in climate and energy research. The table does not claim to be comprehensive but gives an overview of prominent scenarios that have contributed significantly to developing the method. On the basis of the scenarios listed in Table 1, we also conduct a classification of existing energy scenarios (see Section 2.3).

While early scenarios like the first and second Report to the Club of Rome [40,41] were motivated by examining the drivers of resource depletion, from the late 1970s, studies like Leontief et al. [42] were already quantifying the environmental impacts caused by the need for energy if the world's economy grew in line with the scenarios proposed by the authors. Others, such as Häfele et al., already proposed pathways to a sustainable energy system concerning primary energy sources and secondary energy carriers [43]. A quantitative approach is common to all the scenarios mentioned, although the models applied were less complex than those used today.

From the 1990s, researchers working in the framework of the IPCC started developing and computing climate scenarios and making corresponding impact assessments. The first of them were the "SA90 Scenarios", which developed a set of four emission pathways [44]. These were followed by the "IS92 Scenarios", six scenarios quantifying the effects of different paths concerning population, economic growth and technology development [45].

In order to integrate the advantages of qualitative elements, many well-known energy and climate scenarios also include qualitative narratives in their approach. The IPCC, for example, expanded its approach for the "Special Report on Emission Scenarios" (SRES, [46]) by combining qualitative elements with quantitative models. The report consists of 40 scenarios built on four narratives [47]. In its more recent scenarios, the IPCC has integrated qualitative and quantitative elements as well but has extended its scenario development method even further, as it aims to address the interdependencies between human decisions, the climate system and climate impacts [48]. The process of developing the method and the corresponding scenarios was organised as a participatory approach instead of through the framework of an IPCC Special Report [48,49]. This led to an extensive method, which was first reviewed and explained by Moss et al. [49] and described in detail in two different special issues [48,50]. The first special issue by van Vuuren et al. introduced a set of four pathways defining GHG concentrations, the so-called "Representative Concentration Pathways" (RCPs) [51] and then quantified them in a set of four papers, which again were supported by four papers. In the second special issue by Nakicenovic et al., the RCPs were combined with socioeconomic pathways (SSP) and shared policy assumptions (SPA) [48]. The SSPs can be seen as storylines describing trends in the evolution of society and natural systems on a global scale [52]. SPAs, specifically defined in reference [53], summarise policy goals, instruments and political challenges.

Table 1. Overview of scenarios in the field of environment and energy.

Year	Name of Scenario	Content	Reference
1972 and 1974	1st and 2nd Report to the club of Rome	Futures studies, which explored the long-term sustainability of natural resources	[40,41]
1976	The future of the world economy	Global projection of the economy using a mathematical model	[42]
1981	Energy in a finite world	Sustainability of natural resources in the long term	[43]
1990	IPCC SA90	Common population projection and two alternative economic development paths	[44]
1992	IPCC IS92	6 scenarios quantifying different paths concerning population, economic growth and technology development	[45]
1995	IPCC Special Report	Evaluation of different emissions scenarios	[54]
1996	IPCC Special Report on Emissions Scenarios (SRES)	40 scenarios based on four qualitative storylines	[46]
2001	IPCC Third Assessment Report (TAR)	80 GHG stabilisation scenarios based on SRES cases	[55]
Since 1977	IEA World Energy Outlook	Quantitative scenarios focusing on the worldwide energy system	[56,57]
Since 1938	World Energy Council	Quantitative scenarios focusing on the worldwide energy system using storytelling	[58]
Since 1972	Shell Scenarios	Worldwide scenarios covering the whole economy. Focus on storytelling	[59–61]
2016	EU Reference scenario 2016	EU energy system, transport and GHG emission trends to 2030	[62]
2019	REFLEX	Analysis of the European energy system, particularly considering flexibility and technological progress	[63]

While the IPCC scenarios focus on environment and climate change and are thus less detailed with regard to aspects of the energy system, others like the World Energy Outlook [56], the World Energy Scenarios [58] or the EU Reference Scenario [62] use climate scenarios as a basis for more detailed scenarios that focus specifically on the energy system.

Although the scenarios presented above have a quantitative emphasis, many recent energy scenarios have in common that a storyline is included as a supplement or even as their main component (e.g., in the case of the Shell Scenarios [60]). Storylines can be used as one part of the scenario development process to tackle complex energy questions [64] and facilitate discourse among stakeholders. Miller et al. [64] argue that approaches based on narrative strategies are a valuable tool for enhancing societal capacity to meet governance challenges. Nevertheless, Rounsevell and Metzger [65], who made a comparative summary of scenario storyline methods, emphasise that there is a large divergence between studies even within the same scenario storyline group.

Since qualitative and quantitative approaches both have strengths and shortcomings, numerous recent scenarios combine these two approaches [66,67]. Alcamo refers to the meaningful combination of qualitative narratives with quantitative modelling as a "Storyline and Simulation approach" (SAS, [68]). According to Alcamo, combining the two can improve the relevance of scenarios, their credibility (as it combines computer modelling with qualitative methods) and legitimacy, because stakeholders can be involved more easily [68]. The drawbacks concern how to integrate qualitative storylines into quantitative models and the fact that this approach can prove time-consuming [67].

2.2. Multi-Model Energy System Modelling and Model Comparison Approaches

Many of the scenarios presented above rely on models to analyse pathways to the future. For this reason, this section is devoted to examining the energy system models used for scenario analysis. There is a broad range of models within the energy modelling community and published in scientific papers. Since these models focus on distinct aspects of the energy system (technologies, markets, regulatory framework), they possess different strengths. This is why they are sometimes combined to answer specific research questions. Comparing their results can provide particular insights. However, it is difficult to compare the results obtained from different models, because they differ with regard to input data and the definition of the evaluated concepts and parameters.

According to Möst and Fichtner [69], energy system models can be categorised with regard to planning horizon, aggregation level, spatial resolution or modelling approach. Alternatively, they can be clustered into groups according to the research focus set: Energy system optimisation models, energy system simulation models, power system and electricity market models, and qualitative and mixed-methods models [10]. Energy system optimisation models are used to describe "possible evolutions of the energy system", which are optimal under given restrictions [10]. Examples include the model family of "MARKAL/TIMES" [70,71] or the "World Energy Model" used by the IEA [56]. Optimisation models describe how a system evolves under given conditions and when optimising a particular aspect, such as costs. Simulation models, on the other hand, examine the effect of a change in one part of the energy system to tell us "what could be" to reach a certain goal [72]. Their focus is on how a system may evolve [10]. Additionally, it is possible to consider actor behaviour in the simulation process, as demonstrated in the model "PowerACE" [73,74]. Electricity market models are used for decision-making in utilities due to their ability to consider effects in electricity markets.

Beyond and within these methodological categories, energy system models can differ from each other in many ways, such as the technologies considered, or their spatial or temporal resolution. Other distinctions can be made regarding the degree of detail of different sectors (such as heat and transport), or whether only generation facilities or additional grid infrastructure or demand technologies are considered. Thus, each model is suitable for a specific range of research questions. Savvidis et al. [75] describe a metric to quantify the usability of energy models for specific policy research questions. The analysis shows that only some models are suitable for a wide field, while others cannot answer (or only answer a few of) a set of research questions, which does not rule out their applicability to more specific tasks. As there are differences in the models' structure or assumptions, the models' results may vary even when applied to the same research question. This can also be caused by a lack of transparency or standardisation [75].

When it is necessary to combine the advantages of complementary models for a broader focus and to cover a larger part of the energy system, model coupling may be appropriate [76]. Models are coupled by integrating one model's output into another model's calculations. With this approach, also referred to as soft-linking [13], models do not have to be merged or integrated to benefit from their combined individual strengths. The model coupling has been successfully applied in numerous research projects. According to Mehigan et al., this could also be a useful tool when evaluating decentralised (or in our case cellular) energy systems [13].

Different models can, however, also be used to assess the same research question. In this case, additional value is generated by comparing the modelling results of models with an overlapping scope. If the aim is to make joint statements, a high level of transparency is essential in order to interpret deviations between results. A review of recent experiments with multiple models (e.g., references [77,78]) shows that development of scenarios with a framework that accounts for the participating models and their technical requirements is advisable to ensure the comparability of the results. In some cases, a joint analysis of the models helps to answer specific research questions. A harmonised scenario basis supports further analysis of the results. Finally, many studies conclude that a procedure for comparing the results should be defined in advance in order to facilitate the evaluation [78]. However, it is important to limit the effort required.

2.3. Categories of Scenario Development and the Need for a New Approach

Having analysed scenarios, scenario development methods and the use of models in scenarios, we can identify three categories of scenario development approaches. They differ particularly in the motivation behind the development scenarios and the corresponding methodological focuses.

1. **Global, comprehensive expert scenarios** that combine a multitude of scientific disciplines.
   These scenarios, such as those of the IPCC reports, are often well known since they address global issues. They focus on applying methods or even developing new methods to ensure that they meet certain quality standards and guidelines, which are frequently defined in the first stage of the study. Quality standards include consistency, reproducibility, relevance (as many stakeholders from a multitude of disciplines are involved) and legitimacy. These global, high-level expert scenarios are both quantitative and qualitative. Examples include [46,62,79]. The drawback of these scenarios is that their development is very time-consuming, resource-intensive and thus costly. Due to their broad scope, they often remain superficial in terms of reflecting detailed trends in specific sectors as well as analysing financial implications and regulations.
2. **Pure storytelling scenarios that focus on developing images of the future**, e.g., for a certain sector.
   These scenarios focus on qualitative elements and narratives in order to define a possible span of pathways to the future and describe the different drivers and technologies behind the development of these pathways. Examples include [60,80]. While qualitative methods are pursued thoroughly, the use of complex quantitative models and proving that they are consistent is secondary.
3. **Detailed modelling research scenarios** for more profound analyses.
   This kind of research, often organised in research projects, uses scenarios as the background to allow models to compute more detailed aspects and research questions, such as the security of supply or market options in very specific regions [63,78,81,82]. Researchers in this field often use established scenarios [62,79] as the basis for a more detailed scenario framework, because it is beyond their research focus or financial resources to apply the strict methods necessary to develop their own scenarios.

Although the three categories identified cover a wide range of scenario development approaches, none of them meets all the requirements of our project. The research in this paper is part of the demonstration project "C/sells", in which more than 60 institutions examine a cellular energy system, exploring questions such as market design and regulatory framework as well as the technical feasibility and implementation of a decentralised system in a future energy system. The multi-model/multi-perspective context requires a consistent framework, in which the models can be embedded.

The mainly quantitative analysis is carried out from multiple perspectives. Therefore, a multi-model approach using five different models is chosen to answer to a broad spectrum of research questions. The main task is to design detailed modelling research scenarios (category 3).

However, one objective of the analysis is to support decision-making in energy and environmental policy. Many different stakeholders are involved, and cellular energy systems contain innovative (if not disruptive) elements. Consequently, quantitatively-oriented research scenarios have to be complemented by storytelling scenarios that develop images of future energy systems. This means that qualitative storytelling elements also have to be included when developing the scenarios (category 2).

To summarise, the "C/sells" project requires storytelling as well as detailed modelling research scenarios. Its focus is on analysing the impact of new technologies or changing framework conditions, rather than the scenarios themselves. Thus, we see the necessity to provide an efficient, resource-friendly way to develop scenarios that meet the following requirements: Enabling models to jointly answer a research question, giving a scenario a certain direction and capturing specific questions in the scenario. The structured method developed in this paper fills this gap: It addresses the need for a user-friendly scenario development method that combines comprehensive storylines and quantitative input parameters for divergent energy system models. As a result, it enhances the effectiveness of research that depends on a consistent multi-model system.

3. Methodology

This section describes our method of developing energy scenarios. In energy system analysis, research questions often address multiple aspects like supply technologies, markets, the grid and actor perspectives, rather than only one particular field. Since these aspects exceed the capabilities of a single model, the use of multiple models is advisable. The quality of scenarios depends not only on their usability for multiple models but also on the consistency of the relevant assumptions and the authenticity of the scenario storyline [83]. We highlighted the importance of combining qualitative storyline design and quantitative parameter definition for energy system models in Section 2.1. To apply this in a systematic method, we use the findings of Alcamo [68], Rounsvell and Metzger [65] and Miller et al. [84] with regard to storytelling and storylines, and combine them with Reibnitz's approach [11] to designing quantitative scenarios.

One of the aims of this paper is to demonstrate the usefulness of storytelling and narrative scenario development when combined with quantitative scenarios. Thus, we consider both qualitative and quantitative aspects of scenario development. In doing so, we not only combine the above-mentioned existing methods but also develop them further and go beyond them in order to use quantitative elements for several models.

In the following subsections, we outline our method of developing scenarios that address the outlined challenges. It consists of a step-by-step approach that is generic and suitable for various applications. The approach is described schematically in Figure 1. Following the identification of the areas and factors of influence (Step 1), qualitative and quantitative descriptors are determined (Step 2). These serve as the basis for developing a qualitative storyline (Step 3) and quantifying the scenario parameters in coordination with the models' characteristics (Step 4).

3.1. Identifying Areas and Factors of Influence

The first step in the scenario development process was to identify the areas and factors of influence. To do this, we conducted an analysis identifying the areas and factors that had a non-negligible influence on the energy system and other interrelated aspects. The goal was to select areas of influence, which were—in accordance with reference [11]—aspects with an impact on the functionality and efficiency of our area of interest, the energy system. This step was independent of considerations regarding the models used in a later part of the process.

The political framework was a suitable example of an area of influence that affected all kinds of energy scenarios. It defined the situation for both producers and consumers in the energy system. In scenarios that addressed the development of electricity demand, for example, it was important to consider influencing factors from current policies that affected consumer behaviour. For the application of scenarios analysing investment decisions in new generation technologies, political guidelines influenced the decision-making process and the investment security of producers. Further examples for areas of influence were societal trends, socioeconomic aspects or technological developments.

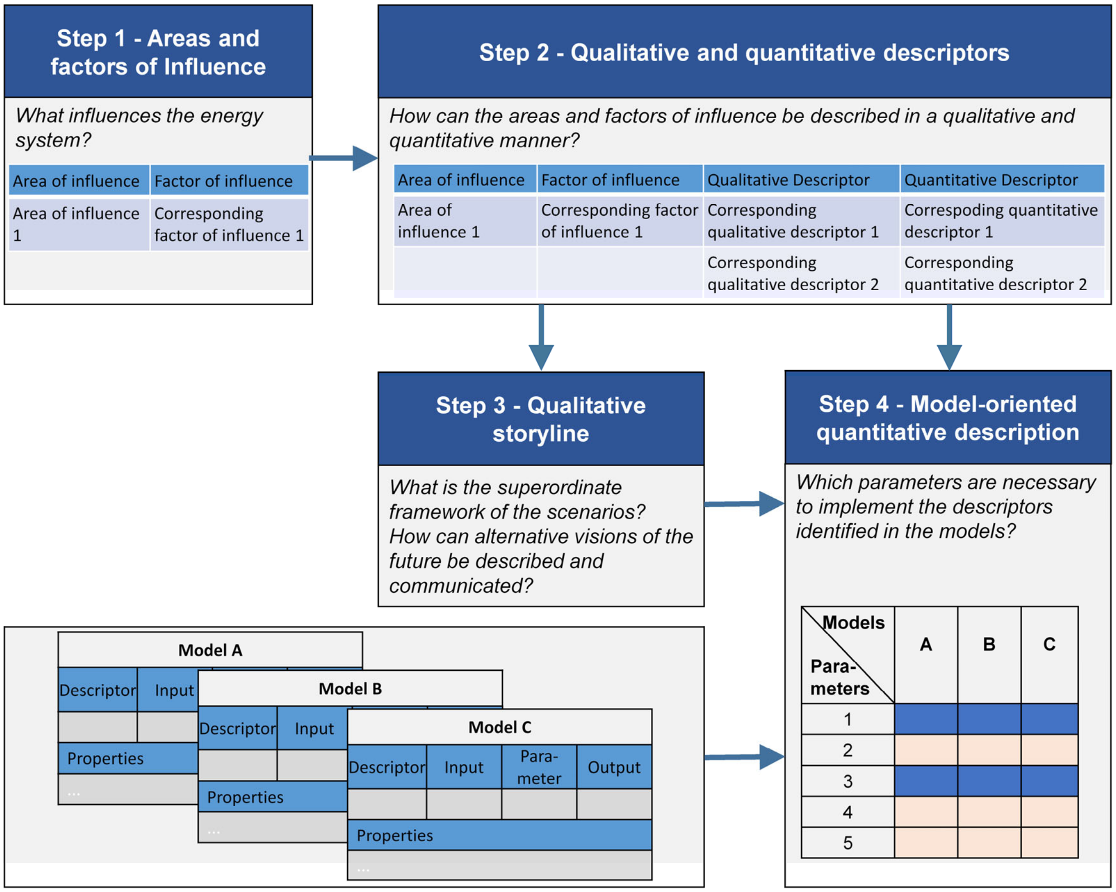

Figure 1. Schematic depiction of the scenario development method.

3.2. Definition of Descriptors

In the second step, we selected qualitative and quantitative descriptors. Descriptors characterised the influencing factors defined in the first step by capturing their central constituents. They described the current state as well as future developments in the areas of influence [11]. Descriptors can affect a specific area of influence but might affect other areas of influence as well [11]. Typical descriptors for the above-mentioned area of influence technological developments, for instance, were investment costs or drivers of technology development. Unlike parameters, descriptors were neutral in order to ensure that the wording did not predefine the direction in which future trends were assumed to evolve [11].

We defined both qualitative and quantitative descriptors. This ensured that descriptors were not only suitable for communicating the scenarios and describing the scenario worlds accurately, but for model input as well. Qualitative descriptors captured unquantifiable elements of a future vision of the energy system, such as drivers of technological development, while quantitative descriptors could be converted into parameters more directly, e.g., investment costs.

The identification and determination of descriptors took place in a collaborative process, in the form of a workshop for example. Participants in this process included modellers and—depending on the scope of a scenario—other stakeholders. An unbiased person should moderate the process. As a starting point, all the involved parties suggested descriptors that fit their model-specific features or that were important within the storyline of a universal energy scenario framework.

After all the necessary descriptors had been identified, the process was split into 2 parts: A narrative part (the storyline), which included how to describe a future energy world, and a model-oriented quantitative part. The narrative part (Section 3.3) enabled a qualitative discussion of future energy worlds. Within the model-oriented quantitative part, the overall quantitative framework was outlined first, e.g., by defining a CO_2 emission reduction path. Then, the modellers identified differences between their models and captured the requirements of all the models used (Section 3.4). This helped to ensure consistency between the different models' results and to ensure that the qualitative parts of the scenario and their translation into quantitative aspects were plausible.

3.3. Qualitative Storylines

The narrative storylines described the scenarios qualitatively. Qualitative storylines depicting the commonalities and differences between scenarios supported the discussion regarding future developments and scenario design. Formulating qualitative storylines had two objectives: On the one hand, storylines made the scenarios easier to communicate [68]. On the other hand, we could define the general direction and ambition of the scenarios.

The storylines were formulated building on the preceding steps. This means we used the areas of influence and descriptors as a frame to describe potential energy futures. To distinguish possible pathways, a tendency or direction was assigned to the descriptors, which were formulated neutrally to start with, i.e., without a direction.

This step of the scenario development process ensured that discourse regarding the configuration of scenarios was possible among stakeholders [4,68]: The scenarios were applied in energy system models and developed by modellers with detailed knowledge of the energy system. However, if they were to have an impact on decision-making, e.g., on a political level, it was important to ensure that the scenarios were also comprehensive to persons not familiar with energy system modelling. To facilitate the comprehension of qualitative storylines and to create a common understanding of a possible energy future, storyline formulation should be accompanied by workshops as well as involving stakeholders with different backgrounds.

3.4. Model-Oriented Quantitative Description and Parametrisation of the Scenarios

Thus far, we have outlined the selection of areas of influence and descriptors and established the narrative part of the scenario framework without considering the models that will eventually be used to conduct scenario analysis. The model-oriented part explained in this section pursued two different goals. On the one hand, it facilitated comparability of the models involved, as it established a process to select the relevant descriptors. On the other hand, it produced a consistent quantitative definition of a scenario. For this purpose, neutral descriptors were used to determine non-neutral parameters. To obtain a set of all the relevant parameters, all the involved modellers independently analysed which parameters quantified the descriptors within their models. In doing so, they distinguished between generic parameters and model-specific input and output parameters. An energy system modelling example of a generic parameter for the descriptor "transmission system capacity" would be "interconnector capacity in MW". Corresponding model-specific parameters could be "thermal interconnector capacity per year" or "NTC values" on the input side, and "difference in interconnector capacity per year before and after optimisation" on the output side.

Model-specific matrices summarised the resulting combinations of descriptors, generic parameters and model-specific parameters. They showed how a descriptor was utilised in a model and how it translated into a parameter in an explicit and transparent way. This helped to assure and monitor that there was no bias in the selection of descriptors that might hamper the validity of the scenario development process.

After obtaining a matrix for each model, we merged them into one single matrix. This is illustrated in Figure 2. The resulting matrix shows intersections and overlaps in the use of descriptors and parameters in the models. Thus, it helps to identify a common set of descriptors and parameters applied by all the models. Descriptors that were only relevant for one or a few models can be used for sensitivity analyses. Descriptors that had no impact on any of the model calculations were excluded from this point onwards. The model-matrices A, B and C were merged in Figure 2. The parameters that were relevant for all models are highlighted in orange, while parameters that were only used by some of the models are shown in blue.

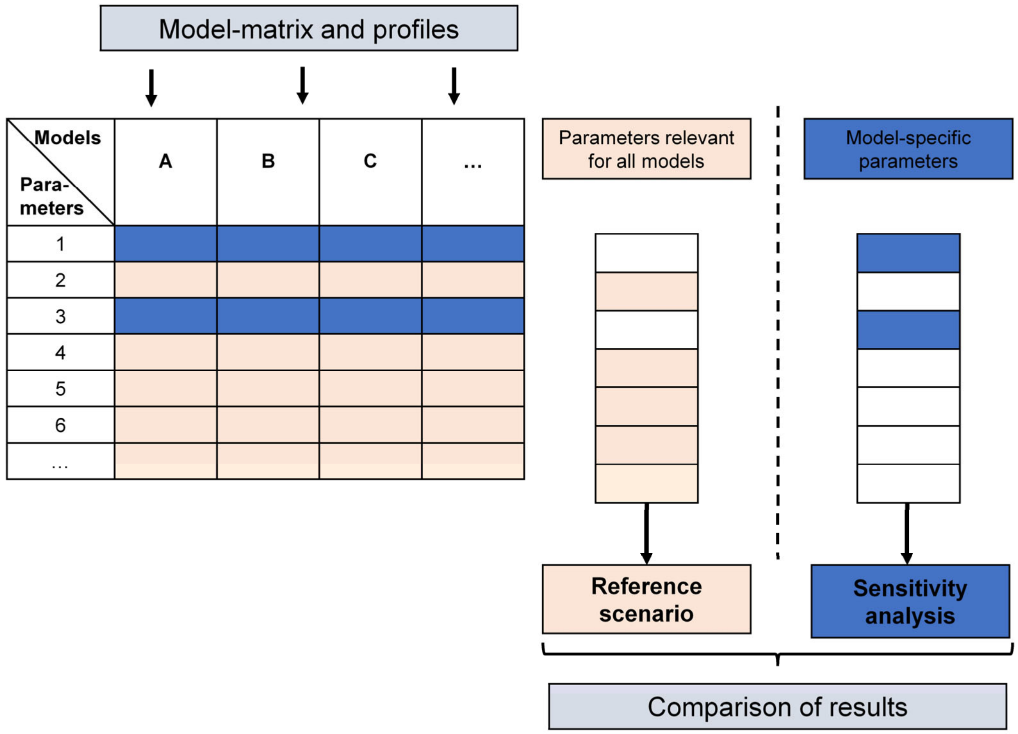

Figure 2. Determination of model overlaps with respect to parameters and identification of relevant parameters.

The example of grid transmission capacity shows that there might be important differences in the parameters used when combining different energy models. While many models might not consider grid capacities at all or only in a simplified way, these may be part of the endogenous optimisation in more technical models. The combined model matrix highlights these differences. In addition, the combined matrix helps to identify the unique selling points of each model.

The combined matrix encourages modellers to discuss the relevance of each parameter and agree on a common source when quantifying those input parameters that are relevant for all (or at least 2) models. In doing so, the storyline of the scenario has to be kept in mind, thus that the quantification of all parameters is in line with the general scenario idea. Usually, modellers agree on a detailed long-term scenario as a basis for their input parameters, such as the ENTSO-E (European Network of Transmission System Operators for Electricity) 'Ten-Year Network Development Plan' [85] or the 'EU Reference Scenario' [62]. When choosing a suitable quantitative basis, they have to consider how consistent the scenario is with their storyline. They also need to ensure that all the relevant parameters are addressed—in an appropriate spatial and temporal resolution as well. Both requirements helped to limit the list of suitable scenarios. Another possibility was for modellers to define their own set of input parameters for each or several of the models. However, this approach was most likely to lead to disputes due to the interdependencies in the development of the individual parameters. Additionally, due to the interdependencies and the complexity of determining individual parameters, this procedure involved a great deal of effort and had to be weighed up against the focus of the planned model analyses.

3.5. Output of the Scenario Development Method

At the end of this step-by-step approach, a set of quantitative descriptors and parameters consistent with the scenario storyline was obtained, which helped to ensure consistent model results. Moreover, since the unique selling points of the models were externalised, their benefits and relevance were clear when discussing the results.

All types of energy system models can apply the approach. If there were substantial differences regarding the system boundary or technical focus, the models could be divided into subgroups and scenario development could be performed separately for each. The common storyline should nevertheless define the scope of research of all the models involved.

In a scenario analysis workflow, this step was followed by allocating values to quantitative parameters, actual model runs and comparing the results. Actual parameter values were determined using existing literature on the one hand, and from the narrative of the scenario and its specific scope on the other. The range of possible quantitative values for parameters depended on the stakeholders involved, the political assumptions and the ambition level on which a scenario was based. Individual values for parameters can also be subject to iterative adjustments. These aspects are beyond the scope of this paper since we focus primarily on identifying the descriptors needed to describe a scenario in a comprehensive way and on deriving parameters from the descriptors that are applicable by the models involved.

4. Application of the Scenario Development Method to a Multi-Model Analysis of Cellular Energy Systems

In Section 3, we described a theoretical method to develop energy scenarios used for a combination of stakeholder communication and multi-model analysis. In this section, we apply this method within the German research project "C/sells", which focuses on the analysis of cellular energy concepts. Its underlying concept is cellular energy autonomy with high regional stakeholder participation in regional market structures [86]. Within the research project, different heterogeneous stakeholders cooperate to demonstrate concepts applying the principle of cellular energy systems [87]. The objective is to create more efficient communication between network operators and other stakeholders [87].

As outlined in Section 1, cellular energy systems are a type of decentralised energy system with an emphasis on subsidiarity. The subsidiarity principle, which characterises the coordination on different hierarchical levels and between different stakeholders and market participants, is a key feature of cellular energy systems [28]. It could improve the market integration of actors and promote acceptance and participation even more than other types of decentralised energy systems [28].

However, it is still unclear whether a cellular energy system possesses the promoted benefits. Given that implementing such a system would necessitate substantial modifications, e.g., in terms of the market regime and regulatory framework, we derived the following research questions:

- To what extent and under which conditions do cellular energy systems perform well in different scenarios of energy system development?
- Are cellular energy systems efficient in terms of system costs and ecological factors?

The possible future contribution of cellular energy systems is a good test subject for our scenario development method as a multitude of different stakeholders and energy system-related aspects (e.g., technical, socioeconomic and political) are affected. On the one hand, we discuss the possible role of cellular energy systems with a wide range of stakeholders, such as scientists, citizens, grid operators, utilities and political decision-makers. On the other hand, the research project has to investigate the effects on today's energy system of implementing cellular energy systems. Such a comprehensive investigation requires a variety of energy models covering different aspects of the energy system and its transformation.

Following the method outlined in Section 3, we developed a scenario framework for the analysis of cellular energy systems. We facilitated high stakeholder participation in building the scenarios and ensured that all the involved energy system models were able to apply them. Additionally, though beyond the scope of this paper, modelling results were comparable and interpretable based on the set of parameters developed following the methodological steps.

4.1. Identifying Areas and Factors of Influence

The objective of identifying areas and factors of influence was to define generic areas or categories that affected the future development of the energy system. Subsequently, all the areas of influence were specified by categories we called influencing factors. Table 2 shows examples of areas and factors of influence in energy systems identified as particularly relevant within the research field. They were discussed and selected in a collaborative dialogue involving modellers but also a wider set of stakeholders. "Energy conversion technology development", for example, refers to technological advances and technological learning, e.g., in certain power plant technologies or the learning rates for electricity generation and storage options. Since one goal of the scenario development process is to evaluate concepts related to cellular energy systems, an important area of influence is "Energy system organisation". This area of influence covers many features related to cellular concepts, such as the size of market areas or the control hierarchy. Moreover, the area of influence "Socioeconomic aspects" is crucial to the analysis of cellular energy systems: It comprises questions such as participation in specific actions or the general acceptance of the energy transition. The list of identified areas of influence in Table 2 is representative for this application, but does not claim to be exhaustive; the same applies to the influencing factors.

Table 2. Identified areas of influence in the context of cellular energy systems.

Areas of Influence	Influencing Factors
Energy Conversion Technology Development	Technological innovations and breakthroughs
Infrastructure	Electricity grid; gas network; degree of digitalisation
Demand	Demand in sectors; flexibility options
Socioeconomic Aspects	Participation; acceptance; consumer behaviour
Energy System Organisation	Size of market areas; control hierarchy; types of energy-related products

4.2. Definition of Descriptors

As defined in Section 3, descriptors are a means of characterising the influencing factors defined in the first step. "Energy conversion technology development" with the influencing factors "generation technologies" and "technological innovations" is a good example for the gradual breakdown of an area of influence into descriptors: The qualitative descriptors describe which types of technologies are available, the drivers of technology expansion as well as assumptions regarding, e.g., large international PV or hydrogen projects. The quantitative descriptors then describe the assumed development of the actually available installed capacity per technology as well as the technology-specific investment costs, for example. We use the same procedure for each area of influence in order to describe the scenario framework in as much detail as necessary and possible.

Our application considers quantitative and qualitative descriptors of cellular as well as non-cellular energy systems. Considering both types of system is necessary to capture the fundamental modifications of energy systems. Some of the descriptors, especially in the area of influence "Energy system organisation", are directly linked to the cell concept, such as "cell size". Others represent the cell system via crosslinks, such as the level of decision making, which includes the subsidiary principle, "degree of prosumer participation in local electricity supply concepts" or the "degree of digitalisation".

Table 3 shows a selection of example areas of influence and the corresponding influencing factors and descriptors. Our approach allows us to make generic assumptions first, which are then specified in the following steps. Regarding cellular energy systems, we define the level of control hierarchy to start with and the interactions between market participants, and then we derive the cell concept together with additional assumptions. Finally, in the last step, the actual cell size is defined.

Table 3. Selection of identified descriptors and corresponding areas of influence in the model application.

Areas of Influence	Influencing Factors	Qualitative Descriptors	Quantitative Descriptors
Energy Conversion Technology Development	Generation technology	Types of generating capacities; drivers of RES-expansion; assumptions about international projects	Installed capacities [MW/a]; RES-feed-in [MWh/a] technology costs [€/MW]; distance of wind turbines to closest settlement [m]
	Technological innovations and breakthroughs	Technological maturity (e.g., of hydrogen-based industrial processes)	Installed capacity [MW]
Demand	Demand in sectors	Considered sectors (transport, industry, households)	Annual demand for energy in the sectors [GWh]; demand profiles
	Flexibility options	Diffusion of different flexibility options and availability for flexible use	Installed capacity per flexibility type [MW]
Infrastructure	Energy grid infrastructure	Political decisions regarding relevant technologies	Transmission system capacity; interconnector capacity [MW]
	ICT infrastructure	Technologies being digitalised; use cases resulting from digitalisation of technologies	Degree of digitalisation
Socioeconomic Aspects	Acceptance	Barriers to RES expansion	Share of BEV (Battery electric vehicle) car owners accepting flexible load control [%]
	Participation		Degree of prosumer participation in local electricity supply concepts [%]
Energy System Organisation	Control hierarchy; number of cells	Level of decision making; interactions between market participants and infrastructure operators; cell definition and boundaries	Spatial dimension and location of energy cell size [number of participants (supply/demand)]
	Markets	Type of markets; market participants; products (e.g., energy, flexibility)	Flexibility offers in a certain market [GW]; market prices [Euro/MW]

4.3. Qualitative Storylines

Storylines represent a narrative description of the scenarios. We constructed two different scenarios to answer the research questions formulated above. The storylines described two heterogeneous energy futures and the corresponding pathways leading to them. Two energy futures were determined to create two opposing scenario worlds and analyse elements of cellular energy systems in both of them. Both worlds have some elements in common but differ in the characteristics of many descriptors. From a methodological point of view, there are no restrictions with regard to the number of scenarios. However, in our case, the two scenarios function as "guideposts".

In the process of creating narrative storylines, each scenario's ambition level is set from the beginning. Consequently, the scenarios developed here have a normative nature, in which the future outcome in terms of climate objectives is already determined [7,38,88]. We, therefore, used a backcasting approach—in contrast to explorative forecasting methods, which are used to examine which future state will be reached under certain conditions [5,7]. This approach allows us to analyse different paths while avoiding a bias stemming from different levels of ambition. As a result of this logic, neither of the scenarios developed here can be categorised as a "baseline" or "business-as-usual" scenario, as is the case for many scenario studies [7]. Instead, all scenarios (two—in our example) should be seen as policy scenarios, which were based on different policy assumptions and evolved in different directions.

However, unlike many other scenarios, which focus on cost and technological features, the scenarios defined here were additionally based on developments induced by societal trends [89]. An important example of such a trend with the potential to affect issues of sustainability, value creation and electricity market design is the emergence of "prosumers", small consumers, who are beginning to control and manage their own energy use and often operate their own small generation units [3].

At the beginning of the storyline process, we held several workshops with different stakeholders and defined superordinate framework conditions that were valid in both scenarios (cf. Figure 3). For example, the level of ambition was in line with the targets defined in Germany's "Climate Action Plan 2050", which was adopted in 2016. In this plan, the German government has committed to reducing GHG emissions from the energy sector by at least 55% (baseline 1990) by 2030 and by 80–95% by 2050 [90].

Once the stakeholders had agreed on the superordinate framework conditions, we discussed the characteristics of the two scenarios using the storylines approach. Using storylines instead of quantitative descriptors in this step of the process guaranteed that all the stakeholders were able to discuss possible energy futures, even though not all of them were energy experts. The resulting storyline of the first scenario, "Reference A", describes a development that follows current conditions regarding investment decisions and principal actors (cf. Figure 3). This scenario was characterised by large-scale electricity generation technologies, centralised markets and hierarchical control structures. The second scenario world, "Reference B", describes a future with a higher penetration or a stronger impact of smart digital infrastructure. Small-scale technologies for power generation or provision of demand flexibility are more incentivised in this scenario world. However, both scenarios guaranteed the same level of CO_2 reductions. While large-scale offshore wind parks, hydrogen facilities and sector coupling guaranteed the achievement of the climate goals in "Reference A", a high share of small-scale RES-E and a high degree of flexibility reached the same goals in "Reference B".

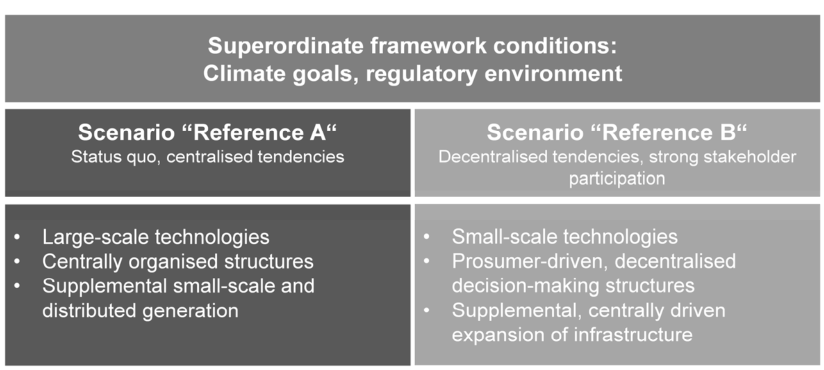

Figure 3. The two scenarios "Reference A" and "Reference B" define the scenario framework.

We decided not to create a "Cellular energy system scenario". Instead, elements of cellular energy systems were tested in both scenarios in order to derive statements regarding the effect of this concept on different energy futures. Our intention was to analyse the efficiency of cellular concepts independently in two likely future worlds. However, some cell-related descriptors differ strongly between the scenarios. This concerns, in particular, the decentralised tendencies in market structure and control hierarchy and strong stakeholder participation, which are key parts of the concept of cellular energy systems. For example, in a world with decentralised tendencies (scenario "Reference B"), complexity increases due to the larger number of plants. Therefore, a concept that supports the control of a large number of installations might have a greater impact in this scenario than in "Reference A".

4.4. Model-oriented Quantitative Description and Parametrisation of the Scenarios

In the last part of our scenario method application, we constructed model matrices containing the qualitative description of the scenario. We conducted several workshops with all the energy system modellers that were moderated by a neutral person. Within the Project "C/sells", we used five energy system models to answer questions regarding the systemic effects of cellular concepts: Four linear optimisation models and one agent-based simulation model. The models differed in their basic structure, outputs and research focus: One analyses the use of flexibility options within multiple electricity markets, while others calculate the optimal power plant investments. Furthermore, some of the models optimised power plant dispatch in terms of electricity grid structures. The agent-based approach was able to consider the behaviour of prosumers. All the models used depicted the energy system but differed in their system boundaries and the level of detail of different technologies, flexibility options and sectors.

Table 4 shows an example of a model-specific matrix (please note that Table 4 only shows part of a full model matrix, since showing a full matrix would require several pages due to the long list of parameters). The left part of the matrix lists generic parameters for each descriptor that are not dependent on a specific model. The right part of the matrix contains the model-specific input and output parameters.

Input parameters for the descriptor "Energy conversion technology development" are investment costs (in a certain year) or efficiency ratios (e.g., for power plants). The amount of flexible demand within a region is an input parameter for the descriptor "Cell definition and boundaries". This matrix (Table 4) also contains a column "Model Output", i.e., information about the characteristics of the respective model's results (result format, system boundaries, mathematical formulation, model type) in order to improve comparability. Analysing the actual modelling results is, however, outside the scope of this methodology paper.

Table 4. Extraction of a model-specific matrix containing information on how descriptors are captured in the models used.

Generic			Model-Specific	
Areas of influence	**Descriptor**	**Parameter**	**Model Input**	**Model Output**
Energy Conversion Technology Development	Installed capacities [MW]	Installed generation capacity in the base year [MW]	Installed generation capacity in the base year [MW]	New generating capacities build [MW]
	Technology costs	Cost [€/kW; €/kWh] for all technologies considered	Investment and variable costs per technology and year [Euro/MW; Euro]	
	Efficiency	Efficiency [%] for all technologies considered	Efficiencies per technology and year [%/a]	
Demand	Annual demand for energy in the sectors [GWh]	Electricity demand [TWh/a]; total load [GW/h]	Electricity demand induced by sector [GWh]	Resulting total load [GW/h]
	Demand profiles	Relative load profile [-]	Electricity demand profiles of industry, household and tertiary sector	Load profile after flexibility optimisation [GW/h]
	Installed capacity per flexibility type [MW]	Installed capacity [MW]	Storage capacities [MW]; DR-technologies [MW; MWh]; curtailment restrictions	Investment of flexibility options [Euro/MW]; dispatch of flexibility options
	Cost of flexibility	Costs [€/kW; €/kWh]	Costs [€/kW; €/kWh] per flexibility type	

Energy System Organisation	Market prices	Fuel prices [€/kWh$_{thermal}$]	Fuel prices per fuel and year	Fuel use per fuel and year
	Cell definition and boundaries	Capacity available for regional balancing	Flexible demand on a regional market [MW; MWh/h], available regional generation [MW; MWh/h]	Share of electricity balanced regionally [%]

5. Discussion and Limitations

The scenario development method presented can be used in research projects in the field of energy system modelling, which require a high level of stakeholder participation. The resulting scenarios make it possible to address very specific research questions. At the same time, due to their qualitative elements, they facilitate the discourse with different stakeholders and thus support decision-making.

In Section 2.3, we identified three motivations for developing energy scenarios: Global, comprehensive expert scenarios, pure storytelling scenarios and detailed modelling research scenarios. Scenarios developed with our method have to be part of the third category but also feature storytelling parts. Pure storytelling scenario approaches (e.g., [11,39,60,80]) combine elaborate but time-consuming instruments like stakeholder workshops, expert Delphi, multi-criteria decision analysis and cross-impact balance analysis [91]. They are, therefore, likely to provide sophisticated results in terms of identifying suitable areas of influence and ensure consistency between different scenarios as well as between descriptors, but the process of scenario development is very time-consuming. The latest IPCC scenarios ([46] as well as [48–50]), for example, combine the development of consistent storylines with the use of models and embed this in an extensive series of workshops and research papers. Even though their level of detail in energy system modelling is rather limited, the aforementioned scenarios are certainly to be rated higher than the scenarios created using the method proposed in this paper in terms of relevance, legitimacy or credibility, the factors identified as success criteria for scenarios [68]. In addition, the IPCC scenario development process lasts several years and is very resource consuming.

The strength of our method, on the other hand, is its clearly structured development process that provides a useful set of descriptors, while remaining simple and easy to conduct. With a reasonable use of resources in terms of time and effort, it generates scenarios applicable in multiple models and facilitates the discussion and communication of visions of the future.

The method developed here allows researchers to design scenarios for energy system analysis. While the models considered in this process are heterogeneous in terms of type (simulation vs. optimisation) or geographical resolution, they are all categorised as energy system models. This limits the need to adjust scenarios with regard to the models involved. It is not necessary to define an extensive landscape of models, as proposed by Trutnevyte et al. [67]. However, the evaluation of innovative use cases with the method developed here could be enriched by integrating a wider variety of models into the scenario analysis. Increasing the number of models involved increases the number of aspects that can be assessed. Additionally, there is the possibility to couple models within the scenario development process. Both approaches, integrating a higher number of models or model-coupling, are ways of expanding the range of futures considered [67] and can add more details and insights. In such a case, the approach developed and the identification of common descriptors reached their limits (due to a much wider scope of the models involved) and would have to be extended.

Our approach is based on a collaborative process, in which we identify areas and factors of influence as well as the descriptors needed to describe an energy world in qualitative and quantitative terms. However, the process does not depend on the specific models to be used. Instead, its focus is on the development of consistent scenarios. Thus, the method's starting points are areas of influence and descriptors and not specific model parameters. For this reason, some descriptors might need to be implemented in an unusual way for particular models.

Maintaining the comparability of input data can lead to a situation in which modellers need to simplify some elements of the models that are capable of incorporating and examining an aspect in a very precise way. This reduces complexity but might also reduce insights. We advise compensating such losses by running additional model-specific sensitivity calculations outside the consistent scenario framework.

When developing pathways towards a future state of a system, scenarios have proven particularly effective in describing incremental changes and their interactions. This is one of the focal points of the scenarios developed here. However, van Notten et al. [30] criticise such scenarios because they do not consider unexpected events or disruptive societal changes. Unforeseen changes lead to discontinuities in the design of scenarios. In recent years, however, it can be observed that certain occurrences can trigger reactions and trends within societies that have a strong influence on policy-making. An example of this is the Fukushima nuclear disaster. In contrast to other scenario development processes (e.g., [58]), such disruptive changes are not covered by the method developed in this paper. Therefore, integrating discontinuities might be a possible extension to the scenario development method, which could enhance the robustness of the scenarios.

Another aspect to be considered in the context of analysing cellular energy systems is that, although the decentralisation of the energy system is already underway, it is not yet clear to what extent the entire system will be transformed. One of the scenarios developed in Section 3.3 assumes the integration of cellular structures into a centralised energy system. In this case, cellular energy systems might be seen as a disruptive innovation, i.e., not emerging from existing structures, markets and infrastructures. However, the current set of areas of influence and descriptors is tailored to existing structures and their progressive transformation. Therefore, if cellular energy systems emerged not as a result of the ongoing transformation but suddenly and abruptly, e.g., due to political decisions, both the storyline and the quantitative descriptors would have to be adapted.

The presented method increases the transparency of model runs and results because it reveals the input and output parameters and the relevant formats used to design a consistent parameter set. The objective is not to harmonise the models in order to benefit from their complementary capabilities. Nevertheless, the models are "black boxes" regarding the internal processing of data. This might give rise to a situation in which discrepancies between results cannot be sufficiently explained using input data. This issue might be solved by integrating open model principles into the scenario development process. However, some institutions are—for various reasons—not always able or willing to make their model accessible to the public. In such a case, comparing models and enhancing a model's degree of transparency and its results is at least facilitated by applying the method presented here.

6. Conclusions

The aim of this study was to present a method of developing energy scenarios with a variety of stakeholders, which were easy to communicate on the one hand and easy to use in a multi-model environment on the other hand. We applied the developed method to scenarios analysing cellular energy systems. The process-oriented method consists of four steps (cf. Section 3), which guarantee that we obtain a scenario framework consisting of qualitative as well as quantitative aspects:

- **Step 1:** Identifying areas and factors of influence: An analysis is conducted to identify the areas and factors that have a non-negligible influence on the energy system and other interrelated aspects.
- **Step 2:** Definition of descriptors: For the areas and factors of influence identified in step one, qualitative and the quantitative descriptors are selected, which capture their current state and future developments.

Once the descriptors have been selected, the process is split into two separate parts:

- **Step 3:** Formulation of qualitative storylines: A qualitative narrative is developed in order to facilitate understanding of the scenario pathways among stakeholders from different backgrounds.
- **Step 4:** Model-oriented specification: Model matrices with suitable parameters are elaborated. Overlapping descriptors and corresponding parameters are identified.

When applying this method to the analysis of cellular energy system concepts, it results in two normative energy scenarios, one with a focus on small-scale technologies, and another with large-scale installations as the energy system's backbone. However, the number of scenarios is not necessarily limited to two. The step-by-step process of defining descriptors, qualitative storylines and quantitative model specifications using descriptor matrices is justified by the need for a high degree of stakeholder involvement in the scenario design as well as the heterogeneity of the models used to assess similar research questions. The energy scenarios developed using this method can be used by different types of energy system models, but also to support a discourse of experts and stakeholders. Based on the model matrix, researchers with differing system boundaries are also able to compare their results. The model-matrix is, therefore, a suitable tool for modellers to discuss their approaches on a common basis and to identify necessary adjustments to their models.

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References

1. Goldfarb, D.L.; Huss, W.R. Building scenarios for an electric utility. *Long Range Plan.* **1988**, *21*, 78–85, doi:10.1016/0024-6301(88)90125-2.
2. Capros, P.; Paroussos, L.; Fragkos, P.; Tsani, S.; Boitier, B.; Wagner, F.; Busch, S.; Resch, G.; Blesl, M.; Bollen, J. European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis. *Energy Strategy Rev.* **2014**, *2*, 231–245, doi:10.1016/j.esr.2013.12.007.
3. Parag, Y.; Sovacool, B.K. Electricity market design for the prosumer era. *Nat. Energy* **2016**, *1*, doi:10.1038/nenergy.2016.32.
4. Pruditsch, N.; Zöphel, C. Szenarien für ein europäisches Energiesystem [Scenarios for a European energy system]. *uwf* **2017**, *25*, 81–90, doi:10.1007/s00550-017-0443-x.
5. Grunwald, A. Energy futures: Diversity and the need for assessment. *Futures* **2011**, *43*, 820–830, doi:10.1016/j.futures.2011.05.024.
6. Amer, M.; Daim, T.U.; Jetter, A. A review of scenario planning. *Futures* **2013**, *46*, 23–40, doi:10.1016/j.futures.2012.10.003.
7. Rotmans, J.; van Asselt, M.; Anastasi, C.; Greeuw, S.; Mellors, J.; Peters, S.; Rothman, D.; Rijkens, N. Visions for a sustainable Europe. *Futures* **2000**, *32*, 809–831, doi:10.1016/S0016-3287(00)00033-1.
8. Greeuw, S.C.H. An assessment of recent European and global scenario studies and models. In *Cloudy Crystal Balls*; Experts' Corner Report; 2000. Available online: http://publications.europa.eu/en/publication-detail/-/publication/79246fde-65a8-4bcc-a58d-ebf050a649b6 (accessed on 09 June 2019).
9. Dieckhoff, C. Modellierte Zukunft. In *Energieszenarien in Der Wissenschaftlichen Politikberatung [Modelled Future. Energy Scenarios in Scientific Policy Consulting]*; Karlsruhe Institute for Technology (KIT): Karlsruhe, Germany, 2015; ISBN 9783837630978.
10. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* **2014**, *33*, 74–86, doi:10.1016/j.rser.2014.02.003.
11. Reibnitz, U. Szenario-Technik. Instrumente für die unternehmerische und persönliche Erfolgsplanung. [Scenario technique. In *Instruments for Corporate and Personal Success Planning*; 2. Auflage, Gabler Verlag: Wiesbaden, Germany, 1992; ISBN 9783409234313.
12. Steinmüller, K. Workshop Zukunftsforschung. Teil 2 Szenarien: Grundlagen und Anwendungen. In *Futurology Workshop. Part 2 Scenarios: Basics and Applications*; Z_Punkt GmbH: Essen, Germany, 2002.
13. Mehigan, L.; Deane, J.P.; Gallachóir, B.P.Ó.; Bertsch, V. A review of the role of distributed generation (DG) in future electricity systems. *Energy* **2018**, *163*, 822–836, doi:10.1016/j.energy.2018.08.022.

14. Iyer, G.C.; Brown, M.; Cohen, S.M.; Macknick, J.; Patel, P.; Wise, M.; Binsted, M.; Voisin, N. Improving consistency among models of overlapping scope in multi-sector studies: The case of electricity capacity expansion scenarios. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109416, doi:10.1016/j.rser.2019.109416.
15. Lehmann, N.; Huber, J.; Kießling, A. Flexibility in the context of a cellular system model. In Proceedings of the 2019 16th International Conference on the European Energy Market (EEM), Ljubljana, Slovenia, 18–20 September 2019; pp. 1–6, ISBN 2165-4077.
16. Funcke, S.; Bauknecht, D. Typology of centralised and decentralised visions for electricity infrastructure. *Util. Policy* **2016**, *40*, 67–74, doi:10.1016/j.jup.2016.03.005.
17. Ackermann, T.; Andersson, G.; Söder, L. Distributed generation: A definition. *Electr. Power Syst. Res.* **2001**, *57*, 195–204, doi:10.1016/S0378-7796(01)00101-8.
18. Bouffard, F.; Kirschen, D.S. Centralised and distributed electricity systems. *Energy Policy* **2008**, *36*, 4504–4508, doi:10.1016/j.enpol.2008.09.060.
19. Dondi, P.; Bayoumi, D.; Haederli, C.; Julian, D.; Suter, M. Network integration of distributed power generation. *J. Power Sources* **2002**, *106*, 1–9, doi:10.1016/S0378-7753(01)01031-X.
20. Di Silvestre, M.L.; Favuzza, S.; Riva Sanseverino, E.; Zizzo, G. How Decarbonization, Digitalization and Decentralization are changing key power infrastructures. *Renew. Sustain. Energy Rev.* **2018**, *93*, 483–498, doi:10.1016/j.rser.2018.05.068.
21. Pepermans, G.; Driesen, J.; Haeseldonckx, D.; Belmans, R.; D'haeseleer, W. Distributed generation: Definition, benefits and issues. *Energy Policy* **2005**, *33*, 787–798, doi:10.1016/j.enpol.2003.10.004.
22. Allan, G.; Eromenko, I.; Gilmartin, M.; Kockar, I.; McGregor, P. The economics of distributed energy generation: A literature review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 543–556, doi:10.1016/j.rser.2014.07.064.
23. Walker, G. What are the barriers and incentives for community-owned means of energy production and use? *Energy Policy* **2008**, *36*, 4401–4405, doi:10.1016/j.enpol.2008.09.032.
24. Rae, C.; Bradley, F. Energy autonomy in sustainable communities—A review of key issues. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6497–6506, doi:10.1016/j.rser.2012.08.002.
25. Abegg, B. Energy Self-sufficient Regions in the European Alps. *Mt Res. Dev.* **2011**, *31*, 367–371, doi:10.1659/MRD-JOURNAL-D-11-00056.1.
26. Schlachtberger, D.P.; Brown, T.; Schramm, S.; Greiner, M. The benefits of cooperation in a highly renewable European electricity network. *Energy* **2017**, *134*, 469–481, doi:10.1016/j.energy.2017.06.004.
27. Tröndle, T.; Pfenninger, S.; Lilliestam, J. Home-made or imported: On the possibility for renewable electricity autarky on all scales in Europe. *Energy Strategy Rev.* **2019**, *26*, 100388, doi:10.1016/j.esr.2019.100388.
28. VDE.; ETG. *The Cellular Approach—The Basis of Successful, Cross-Regional Energy Transition*; VDE: Frankfurt, Germany, 2015.
29. ETG. Congress Energietechnische Gesellschaft; International ETG Congress. In Proceedings of the International ETG Congress 2017. Die Energiewende: Blueprints for the new energy age, Bonn, Germany, 28–29 November 2017; VDE Verlag: Berlin, Germany; Offenbach, Germany, 2017; ISBN 9783800745050.
30. van Notten, P.W.F.; Rotmans, J.; van Asselt, M.B.A.; Rothman, D.S. An updated scenario typology. *Futures* **2003**, *35*, 423–443.
31. Kahn, H.; Wiener, A. *The Year 2000*; Macmillan: New York, NY, USA, 1967.
32. Dönitz, E.J. Effizientere Szenariotechnik durch teilautomatische Generierung von Konsistenzmatrizen. In *More Efficient Scenario Technique through Semi-Automatic Generation of Consistency Matrices*; Gabler: Wiesb, Germany, 2009; ISBN 978-3-8349-1668-6.
33. Ratcliffe, J. Scenario planning: An evaluation of practice. *Futures Res. Quart.* **2003**, *19*, 5–26.
34. Mietzner, D.; Reger, G. Advantages and disadvantages of scenario approaches for strategic foresight. *IJTIP* **2005**, *1*, 220, doi:10.1504/IJTIP.2005.006516.
35. Bishop, P.; Hines, A.; Collins, T. The current state of scenario development: An overview of techniques. *Foresight* **2007**, *9*, 5–25, doi:10.1108/14636680710727516.
36. Bradfield, R.; Wright, G.; Burt, G.; Cairns, G.; van der Heijden, K. The origins and evolution of scenario techniques in long range business planning. *Futures* **2005**, *37*, 795–812, doi:10.1016/j.futures.2005.01.003.
37. Chermack, T.J.; Lynham, S.A.; Ruona, W.E.A. A review of scenario planning literature. *Futures Res. Quart.* **2001**, *17*, 57–70.
38. Börjeson, L.; Höjer, M.; Dreborg, K.-H.; Ekvall, T.; Finnveden, G. Scenario types and techniques: Towards a user's guide. *Futures* **2006**, *38*, 723–739, doi:10.1016/j.futures.2005.12.002.

39. Godet, M.; Roubelat, F. Creating the future: The use and misuse of scenarios. *Long Range Plan.* **1996**, *29*, 164–171, doi:10.1016/0024-6301(96)00004-0.
40. Meadows, D.H.; Meadows, D.L.; Randers, J. The Limits to Growth. In *A Report for The Club of Rome's Project on the Predicament of Mankind*; Universe Books: New York, NY, USA, 1973; ISBN 0876631650.
41. Mesarovic, M.; Pestel, E. Mankind at the Turning Point. In *The Second Report to the Club of Rome*; Hutchinson: London, UK, 1975; ISBN 9780091234713.
42. Leontief, W.; Carter, A.P.; Nations, U.; Petri, P.A. The future of the world economy. In *A United Nations Study*; Oxford University Press: Oxford, UK, 1977.
43. Häfele, W.; Anderer, J.; MacDonald, A.; Nakicenovic, N. *Energy in a Finite World*; Ballinger: Cambridge, MA, USA, 1981; ISBN 9780884106418.
44. Response Strategies Working Group. Climate change: The Intergovernmental Panel on Climate Change (IPCC) scientific assessment. In *The IPCC Scientific Assessment*; Houghton, J.T., Jenkins, G.J., Ephraums, J.J., Eds.; Cambridge University Press: Cambridge, UK, 1990; pp. 329–341.
45. Pepper, W.; Leggett, J.; Swart, R.; Wasson, J.; Edmonds, J.; Mintzer, I. Emission scenarios for the IPCC. An update: Assumptions, methodology and results. In *Climate Change 1992: Supplementary Report to the IPCC Scientific Assessment*; Houghton, J.T., Callander, B.A., Varney, S.K., Eds.; Cambridge University Press: Cambridge, UK, 1992; pp. 69–95.
46. Nakicenovic, N.; Alcamo, J.; Davis, G.; de Vries, B.; Fenham, J.; Gaffin, S.; Gregory, K.; Grübler, A.; Jung, T.-Y.; Kram, T.; et al. Special report on emissions scenarios. In *A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2000; ISBN 9780521804936.
47. Nakicenovic, N.; Kolp, P.; Riahi, K.; Kainuma, M.; Hanaoka, T. Assessment of emissions scenarios revisited. *Environ. Econ. Policy Stud.* **2006**, *7*, 137–173, doi:10.1007/BF03353998.
48. Nakicenovic, N.; Lempert, R.J.; Janetos, A.C. A Framework for the Development of New Socio-economic Scenarios for Climate Change Research: Introductory Essay. *Clim. Chang.* **2014**, *122*, 351–361, doi:10.1007/s10584-013-0982-2.
49. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, doi:10.1038/nature08823.
50. van Vuuren, D.P.; Edmonds, J.A.; Kainuma, M.; Riahi, K.; Weyant, J. A special issue on the RCPs. *Clim. Chang.* **2011**, *109*, 1, doi:10.1007/s10584-011-0157-y.
51. van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; et al. The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5, doi:10.1007/s10584-011-0148-z.
52. O'Neill, B.C.; Kriegler, E.; Riahi, K.; Ebi, K.L.; Hallegatte, S.; Carter, T.R.; Mathur, R.; van Vuuren, D.P. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim. Chang.* **2014**, *122*, 387–400, doi:10.1007/s10584-013-0905-2.
53. Kriegler, E.; Edmonds, J.; Hallegatte, S.; Ebi, K.L.; Kram, T.; Riahi, K.; Winkler, H.; van Vuuren, D.P. A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Clim. Chang.* **2014**, *122*, 401–414, doi:10.1007/s10584-013-0971-5.
54. Alcamo, J.; Bouwman, A.; Edmonds, J.; Grübler, A.; Morita, T.; Sugandhy, A. An evaluation of the IPCC IS92 emission scenarios. In *Climate Change, 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*; Houghton, J.T., Ed.; Cambridge University Press: Cambridge, UK, 1995; ISBN 9780521559621.
55. Morita, T.; Robinson, J.; Adegbulugbe, A.; Alcamo, J.; Herbert, D.; La Rovere, E.L.; Nakicenovic, N.; Pitcher, H.; Raskin, P.; Riahi, K.; et al. Greenhouse gas emission mitigation scenarios and implications. In *Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment*; Cambridge University Press: Cambridge, UK, 2001; pp. 115–166.
56. International Energy Agency (IEA). World Energy Model Documentation. Available online: https://www.iea.org/media/weowebsite/energymodel/WEM2018.pdf (accessed on 24 April 2019).
57. International Energy Agency (IEA). *Energy Technology Perspectives 2017*; International Energy Agency: Paris, France, 2017.
58. World Energy Council. World Energy Scenarios. In *Composing Energy Futures to 2050*; World Energy Council: London, UK, 2013.

59. Shell International, B.V. Shell World Energy Model. Available online: https://www.shell.com/promos/meeting-the-goals-of-the-paris agreement/_jcr_content.stream/1530643931055/eca19f7fc0d20adbe830d3b0b27bcc9ef72198f5/shell-scenario-sky.pdf (accessed on 25 April 2019).
60. Shell International, B.V. Shell Scenarios Sky, 2018. Available online: https://www.shell.com/promos/meeting-the-goals-of-the-paris-agreement/_jcr_content.stream/1530643931055/eca19f7fc0d20adbe830d3b0b27bcc9ef72198f5/shell-scenario-sky.pdf (accessed on 25 April 2019).
61. Shell International, B.V. New Lens Scenarios, 2013. Available online: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/new-lenses-on-the-future.html (accessed on 25 April 2019).
62. Capros, P.; de Vita, A.; Tasios, N.; Siskos, P.; Kannavou, M.; Petropoulos, A.; Evangelopoulou, S.; Zampara, M.; Papadopoulos, D.; Nakos, C.; et al. *EU Reference Scenario 2016-Energy, Transport and GHG Emissions Trends to 2030*; Publications Office of the European Union, Luxembourg, Luxembourg, 2016; ISBN 978-92-79-52374-8.
63. REflex. REflex—Analysis of the European Energy System. Available online: http://reflex-project.eu/ (accessed on 5 May 2019).
64. Miller, C.A.; O'Leary, J.; Graffy, E.; Stechel, E.B.; Dirks, G. Narrative futures and the governance of energy transitions. *Futures* **2015**, *70*, 65–74, doi:10.1016/j.futures.2014.12.001.
65. Rounsevell, M.D.A.; Metzger, M.J. Developing qualitative scenario storylines for environmental change assessment. *WIREs Clim. Chang.* **2010**, *1*, 606–619, doi:10.1002/wcc.63.
66. O'Mahoney, T. Integrated Scenarios for Energy: A Methodology for the Short Term; Working Paper, DIT; Available online: https://arrow.tudublin.ie/futuresacart/23/ (accessed on 11 February 2020).
67. Trutnevyte, E.; Barton, J.; O'Grady, Á.; Ogunkunle, D.; Pudjianto, D.; Robertson, E. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. *Technol. Forecast. Soc. Chang.* **2014**, *89*, doi:10.1016/j.techfore.2014.08.018.
68. Alcamo, J. Environmental futures. In *The Practice of Environmental Scenario Analysis*; Elsevier: Amsterdam, The Netherlands, 2009; ISBN 0080932983.
69. Energiesystemanalyse. Energy System Analysis. In *Tagungsband des Workshops "Energiesystemanalyse"*; Möst, D., Fichtner, W., Grunwald, A., Eds.; Univ.-verl.: Karlsruhe, Germany, 2008; Volume 27, ISBN 9783866443891.
70. Fishbone, L.G.; Abilock, H. Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. *Int. J. Energy Res.* **1981**, *5*, 353–375, doi:10.1002/er.4440050406.
71. Loulou, R.; Goldstein, G.; Kanudia, A.; Lettila, A.; Remme, U. Documentation for the TIMES Model PART I. Available online: https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf (accessed on 5 January 2019).
72. Ma, T.; Nakamori, Y. Modeling technological change in energy systems—From optimization to agent-based modeling. *Energy* **2009**, *34*, 873–879, doi:10.1016/j.energy.2009.03.005.
73. Weidlich, A. Engineering Interrelated Electricity Markets. In *An Agent-Based Computational Approach*; Physica-Verlag HD: Heidelberg, Germany, 2008; ISBN 3790820687.
74. Sensfuß, F.; Ragwitz, M.; Genoese, M. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy* **2008**, *36*, 3086–3094, doi:10.1016/j.enpol.2008.03.035.
75. Savvidis, G.; Siala, K.; Weissbart, C.; Schmidt, L.; Borggrefe, F.; Kumar, S.; Pittel, K.; Madlener, R.; Hufendiek, K. The gap between energy policy challenges and model capabilities. *Energy Policy* **2019**, *125*, 503–520, doi:10.1016/j.enpol.2018.10.033.
76. Hladik, D.; Fraunholz, C.; Manz, P.; Kühnbach, M.; Kunze, R. A Multi-Model Approach to Investigate Security of Supply in the German Electricity Market. In Proceedings of the 2018 15th International Conference on the European Energy Market (EEM), Piscataway, NJ, USA, 27–29 June 2018; pp. 1–5, ISBN 978-1-5386-1488-4.
77. Ellersdorfer, I.; Blesl, M.; Fahl, U.; Remme, U.; Zürn, M. Energiemodelle zu Innovation und moderner Energietechnik. Analyse exogenen und endogenen technischen Fortschritts in der Energiewirtschaft. In *Energy Models for Innovation and Modern Energy Technology. Analysis of Exogenous and Endogenous Technical Progress in the Energy Industry*; LIT: Münster, Germany, 2007; ISBN 9783825800260.

78. Lechtenböhmer, S.; Palzer, A.; Pregger, T.; Gils, H.C.; Sterchele, P.; Kost, C.; Brucker, L.; Janßen, T.; Krüger, C.; Schüwer, D.; et al. RegMex—Modellexperimente und -vergleiche zur Simulation von Wegen zu einer vollständig regenerativen Energieversorgung [RegMex - Model experiments and comparisons for the simulation of paths to a completely renewable energy supply], 2018. Available online: https://epub.wupperinst.org/frontdoor/index/index/docId/7096 (accessed on 15 September 2018).
79. International Energy Agency (IEA). *World Energy Outlook 2018*; IEA: Paris, France, 2018. Available online: https://doi.org/10.1787/weo-2018-en (accessed on 11 February 2020).
80. Dönitz, E.; Shala, E.; Leimbach, T. Future Threat Scenarios for Identifying Societal Security Needs—The Methodological Approach Based on European Project Ettis. In Proceedings of the 9th Future Security—Security Research Conference, Berlin, Germany, 16–18 September 2014; Thoma, K., Häring, I., Leismann, T., Eds.; Fraunhofer Verl.: Stuttgart, Germany, 2014; pp. 516–526, ISBN 9783839607787.
81. Karlsruhe Institute of Technology; TU Dresden; Fraunhofer ISI. AVerS—Analyse der Versorgungssicherheit in Süddeutschland unter Berücksichtigung der europaweiten Kopplung der Strommärkte [Analysis of the Security of Supply in Southern Germany under Consideration of the Europe-Wide interconnection of electricity markets]. Available online: http://www.isi.fraunhofer.de/isi-de/e/projekte/318191_AVerS_Mij_2019.php (accessed on 7 December 2017).
82. SET-Nav. Strategic Energy Roadmap—The SET-Nav Project. Available online: http://www.set-nav.eu/ (accessed on 5 May 2019).
83. Rasmussen, L.B. The narrative aspect of scenario building—How story telling may give people a memory of the future. *AI Soc.* **2005**, *19*, 229–249, doi:10.1007/s00146-005-0337-2.
84. Miller, M.; Alberini, A. Sensitivity of price elasticity of demand to aggregation, unobserved heterogeneity, price trends, and price endogeneity—Evidence from U.S. Data. *Energy Policy* **2016**, *97*, 235–249.
85. ENTSO-E. Ten Year Net Development Plan 2018. Available online: https://tyndp.entsoe.eu/#cost-benefit-analysis-methodology-cba-20-for-tyndp-project-assessment (accessed on 11 November 2019).
86. C/sells. C/sells-Facts. Available online: https://www.csells.net/en/about-c-sells/fakten.html (accessed on 10 December 2018).
87. C/sells. C/sells Guiding Principle. Available online: https://www.csells.net/en/about-c-sells/guiding-principle.html (accessed on 11 November 2019).
88. Ducot, G.; Lubben, G.J. A typology for scenarios. *Futures* **1980**, *12*, 51–57, doi:10.1016/S0016-3287(80)80007-3.
89. Kronenberg, T.; Martinsen, D.; Pesch, T.; Sander, M.; Fischer, W.; Hake, J.-F.; Markewitz, P.; Kuckshinrichs, W. Energieszenarien für Deutschland: Stand der Literatur und methodische Auswertung [Energy scenarios for Germany: State of the literature and methodological evaluation], 2011. Available online: www.fz-juelich.de/SharedDocs/Downloads/IEK/IEK-STE/EN/publications/research_reports/2011/report_13_2011.pdf?__blob=publicationFile (accessed on 19 November 2018).
90. Federal Ministry for the Environment; Nature Conservation; Building and Nuclear Safety (BMUB); Climate Action Plan 2050—Principles and Goals of the German government's Climate Policy, 2016. Available online: https://www.bmu.de/en/publication/climate-action-plan-2050-principles-and-goals-of-the-german-governments-climate-policy/ (accessed on 19 November 2018).
91. Weimer-Jehle, W. Cross-impact balances: A system-theoretical approach to cross-impact analysis. *Technol. Forecast. Soc. Chang.* **2006**, *73*, 334–361, doi:10.1016/j.techfore.2005.06.005.