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Tim Höfer and Reinhard Madlener

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Institute for Future Energy Consumer Needs and Behavior (FCN)

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Authors’ addresses:

Tim Höfer, Reinhard Madlener  
Institute for Future Energy Consumer Needs and Behavior (FCN)  
School of Business and Economics / E.ON Energy Research Center  
RWTH Aachen University  
Mathieustrasse 10  
52074 Aachen, Germany  
E-Mail: THoefer@eonerc.rwth-aachen.de, RMadlener@eonerc.rwth-aachen.de

Publisher:  
Prof. Dr. Reinhard Madlener  
Chair of Energy Economics and Management  
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)  
E.ON Energy Research Center (E.ON ERC)  
RWTH Aachen University  
Mathieustrasse 10, 52074 Aachen, Germany  
Phone: +49 (0) 241-80 49820  
Fax: +49 (0) 241-80 49829  
Web: www.fcn.eonerc.rwth-aachen.de  
E-mail: post_fcn@eonerc.rwth-aachen.de
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Tim Höfer and Reinhard Madlener

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany

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Abstract

This paper presents an evaluation of four energy transition scenarios under consideration of multiple stakeholder opinions. We construct a multi-criteria group decision model that applies Value-Focused Thinking to construct a holistic objective system and Multi-Attribute Utility Theory to evaluate the energy transition scenarios. Although the individual scenario evaluations show that the opinions of the stakeholders towards a sustainable energy transition differ largely, we are able to derive three main strands of opinions among the considered stakeholders. For this, we apply a clustering technique to identify and bundle the stakeholders into three groups. This bundling of stakeholder interests enables the identification of the most important policy recommendations for a sustainable energy transition. For the case of Germany, these are to reduce GHG and pollutant emissions and at the same time enable citizens’ participation, limit the visual impact on landscapes, and ensuring internationally comparable energy-related political frameworks for the economy. For the case of a sustainable energy transition in Germany, we find that the stakeholders considered prefer either the highly ambitious climate protection scenario (Scenario B) or the Pan-European scenario (Scenario C). The reference scenario, which was developed by the German Transmission System Operators (TSOs), turns out to be relatively unpopular.

JEL Classification: D70, D81, O52, Q48
Keywords: Value-Focused Thinking, Group Decision Making, MAUT, Energy Scenarios
1 Introduction

In order to tackle climate change, governments all over the world have launched initiatives to reduce greenhouse gas (GHG) emissions. The initiatives involve the decarbonization of the energy, transport, heat, and industry sectors, amongst others. However, there is not yet a social consensus on the pathway and the intensity of decarbonization of these sectors. Besides limiting climate change, some key objectives of the energy transformation comprise the reduction of local ecological effects on the ecosystem, enhancing economic welfare in the country by, for example, minimizing the costs for consumers and maintaining the acceptance of citizens, amongst others. A sustainable energy transition needs to consider all of these objectives. However, the different objectives inherit trade-offs, since achieving one objective might imply that another objective cannot be fulfilled to an acceptable degree.

Policy-makers who want to regulate a sustainable energy transition need to consider and trade off a multitude of such objectives. This challenging situation is aggravated by the fact that different stakeholders have diverging interests and opinions on how the energy transformation should take place. The task of policy-makers is to incorporate these opinions into the implementation of the energy transformation. There is a need to help decision-makers in managing these challenges by deriving different stakeholder opinions towards the future energy transformation and by condensing the guiding principles of the stakeholder interests. In this study, we have conducted workshops with different stakeholders from energy-policy-related fields to assess the suitability of four sustainable energy transition scenarios. In the first step, we apply the Value-Focused Thinking (VFT) method (Keeney, 1992) in order to determine and structure the objectives of the stakeholders. We then define indicators that allow us to calculate the fulfillment of the objectives by the scenarios. Subsequently, we use Multi-Attribute-Utility-Theory (MAUT) (Keeney, 1982; Raiffa, 1970) to weight these objectives and to evaluate the scenarios based on the subjective preferences of the stakeholders. Finally, we use a clustering technique to allocate the stakeholders to groups and to derive the essence of their interests. Based on these findings, advice on how to address the different groups is given.
The analysis presented is based on the group decision-making process developed in Höfer et al. (2019). While Höfer et al. (2019) lay the methodological foundation for eliciting stakeholder preferences, we use the developed process to derive policy implications for the future energy transition in Germany. More specifically, Höfer et al. (2019) define the objective system, comprising means and fundamental objectives, and elicit the relevance of the objectives, which is expressed by the relative impact of the means objective on the fundamental objectives and the relative weights of the fundamental objectives. In their analysis, Höfer et al. (2019) apply these results in order to evaluate four qualitative energy transformation alternatives. We use that objective system and the derived relevance of the objectives to evaluate quantitative energy transition scenarios, to form stakeholder groups with similar opinions on how the future energy system should look like, and to derive policy implications based on the stakeholder assessments. Both analyses are conducted in the same workshops and incorporate the same stakeholders.

The original contribution of our analysis compared to the related scientific literature is essentially threefold. First, we apply a sound methodological framework to cover all relevant steps for giving scientific policy advice for a sustainable energy transition. In contrast, other studies either focus on specific methodological parts of evaluating energy transition scenarios and omit others, do not include stakeholders in all parts of their analysis, restrict the study to very basic scenarios or individual energy generation technologies, or do not give policy recommendations based on their findings. Second, we incorporate stakeholders from different energy-related fields in defining the objective system by means of the VFT method, in evaluating the energy transition scenarios with MAUT, and in creating the scenarios. Thereby, the scenarios encompass the most relevant aspects of the energy transition, such as the electricity generation structure and the energy demand in the electricity, heat, transport, and industry sectors, amongst others. Third, we apply a clustering technique in order to identify stakeholder groups and to give policy advice. This policy advice incorporates and elaborates diverging stakeholder opinions. Although each of these elements has been applied individually in the energy context, the combination of all aspects constitutes a unique and meaningful concept. In the following, we present the most relevant related literature on Multi-Criteria Decision Methods (MCDM) in the
energy field and explain some of its limitations.

One of the first multi-criteria evaluation studies on energy scenarios was conducted by Georgopoulou et al. (1998). The authors include eleven stakeholders in developing and assessing six energy scenarios with the PROMETHEE II outranking method. The scenarios depict a high, medium, and low penetration of RES, and put different emphasis on wind, solar, and biomass power plants. However, the stakeholders are not involved in establishing the evaluation of the criteria and no policy recommendations are given. Diakoulaki et al. (2005) also examine the Greek energy transition and apply the PROMETHEE method in order to evaluate different scenarios. The scenarios comprise different installed capacities and the amount of electricity generation of conventional power plants and RES. While official authorities develop the scenarios and an MCDM is applied, no stakeholders are involved in establishing the criteria and evaluating the scenarios. Furthermore, the authors do not give any advice on how policy-makers should deal with the results. Stagl (2006) investigates the opinions of UK citizens for the future supply of electricity. Three scenarios with different capacities of gas, coal, nuclear, and RES, varying degrees of energy efficiency, and a distinct amount of energy imports depict the possible future energy system. A simple version of a multi-criteria analysis is performed but no policy recommendations are given based on the results. Madlener et al. (2007) conducted the most similar study to ours. In their study, stakeholders develop qualitative energy transformation alternatives for Austria, which are then translated into quantitative scenarios by the researchers, and evaluated by the stakeholders. The qualitative alternatives vary in their energy demand (high/low), the amount of RES (high/low), the technology mix (heat/power), and the deployment of RES (decentral/central). The five quantitative scenarios depict the amount of energy produced per RES. The PROMETHEE method yields a ranking of the scenarios based on the stakeholder assessment. However, the authors do not elicit on different stakeholder opinions towards the scenarios, do not give policy recommendations on how to implement their findings, and do not include the stakeholders in the formulation of the evaluation criteria. The most recent related study that we are aware of was conducted by Santoyo-Castelazo and Azapagic (2014). The authors apply a life-cycle assessment and a multicriteria decision analysis in order to evaluate eleven
possible developments of the energy system in Mexico until 2050. The study presents a
detailed depiction of electricity generation scenarios under different climate change tar-
ggets and a comprehensive set of evaluation criteria. The focus is to assess the fulfillment
of the criteria by the scenarios. A major drawback of this analysis is that the authors do
not include stakeholders in the evaluation of the scenarios. Furthermore, stakeholders are
not involved in creating the energy scenarios and defining the evaluation criteria. Due to
the lack of different stakeholder opinions, the authors refrain from giving policy advice.
In addition to the described papers, there are multitudes of studies that evaluate single
energy technologies or single projects instead of comprehensive energy scenarios. The
literature reviews by Kumar et al. (2017), Mardani et al. (2015), Abu Taha and Daim
(2013), or Kowalski et al. (2009) give a good overview of such studies. Finally, to the best
of our knowledge, none of the studies applies VFT in order to derive objectives for the
energy transition.

In summary, the three goals of this paper are: (1) the evaluation of comprehensive
energy transformation scenarios where multiple stakeholders are involved in every evalua-
tion step; (2) the assessment of similarities and differences in the stakeholder evaluations;
and (3) the derivation of recommendations for policy-makers. (1) depicts which alter-
native energy transformation scenario is the one most preferred by the relevant societal
stakeholders. (2) explains why certain stakeholders favor a specific scenario by investigat-
ing their preferences. (3) concludes with practical advice for policy-makers on how to
address different stakeholders in order to implement a sustainable energy transition. Note
that, although the application of the decision-making process is illustrated for the case of
Germany, it can be applied to other energy systems worldwide.

The remainder of the paper is structured as follows. Section 2 describes the method-
ology and the applied procedure for evaluating the scenarios. Section 3 introduces the
considered stakeholders, describes the scenarios and the objective system, and explains
how the fulfillment of the scenarios is measured. The results of the analysis are described
in Section 4. Section 5 summarizes the policy insights and concludes.
2 Group Decision-Making Procedure

The evaluation of the energy transition scenarios is based on the MAUT procedure proposed by Keeney (1982) and Raiffa (1970). This process involves four steps, which are (1) structuring the decision problem, (2) determining the performance of alternatives, (3) assessing the preferences of decision-makers, and (4) evaluating the alternatives. Figure 1 shows the process for evaluating the scenarios, which is based on Höfer et al. (2019). The study at hand focuses on the methodological approach to establish a group decision-making process. We alter this procedure to fit it to the evaluation of quantitative scenarios instead of qualitative alternatives. This is an important step for giving meaningful policy recommendations. The modifications concern steps 1.1, 2.1, and 4.2. In step 1.1, we model quantitative scenarios based on the specifications of the previously developed qualitative alternatives. In step 2.1, we define indicators that enable the calculation of the degree of fulfillment of the objectives based on the scenario results, instead of letting experts assess the achievement of the objectives based on qualitative information. Lastly, we have added step 4.2 in which we allocate the stakeholders to three main interest groups, which enables us to derive some concrete energy policy implications.

The first step (1) of the procedure involves generating the scenarios and specifying the objectives of the decision-makers (Keeney, 1982). The development of the scenarios is a two-step procedure (step 1.1). First, the considered stakeholders define mostly qualitative energy transformation alternatives, which depict a variety of self-consistent and socially acceptable developments in the German energy sector until 2030. Thereby, the qualitative alternatives encompass the developments in the electricity, transport, and heat sectors under different GHG emission reduction ambitions. The complete process of how to establish qualitative alternatives is described in Seebach and Timpe (2019). These alternatives are used as a framework to establish quantitative scenarios with two energy models\(^1\). The second part of step (1) – step 1.2 – comprises the specification of the objectives of the stakeholders for the energy transition. We apply VFT in order to identify and structure these objectives (Keeney, 1992). The rationale behind this method is that the

\(^1\)The Öko-Institut is responsible for defining the qualitative alternatives and both the Institute of Energy Economics at the University of Cologne (EWI) and the Öko-Institut model the scenarios.
decision-makers define objectives for the decision context based on their own values. The identification of the objectives is structured in an individual part, where all stakeholders list their objectives individually, and a group part, where the stakeholders discuss these objectives. The group discussion comprises the reformulation and the selection of the relevant objectives. Subsequently, we structure these objectives in fundamental and means objectives. *Fundamental objectives* stem directly from the value system of the decision-maker and are pursued for their own sake. In contrast, *means objectives* only contribute to the achievement of other (fundamental) objectives (Keeney, 1992). In this context, we assign each means objective to one or several fundamental objectives (see Figure 2).

In our procedure, the purpose of the means objective is to measure the performance of the scenarios in the fundamental objectives, which are again used to evaluate the energy transformation scenarios. We present and describe the resulting means-end-network in Section 3.3.

The second step (2) determines the performance of the scenarios by, firstly, assessing the fulfillment of the means objectives (step 2.1) and, secondly, identifying the perfor-
mance of the fundamental objectives (step 2.2). In step 2.1, we calculate the fulfillment scores of the scenarios in each means objective based on quantitative indicators. The fulfillment scores determine how well the scenarios achieve the means objectives. Indicators represent measures for assessing the achievement of means objectives. We present all indicators in detail in Section 3.3. In step 2.2, the stakeholders establish impact functions to translate the objective fulfillment scores into individual performance scores. Furthermore, the stakeholders assess the relative impact of the means objectives to calculate the performance of the scenarios in the fundamental objectives. The concept behind the impact functions is that the stakeholders may have different opinions on how well an objective fulfillment score achieves a means objective. The idea behind determining the relative impacts of the means objectives is that these have different effects on the achievement of the fundamental objective. Notice that whereas step 2.1 is a unique outcome of this study, the results of step 2.2 originate from Höfer et al. (2019). Figures A.1 and A.2 in the Appendix show the derived individual impact functions of the stakeholders. The individual relative impacts of the means objectives on the fundamental objectives are depicted in Figure A.3 in the Appendix. Equation (1) shows a formal representation of calculating the performance score in each fundamental objective:

\[
IP_{n,k}(FO_i) = \sum_{j=1}^{l} RI_k(MO_j) \cdot IP_{n,k}(MO_j),
\]

where \( IP \) is the individual performance score, \( n \) represents the respective scenario, \( k \) is the considered stakeholder, \( FO_i \) is the \( i \)-th fundamental objective, \( RI \) denotes the relative impact of the \( j \)-th means objective \((MO)\), and \( IP \) indicates the individual performance of the scenario in the respective means objective.

In step (3) we determine the preferences of the stakeholders. For this, the stakeholders assess the weights of the fundamental objectives, which indicate how important the objectives are for evaluating the scenarios. The stakeholders assess these relative weights by applying the trade-off method (Keeney, 1982). In this method, the stakeholders are asked to compare two alternatives, whereby each alternative fulfills two fundamental objectives to a certain degree. The fulfillment score of the objectives is varied until the stakeholder
states that s/he is indifferent between the two alternatives. The results of step (3) are generated in Höfer et al. (2019) and are only reported here for completeness. Figure A.4 in the Appendix depicts the individual relative weights of the fundamental objectives.

The last step (4) of the evaluation of the scenarios is to compute the stakeholder-individual utilities (step 4.1) for the scenarios and allocate the stakeholders to groups (step 4.2). MAUT assumes that a rational decision-maker chooses the scenario with the highest utility. We calculate these utilities by combining the performance scores of the scenarios in each fundamental objective – step (2) – with the relative weights of the fundamental objectives – step (3). A formal representation of this is:

$$u_k(SC_n) = \sum_{i=1}^{m} RW_k(FO_i) \cdot IP_k(FO_i),$$  

where $u_k$ is the utility of stakeholder $k$, $SC_n$ stands for the $n$-th scenario, $RW$ is the relative weight, $FO_i$ is the $i$-th fundamental objective, and $IP$ denotes the individual performance of the scenarios in the respective fundamental objective. To use this additive utility function, the objective system needs to be fundamental, complete, non-redundant, preference-independent, and measurable (von Nitzsch, 2017). The last part of the analysis is the configuration of stakeholder groups and the interpretation of the results (step 4.2).

We perform a $k$-means clustering technique based on the stakeholder-individual scenario evaluation to form stakeholders groups. The technique aims at partitioning the stakeholders into $k$ clusters, where each stakeholder belongs to the cluster with the nearest mean utility score. The number of clusters ($k$) is fixed $a$ priori and is determined by applying the Bayesian Information Criterion (BIC). The BIC is a procedure that chooses a model for which the BIC criterion is maximized (Schwarz, 1978). Thereby, the likelihood criterion is penalized by the model complexity. We analyze the resulting stakeholder groups regarding the evaluation of the scenarios (step 4.1), the assessment of relative impacts of the means objectives (step 2.2), and the determination of the relative weights of the fundamental objectives (step 3). Based on this, we explain why the stakeholder groups prefer specific scenarios, and we derive policy implications for the implementation of a socially accepted energy transition.
3 Scenario Evaluation Process

The presented conceptual framework was applied in a recently conducted project. The aim of the project was to develop and evaluate a variety of self-consistent and socially acceptable developments of the transformation of the German energy system until 2030. Thereby, the transformation scenarios need to consider all imaginable and exclude all unlikely developments in the energy system. To include a variety of different opinions on this, multiple stakeholders with different political interests were incorporated in the project and participated at several workshops. The idea of including multiple stakeholders in developing and evaluating the energy transition scenarios is to ensure a strong validity of the results. In the following, we give an overview of the main components of the scenario evaluation – the involved stakeholders, the developed scenarios, the derived objective system, and the applied procedure for calculating the fulfillment of the means objectives – to illustrate the meaningfulness of the results.

3.1 Stakeholders

To represent the opinions of various actors in the field of energy policy, the project team\textsuperscript{2} elicited eleven stakeholders from five main interest groups. The selection of the stakeholders is in line with the recommendations of Henseling et al. (2016) and Hänlein and El-Alaoui (2015), respectively, who recommend incorporating stakeholder groups from politics/administration, environment, science, media, industry, civil society, consumer organizations, landowners, or power generators.

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
Interest group & Stakeholders \\
\hline
Energy & Utility association \\
& Association for renewable energy \\
& Association of municipal utilities \\
Economy & Industry association \\
& Labor union \\
Environment & Environmental NGOs (2) \\
Landowners & Agriculture association \\
Society & Consumer organization \\
& Municipal association \\
& Church \\
\hline
\end{tabular}
\caption{Considered stakeholders for the evaluation of energy transition scenarios}
\end{table}

\textsuperscript{2}The elicitation of stakeholders was led by 'Environmental Action Germany' (Deutsche Umwelthilfe, DUH) and supported by the Karlsruhe Institute of Technology (KIT) and the Öko-Institut.
3.2 Scenarios

Scenario A is the ‘reference scenario’ and is based on the latest National Grid Development Plan (Netzentwicklungsplan, NEP\textsuperscript{3}) of the German Transmission System Operators (TSOs). This scenario has the least ambitious climate protection goals of all scenarios considered. Hence, the share of RES is comparatively low and the energy demand is relatively high. Scenario B is in many ways contrasting to Scenario A. It has the highest climate protection goals of all scenarios, which induces a very low energy demand accompanied by a very high share of RES. Coal-fired power plants do not operate anymore in 2030. Scenarios C and D have the same climate protection ambitions – which lie in between the ambitions of Scenarios A and B – and the same energy demand characteristics. The difference between the two scenarios is that Scenario C is a more European-oriented energy transition (‘Pan-European scenario’), whereas Scenario D is a ‘decentral scenario’. In this context, \textit{decentral} means that RES are located close to demand centers and that citizens have a large influence on energy system planning. In contrast, the location of RES is chosen based on the lowest generation costs in Scenario C. Table A.1 in the Appendix summarizes the main characteristics of the scenarios.

3.3 Objective System

The objective system consists of 13 means objectives and four fundamental objectives (see Figure 2). Thereby, the four fundamental objectives are comprised of one or several means objectives and the means objectives contribute to one or multiple fundamental objectives. Theoretically, a fundamental objective is achieved completely if all means objectives are fulfilled entirely. The fundamental objectives comprise two ecological objectives (\textit{FO 1} and \textit{FO 2}), one economic objective (\textit{FO 3}), and one social objective (\textit{FO 4}). Thereby, \textit{FO 4} incorporates six means objectives that are genuine ecological or economic objectives. This highlights that economic and ecological objectives also have implications for the approval of the energy transition. Table A.2 in the Appendix further describes the objectives and their consequences.

\textsuperscript{3}Scenario B of the National Grid Development Plan (NEP 2030, version 2019) is the basis for Scenario A of our analysis.
3.4 Indicators

We use so-called indicators to assess the fulfillment of the means objectives (step 2.1), which indicate how well the scenarios will achieve the means objectives. Nine of the means objectives are described by a single indicator. For these means objectives we can calculate the indicator score directly. Four of the means objectives are composed of multiple indicators. In the case of multiple indicators being present, the stakeholders assess the impact of the single indicators on the means objective. This results in a weighting of the indicators, in which a higher weight signifies a higher impact of the indicator on the fulfillment of the means objective. We use the mean weight of the indicators over all stakeholders to calculate the indicator score. We compute this indicator score for all scenarios and the base year, which is 2015. The best of these indicator scores – the highest score for \( MO \, 1, \, 3, \, 5, \, 10, \) and \( 13 \) – and the lowest score for all other means objectives – receives a fulfillment score of 100\% and the worst indicator score gets a fulfillment score of 0\%. Table 2 gives an overview of all indicators. The results of the fulfillment score are shown in Figure 3.

**Figure 2**

*Objective system for the evaluation of energy transition scenarios. Source: based on Höfer et al. (2019)*
<table>
<thead>
<tr>
<th>MO</th>
<th>Indicator</th>
<th>Scope</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GHG emissions reduction</td>
<td>Reduction from 1990 to 2030 [%]</td>
<td>UBA (2017), UBA (2018b)</td>
</tr>
<tr>
<td>2</td>
<td>Impact score</td>
<td>Onshore wind [MW], offshore wind [MW], open-cast mining [m²], open-space PV [m²], biomass [m³], biogas [m³], transmission grid [m²], location of RES</td>
<td>Aretz et al. (2013); Hirschl et al. (2013)</td>
</tr>
<tr>
<td>3</td>
<td>Reduction of air pollutants</td>
<td>Unweighted, arithmetic mean reduction of ammonia (NH₃), nitrogen oxide (NOₓ), sulfur dioxide (SO₂), volatile organic compounds (NMVOC), particulate matters (PM₂.₅)</td>
<td>UBA (2017), UBA (2018b)</td>
</tr>
<tr>
<td>4</td>
<td>Impact score</td>
<td>Onshore wind [m²], open-space PV [m²], conventional power plants [m²], transmission towers [m²], transformer stations [m²], biomass [m²], open-cast mining [m²]</td>
<td>BNetza (2017)</td>
</tr>
<tr>
<td>5</td>
<td>Added value of RES</td>
<td>Onshore wind turbines [€], open-space and rooftop PV [€], biomass [€] – separately for including and not including local citizens</td>
<td>Aretz et al. (2013); Hirschl et al. (2013)</td>
</tr>
<tr>
<td>6</td>
<td>Land use</td>
<td>Onshore wind [m²], open-space PV [m²], conventional power plants [m²], transmission towers [m²], transformer stations [m²], biomass [m²], open-cast mining [m²]</td>
<td>BNetza (2017)</td>
</tr>
<tr>
<td>7</td>
<td>Market share</td>
<td>Four largest electricity companies in Germany²</td>
<td>BNetza (2017)</td>
</tr>
<tr>
<td>8</td>
<td>Annualized costs³</td>
<td>Investment costs for additional power plants (RES, gas, pumped storage) and PtX plants [€/a], fuel costs in the electricity sector [€/a], reinforcement costs for the electric transmission and distribution grid [€/a]</td>
<td>APERC (2007), Kuyt et al. (2009)</td>
</tr>
<tr>
<td>9</td>
<td>Net Energy Import Dependency (NEID)⁴</td>
<td>Mineral oil, lignite and hard coal, natural gas, RES, hydrogen PtX⁵</td>
<td>APERC (2007), Kuyt et al. (2009)</td>
</tr>
<tr>
<td>10</td>
<td>Comparability score</td>
<td>Reduction of GHG emissions [%], share of RES on total electricity generation [%], the wholesale electricity prices [€] in Germany and ENTSOE countries⁶</td>
<td>BDEW (2018)</td>
</tr>
<tr>
<td>11</td>
<td>Price spread</td>
<td>Differences between electricity prices for large- and small-scale consumers compared to the spread in 2015</td>
<td>BDEW (2018)</td>
</tr>
<tr>
<td>12</td>
<td>Impact score</td>
<td>Onshore wind [MW], offshore wind [MW], open-cast mining [m²], open-space PV [m²], biomass [m³], biogas [m³], transmission grid [m²], location of RES</td>
<td>BNetza (2017)</td>
</tr>
</tbody>
</table>

1. We assume that the area correlates with the average mining output of the last ten years (BMWi, 2018b). 2. Yearly-generated electricity of the four largest energy companies in Germany (RWE, Vattenfall, EnBW, E.ON) divided by total electricity generated. Ownership structure derived from Monopolkommission (2017) and trend:research (2017). 3. The amortization period for RES and the grid infrastructure is 20 years and 40 years, respectively. The interest rate is 7.91%. The figures stem from the German Electricity Grid Charges Ordinance (StromNEV, http://www.gesetze-im-internet.de/stromnev/). 4. Measures the diversity of supply and the import dependence of an economy. Eq. (A.3) in the Appendix depicts the formula for the calculation of the NEID indicator. 5. PtX refers to electricity that is converted to other energy sources (e.g. hydrogen). 6. ENTSOE stands for European Network of Transmission System Operators (www.entsoe.eu) and is an association of European TSOs, presently comprising members from 36 countries all across Europe.
4 Results

4.1 Fulfillment of the Means Objectives by Scenarios

The output of the energy models is used to calculate the fulfillment of the indicators of each means objective by the scenarios (step 2.1). Figure 3 and Table A.3 in the Appendix show the different fulfillment scores of the scenarios. Here, the fulfillment score of $MO\ 11$ is not depicted. The reason for this is that the stakeholders have different opinions about a fair cost distribution. Table A.4 in the Appendix shows the individual fulfillment scores of $MO\ 11$.

ScENARIO A, which is the reference scenario developed by the German TSOs, performs relatively poorly in the fulfillment score of most means objectives compared to the other scenarios. It only achieves the highest scores of all scenarios in two means objectives ($MO\ 8$, $MO\ 10$), which are mainly associated with economic aspects. The costs related to energy transition measures ($MO\ 8$) are the lowest of all scenarios, since comparably few measures – e.g. expanding RES or incorporating flexibility options – need to be undertaken to achieve the (relatively modest) GHG emission reduction goal. Furthermore, Scenario A performs best of all scenarios in ensuring internationally comparable energy-related political frameworks for the economy ($MO\ 10$). The reason is that the German and European climate protection targets are very similar (as percentages). In contrast, Scenario A induces the lowest GHG emission reductions ($MO\ 1$), reduces the
least amount of energy-related pollutant emissions (MO 3), creates the least added value in the renewable energy sector (MO 5), promotes the competition intensity in the energy market less than the other scenarios (MO 7), and is not primarily oriented towards enabling the participation of citizens in the sustainable energy transformation (MO 13). The main drivers for these developments are that RES have comparably low and conventional power plants relatively high shares in the total energy supply. A further driver is that the level of electrification of the transport, heat, and industry sectors is relatively low compared to the other scenarios.

Scenario B is an extreme scenario in multiple aspects, since it has either the highest or the lowest fulfillment score in several of the means objectives. The majority of the results are caused by the strong expansion of RES and the associated decrease in electricity generation by conventional power plants. Further important factors are the high electrification of the transport and heat sector, and the relatively high participation of citizens in the energy transformation. The significant reduction of GHG and energy-related pollutant emissions (MO 1 and MO 3), the large added value in the renewable energy sector (MO 5) and the increased competition intensity in the energy market (MO 7) can be directly traced back to these factors. Furthermore, the import dependency (MO 9) is reduced more than in the other scenarios, since the share of imported energy sources on the total primary energy demand is lower. The downside of the strong expansion of RES is the increased land use of the energy system (MO 6). This also negatively impacts nature and species (MO 2), the local ecosystem (MO 4), and the visual landscape (MO 12). Additionally, higher costs for the transformation of the energy sector (MO 8) and higher discrepancies in the climate protection ambitions of Germany and of the EU (MO 10) are present. The discrepancies are mainly caused by a greater proportion of RES in the total electricity generation and the higher reductions of GHG emissions in Germany compared to the remaining ENTSOE countries.

Scenarios C and D have the same climate protection ambitions, and thus many similarities in the energy consumption structure. At the same time, these two scenarios differ in the generation structure and the involvement of citizens in the energy transition. Scenario C, like Scenario A, promotes a central power generation and only marginally
engages citizens in the energy transition process. Scenario D, on the other hand, emphasizes a decentralized generation structure and premises, as Scenario B does, a high level of involvement of citizens in the energy transition process. Therefore, Scenarios A and C, as well as Scenarios B and D, follow a similar trend in the fulfillment scores of the means objectives. Thereby, Scenario C performs better than Scenario A in most means objectives. Whereas Scenarios B and D perform well in increasing the added value in the renewable energy sector (MO 5) and enabling the participation of citizens in the energy transformation (MO 13), Scenarios A and C use less land for the energy system (MO 6), which also leads to a lower impact on the ecosystem (MO 4). Furthermore, Scenarios A and C are associated with lower costs for measures related to the energy transition than Scenarios B and D (MO 8). The specific feature of Scenario D is that it highlights the organizational and financial participation of citizens in energy infrastructure projects and enables the generation of electricity by consumers. Therefore, Scenario D performs best in increasing the added value in the renewable energy sector (MO 5) and in enabling the participation of citizens in the energy transformation (MO 13). Scenario C, in contrast, has the least negative impacts on nature and species (MO 2) and the ecosystem (MO 4), and requires the least amount of land.

4.2 Evaluation of Scenarios

4.2.1 Individual Utility Scores of the Scenarios

Figure 4 shows the individual evaluations of the scenarios. It is evident that most stakeholders rate Scenario A as the least preferable and that all stakeholders prefer at least one other scenario over Scenario A. Furthermore, Scenarios B and C are rated as the best alternatives. The other two scenarios are dominated by one or multiple other scenarios.
4.2.2 Group Evaluation of the Scenarios

Next, we apply a $k$-means clustering technique based on the individual scenario evaluations to form stakeholder groups. The result of this analysis yields three stakeholder groups – the socio-ecological group (SH 1-4), the socio-economic group (SH 5-8), and the economic-ecological group (SH 9-11) – based on similar scenario evaluations (Table A.5 in the Appendix depicts the statistics based on which we derive the number of clusters). The socio-ecological group prefers Scenario B over all other scenarios and assesses Scenarios C and D as equally, but less suitable than Scenario B. The socio-economic group also judges Scenario B as the best alternative, however, Scenarios C and D are considered to be almost as good. In comparison, the economic-ecological group prefers Scenario C over all other scenarios, rates the suitability of Scenario A higher than the other stakeholders do, and assigns relatively low utility scores to Scenarios B and D. The main differences in the scenario evaluations stem from the diverging assessment of the relative impacts of the means objectives on the fundamental objectives (step 2.2) and of the relative weights of the fundamental objectives (step 3). Figures 5 and 6 depict the mean relative impacts of the means objectives and the mean relative weights of the fundamental objectives, respectively, as assessed by the groups. Additionally, Figures A.5 and A.6 in the Appendix show the impact functions of $MO\ 1$ and $MO\ 11$, respectively. Tables A.6 and A.7 in the Appendix depict the mean values of the relative impacts of the means objectives the relative weights of the fundamental objectives and the standard deviations for each group.
Figure 5  
Mean relative impact of means objectives on fundamental objectives

Figure 6  
Mean relative weights of the fundamental objectives for each group
4.2.3 Socio-Ecological Group

The socio-ecological group states that limiting global climate change and promoting the approval of the citizens are the most important objectives of the energy transition. In contrast, local ecological effects induced by the energy system and the impacts on economic welfare arising from the changes in the energy system, are less important objectives.

Interestingly, the socio-ecological group thinks that reducing GHG emissions does not only lead to a mitigation of climate change but also helps to foster the approval of citizens for the energy transition. A possible explanation is that the reduction of GHG emissions functions as a benchmark for the energy transition, thus showing the advancements of the transformation. Furthermore, policy-makers should try to reduce the costs of the energy transition and promote the participation of citizens in infrastructure projects in order to increase the acceptance by the citizens. Thereby, guaranteeing organizational and financial participation of citizens in infrastructure projects improves the acceptance of the energy transition the most. In contrast to the other two groups, the socio-ecological group states that the visual impact of the energy system on the landscape has a relatively low impact on the acceptance of the energy transition. Whether people are well disposed or not towards the change of landscapes induced by, for instance, the development of RES or the expansion of transmission lines is a highly subjective matter. While there is a common positive attitude towards RES in general, negative attitudes prevail on the local level (van der Horst, 2007; Wolsink, 2007). The stakeholders of this group maintain their attitudes on the global level. Another, rather unimportant feature of the approval of citizens for the energy transition is the promotion of the competition intensity in the energy market. This might be explained by the relatively high and rising competition in the market since its liberalization (BNetzA, 2017).

Although for this group local ecological effects of the energy system are less important than limiting climate change and promoting the approval of citizens, the stakeholders acknowledge that negative effects on human health and the environment should be mitigated. In their opinion, reducing energy-related pollutant emissions – e.g. by reducing the energy demand or switching to renewable-based fuels – has the highest impact on reducing the negative effects on human health and the environment. This assessment reflects
the fact that air pollutants – especially nitrogen dioxide (NO\textsubscript{2}) and particulate matters (PM\textsubscript{2.5}) – are still very high in urban areas in Germany (UBA, 2018a). In contrast, reducing the direct negative impacts – e.g. effects on bird and bat migration, noise intrusion, and shadow flickering – of the energy system on nature and species and reducing the land use of the energy system are not considered to have a high negative impact on human health and the environment.

The stakeholders claim that reducing the import dependency and decreasing the costs for measures related to the energy transition have the highest positive effects on economic welfare. The reasons for these statements are that fewer imports reduce the political and financial dependency on foreign countries, and that lower costs decrease the burden for small and large consumers alike. This again has positive effects on the purchasing power of consumers. Furthermore, the socio-ecological group states that the energy transition should particularly contribute to increasing the added value in the renewable energy sector and thus to promoting the long-term economic welfare, since this sector is a promising pillar of the future national economy. In contrast, the stakeholders declare that the increasing land prices, due to more land dedicated to the energy system, only affects a small group of people and, therefore, has only a minor impact on the economic welfare. The reason for the low relevance of increasing the competition intensity in the energy market might be that the intensity has been increasing since the liberalization of the energy market (BNetzA, 2017). Apparently, the stakeholders believe that this will not be reversed again. Ensuring internationally comparable energy-related political frameworks for the economy is also not considered to be an important lever to increase or maintain economic welfare. This implies that the stakeholders do not think that diverging climate protection efforts in Germany and the remaining ENTSOE countries will have a significant (negative) effect on the national economy. Finally, the low effect of the cost distribution mechanism indicates that a lower buying power of small consumers or lower revenues for large consumers is regarded to be of low relevance for economic welfare.

Concerning the cost distribution among consumers, the socio-ecological group disagrees with the other two groups. The stakeholders in this group prefer decreasing the costs for small consumers to enhance the economic welfare and to promote the approval
of the citizens for the energy transition (see Figure A.6 in the Appendix). While the other two groups agree with the latter statement, they disagree with the first. The first evaluation implies that the group considers the purchasing power of small consumers, such as households and small to medium-sized enterprises, to be more relevant for the economic welfare than the economic situation of large consumers, such as large industries.

The political implication of the statements of the socio-ecological group is that compared to the challenges posed by climate change, all other ecological, economic, and social impacts caused by the conversion of the energy system are of lower interest for this group. Hence, the stakeholders of this group favor a fast and comprehensive energy transition that reduces GHG emissions as fast as possible – e.g. by the phasing out of coal-fired power plants and by drastically expanding RES. Thereby, the further distribution of wind turbines and the expansion of the transmission grid do not pose a significant problem for this group. A further significant characteristic of the energy transition should be to reduce import dependency, especially by decreasing the imports of fossil energy sources.

### 4.2.4 Socio-Economic Group

The socio-economic group declares that all fundamental objectives are important for a sustainable energy transition. However, increasing the economic welfare and fostering the approval of the citizens for the energy transition are the most important characteristics of the energy transformation for this group. Compared to the socio-ecological group, the objective of limiting global climate change is not as important for the socio-economic group. Furthermore, reducing the direct effects on human health and the environment plays a more important role for this group.

Although the socio-economic group agrees with the socio-ecological group that promoting the approval of citizens for the energy transition is an important objective, they disagree considerably on how to achieve this approval. Based on the socio-economic group, the change of visual landscape, caused mainly by the further expansion of RES and transmission lines, has the highest effects on the acceptance of citizens. The reason for this might be that already today many energy infrastructure projects are being obstructed or even rejected at the local level due to their visual intrusion. Hence, not considering local
acceptance of energy infrastructure projects could impede the whole conversion process. Further important aspects for increasing the approval of the citizens for the energy transition are to enable the participation of citizens at the energy transformation and to secure a fair cost distribution. Thereby, relieving the burden on small consumers is regarded as the best strategy to distribute the costs among consumer groups. While this coincides with the opinion of the socio-ecological group, the relevance of promoting the competition intensity in the energy market differs largely. For the socio-economic group, increasing the competition intensity has a high impact on the approval of citizens for the energy transition. This might stem from the fact that more competition in the market leads to a higher diversification of players and therewith to lower energy prices (Flues et al., 2012). In contrast, reducing GHG and energy-related pollutant emissions, and decreasing the import dependency have only minor effects on the acceptance of citizens.

In terms of increasing the economic welfare, the socio-economic group thinks that increasing the added value in the renewable energy sector, minimizing the costs for measures related to the energy transition, and ensuring a fair cost distribution among end-consumer groups have the highest positive impact. Considering the cost distribution, either the status quo of the cost distribution should be maintained or small consumers should be relieved of costs to enhance the economic welfare (see Figure A.6 in the Appendix). In contrast, limiting the land use of the energy system to prevent rising land prices and ensuring internationally comparable frameworks for the economy are not considered to have a high impact on economic welfare.

The third most important objective for this group is to reduce the negative impacts of the energy system on human health and the environment. In their opinion, this objective is best achieved if energy-related pollutant emissions are reduced. In contrast, the impact of direct effects on nature and species as well as the ecological impacts of land used by the energy system are considered to only have a minor impact on human health and the environment.

The political implications of these assessments for the energy transition is that the socio-economic group acknowledges that limiting the climate change is important but not the only objective which should be pursued to realize a sustainable energy transition.
According to this group, the measures to mitigate global climate change are framed and limited by local ecological and social effects, and by economic constraints. This implies that the energy system should indeed be transformed comprehensively, but that the social acceptance and economic conditions might impede a fast transformation. Thus, a special focus should be laid on the siting of wind turbines and transmission lines to minimize their visual impact and their costs. On the other hand, RES imports – and the related import dependency on other countries – are not viewed as problematic by this group.

4.2.5 Economic-ecological group

The economic-ecological group clearly states that for them, promoting economic welfare is the most important objective for the energy transition. The second-most important objective is to reduce the effects of the energy system on human health and the environment. In contrast, limiting climate change and promoting the approval of citizens for the energy transition is of minor interest to this group. However, it must be mentioned that the group does acknowledge the necessity of reducing GHG emissions, but that it does not matter much for them if 40% or 80% of GHG emissions are reduced by 2030 (based on 1990 values). The lower importance of limiting global climate change compared to minimizing the effects of the energy system on human health and the environment implies that the energy transition should primarily reduce local ecological effects caused by the energy system rather than reducing GHG emissions (considering that the range of GHG emission reductions is 40% - 80%).

To achieve the most important objective of the energy transition – fostering the economic welfare – the economic-ecological group declares that policy-makers need to ensure internationally comparable energy-related political frameworks for the economy. The implication of this is to create internationally comparable competition and investment conditions for the economy by reducing the discrepancy between the German and the international climate protection ambitions. The objective aims at preventing discrimination of national companies that compete internationally. This opinion goes hand in hand with the statement that a fair cost distribution – meaning that either the status quo of the cost distribution, which grants discounts for electricity-intensive companies (BDEW, 2018)
should be maintained or large consumers should be further relieved of the cost burden – has the second-highest impact on economic welfare. Beyond that, the economic-ecological group ascribes a higher impact of minimizing the energy-related land use, which is associated with limiting land prices, to economic welfare than the other two groups do. Another big difference between the economic-ecological group and the other two groups is that reducing the import dependency and increasing the added value in the renewable energy sector have only a minor impact on economic welfare. A reason for the first valuation is that Germany has been dependent on energy imports for the last decades without major shortages and has diversified among the importing countries (BMWi, 2018a). Apparently, the stakeholders assume that this will also apply for future imports of energy sources. The cause for the second assessment might be that the renewable energy sector is only one of several successful industries in Germany. The stakeholders think that solely promoting this sector does not have a big impact on the economic welfare in Germany. A further difference to the other two groups is that the costs associated with measures to convert the energy system do not play a significant role for economic welfare. This might imply that the stakeholders assess the economic growth generated due to an economy-friendly policy as larger than the costs associated with the energy transition. A similarity with the other two groups is that the impact of an increased competition intensity in the energy market is regarded as rather low.

The economic-ecological group does not only ascribe higher importance to reducing local ecological effects but also assesses the impact of reducing pollutant emissions and land use of the energy system differently. For this group, minimizing the land use and, therefore, reducing the ecological effects on the countryside and cultural landscape have the highest effect on human health and the environment. Such impacts on the ecosystem refer to the conversion of farmland, forest, or green land in areas for the energy generation, which may have impacts on natural habitats, prevent the regeneration of groundwater, or change the local climate (Flues et al., 2012). Conversely, reducing pollutant emissions has the lowest impact on decreasing local ecological effects. The reason for this judgment might be that the immission load of nitrogen dioxide (NO₂) and particulate matters (PM₂.₅) in rural areas is low and that sulfur dioxide (SO₂) and carbon monoxide
(CO) no longer exceed European emission impact thresholds in Germany (UBA, 2018a). Nevertheless, both assessments are in stark contrast to the valuation of the other two groups.

The least relevant objective for this group is to promote the approval of citizens for the energy transition. The two major drivers to overcome the resistance of the citizens are to minimize the visual impacts of the energy system and to enable the participation of citizens in energy infrastructure projects. Both aspects underpin the importance of incorporating local acceptability issues in the expansion of RES and transmission lines. Based on this group, only minor effects on the acceptance of the energy transition are related to decreasing the import dependency and increasing the competition intensity. This assessment is consistent with the impact evaluation of the same aspects on economic welfare, and highlights that these aspects are not relevant for the economic-ecological group. Furthermore, the economic-ecological group thinks that the cost burden sharing among consumer groups does not impact the acceptance of the energy transition considerably. However, they do accept that relieving small consumers of electricity costs might be advantageous for the acceptability of the energy transition by the citizens (see Figure A.6 in the Appendix).

The assessment concludes that the economic-ecological group would favor a slower energy transition (see also Figure A.5 in the Appendix). Both, the phase-out of coal power plants and the switch from fossil-fueled to renewable-based energy consumption are not of the highest priority. Instead, the stakeholders prefer an internationally well-coordinated energy transition that does not unilaterally discriminate against the German economy. Similarly to the socio-economic group, the massive expansion of wind turbines and transmission lines is regarded as problematic. In contrast to the other two groups, the economic-ecological group considers large amounts of imports – fossil- and renewable-based energy sources – as not worrisome.
5 Conclusion and Policy Implications

This paper aims at evaluating different energy transition scenarios and deriving policy implications based on multiple stakeholder opinions. To do so, we apply a group decision-making process developed in Höfer et al. (2019). More specifically, we use the objective system – consisting of means and fundamental objectives – and the evaluations of the objectives – comprising the relative impacts of the means objectives on the fundamental objectives and the relative weights of the fundamental objectives – as a basis for our evaluation. We alter this process by calculating the fulfillment of the means objectives by the energy transition scenarios based on indicators instead of relying on expert assessments. Finally, we apply a clustering technique to identify three groups of stakeholders – the socio-ecological, the socio-economic, and the economic-ecological group – based on the scenario evaluations. We analyze the similarities and differences of the group evaluations to give policy recommendations on how to address the groups.

The socio-ecological group states that reducing Germany’s contribution to climate change and promoting the approval of citizens for the energy transition are the most important objectives for a sustainable energy transition. The socio-economic group thinks that promoting the contribution of the energy system to economic welfare and increasing the approval of the citizens are the most relevant fundamental objectives for the conversion of the energy system. For the economic-ecological group, increasing the economic welfare is the most important objective of the energy transformation. The second-most important objective is to reduce local ecological effects on the ecosystem.

What all groups have in common is that they urge the policy-makers to foster the participation of citizens in the energy transition. This indicates that an organizational participation of the citizens in the planning process of energy infrastructure projects and a financial participation in RES projects is likely to enhance the approval of citizens for the energy transition. On the other hand, the stakeholders do not think that protecting nature and species against direct negative effects of the energy system, such as impacts on bird and bat migration or noise intrusion, impacts human health and the environment significantly. Another similarity is that promoting the competition intensity in the energy
market does not really affect the economic welfare or the approval of citizens for the energy transition.

According to these objectives and the evaluation of the stakeholders, Scenario B – the scenario with the highest ambitions for limiting climate change – and Scenario C – the Pan-European scenario, which focuses on European cooperation in converting the energy system – are the best pathways to transform the energy system. In contrast, all stakeholders agree that at least one other scenario is more suitable than Scenario A, i.e. the reference scenario developed by the German TSOs.

The recommendation for energy policy-makers is to foster an energy transition that enables the participation of citizens in infrastructure projects, is well coordinated with international partners, limits the impacts on landscapes, and yet reduces GHG and pollutant emissions markedly. Relatively uncontroversial measures to achieve these objectives are to reduce the energy demand and to switch from fossil to renewable energy sources in order to satisfy the demand in the transport, heat, and industry sectors. Furthermore, the deployment of RES and transmission lines should consider the visual impacts on the landscapes when choosing sites in order to limit the resistance of local citizens. Finally, the stakeholders do not consider energy imports – especially synthetic fuels generated by RES – to be problematic for economic welfare.

The rather comprehensive approach presented also has its limitations, providing leeway for further research of this kind. An extension of the analysis could be to include non-professional stakeholders and local residents in the evaluation of the scenarios. Although asking professional stakeholders with a broad knowledge of the energy system to evaluate energy transformation scenarios is a sound procedure that presumably reveals the most important opinions towards the energy transformation, asking local, non-professional citizens might add further insights into the perspective of citizens for the energy transition. Furthermore, the aim of future studies should be to calculate the fulfillment of the means objectives based on single indicators only. However, substituting multiple indicators by one single indicator necessitates additional and more elaborate energy models. Finally, it will be interesting to see how stakeholder (group) preferences differ among countries and regions, and also over time.
Acknowledgement

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References


Appendix

**Figure A.1**
Opinions of stakeholders on reducing GHG emissions (MO 2). Source: Höfer et al. (2019)

**Figure A.2**
Impact of the three levels of cost distribution (MO 11) on FO 3 and FO 4. Source: Höfer et al. (2019)
Figure A.3

(a) Means objectives of FO 2

(b) Means objectives of FO 3

(c) Means objectives of FO 4

Figure A.3

a,b,c: Relative impact of means objectives on the corresponding fundamental objectives. Source: Höfer et al. (2019)

Figure A.4

Relative weights of fundamental objectives. Source: Höfer et al. (2019)
Enable the participation of citizens in the energy transition

Protect the countryside and cultural landscape

Ensure a fair cost distribution to end-consumer groups

Protect the countryside and cultural landscape (visual landscape)

Enable the participation of citizens in the energy transformation

Comparative summary of scenarios

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Unit</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
<th>Scenario D</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions reduction</td>
<td>[%]</td>
<td>-53</td>
<td>-78</td>
<td>-67</td>
<td>-67</td>
</tr>
<tr>
<td>Energy demand: transport sector</td>
<td>TWh</td>
<td>583</td>
<td>480</td>
<td>541</td>
<td>541</td>
</tr>
<tr>
<td>Electrification: transport sector</td>
<td>[%]</td>
<td>5.2</td>
<td>10.2</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Energy demand: heat sector</td>
<td>TWh</td>
<td>595</td>
<td>455</td>
<td>532</td>
<td>532</td>
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<tr>
<td>Electrification: heat sector</td>
<td>[%]</td>
<td>6.1</td>
<td>11.9</td>
<td>10.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Energy demand: industry sector</td>
<td>TWh</td>
<td>882</td>
<td>852</td>
<td>829</td>
<td>829</td>
</tr>
<tr>
<td>Electrification: industry sector</td>
<td>[%]</td>
<td>39.8</td>
<td>43.8</td>
<td>43.5</td>
<td>43.5</td>
</tr>
<tr>
<td>Share of renewables</td>
<td>[%]</td>
<td>68.8</td>
<td>86</td>
<td>71.6</td>
<td>71.6</td>
</tr>
<tr>
<td>Share of coal power plants</td>
<td>[%]</td>
<td>19.5</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Share of gas power plants</td>
<td>[%]</td>
<td>9</td>
<td>14.8</td>
<td>10.3</td>
<td>10.3</td>
</tr>
<tr>
<td>Share of other power plants</td>
<td>[%]</td>
<td>4.2</td>
<td>1.3</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Share of electricity import</td>
<td>[%]</td>
<td>-1.5</td>
<td>-2.1</td>
<td>16.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Capacity battery storage</td>
<td>GW</td>
<td>8.0</td>
<td>31.5</td>
<td>8.3</td>
<td>40.0</td>
</tr>
<tr>
<td>Import of mineral oil</td>
<td>TWh</td>
<td>610</td>
<td>195</td>
<td>496</td>
<td>493</td>
</tr>
<tr>
<td>Import of natural gas</td>
<td>TWh</td>
<td>599</td>
<td>446</td>
<td>511</td>
<td>459</td>
</tr>
<tr>
<td>Import of hard coal</td>
<td>TWh</td>
<td>184</td>
<td>54</td>
<td>64</td>
<td>72</td>
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<tr>
<td>Import of PtX²</td>
<td>TWh</td>
<td>0</td>
<td>391</td>
<td>6</td>
<td>145</td>
</tr>
<tr>
<td>RES capacity of energy associations</td>
<td>[GW]</td>
<td>86</td>
<td>120</td>
<td>6.8</td>
<td>179</td>
</tr>
<tr>
<td>Location of RES</td>
<td></td>
<td>Balanced</td>
<td>Balanced</td>
<td>Low costs</td>
<td>Close to load</td>
</tr>
<tr>
<td>Deployment of power plants</td>
<td></td>
<td>Central market</td>
<td>Central market</td>
<td>European merit order</td>
<td>Decentral markets</td>
</tr>
<tr>
<td>Participation of citizens</td>
<td></td>
<td>Medium</td>
<td>Strong</td>
<td>Medium</td>
<td>Strong</td>
</tr>
</tbody>
</table>

1 Share on total electricity generation; 2 Lignite and hard coal power plants; 3 e.g. oil or waste power plants; 4 Positive (negative) values imply that more (less) electricity is exported than imported; 5 PtX refers to electricity that is converted to other energy sources e.g. hydrogen; 6 Installed capacity of wind onshore and PV systems that are owned by private persons participating in energy associations; 7 Central market means that all power plants participate in one market. Decentral market means that Germany is partitioned in several local markets and that the power plants are dispatched locally. European merit order signifies that there is only one single market for all European power plants.

Table A.2

Description of means objectives

<table>
<thead>
<tr>
<th>MO</th>
<th>Description</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reduce greenhouse gas (GHG) emissions in Germany by 2030</td>
<td>Limiting the contribution of Germany to the anthropogenic climate change</td>
</tr>
<tr>
<td>2</td>
<td>Protect nature and species against direct negative impacts of the energy system</td>
<td>Reduce negative impacts on bird and bat migration, noise pollution, and shadowing caused by the energy system</td>
</tr>
<tr>
<td>3</td>
<td>Reduce energy-related pollutant emissions</td>
<td>Reduce likelihood of acid rains, eutrophication of soils and water, ozone formations, and respiratory diseases, amongst others (UBA, 2017)</td>
</tr>
<tr>
<td>4</td>
<td>Protect the countryside and cultural landscape (ecosystem)</td>
<td>Reducing the conversion of farmland, forest, or green land in areas where the energy generation may decrease impacts on natural habitats, promote the regeneration of ground water or limit the change of the local climate (Flues et al., 2012).</td>
</tr>
<tr>
<td>5</td>
<td>Increase the added value in the renewable energy sector</td>
<td>Increasing the capacities of RES creates employment, generates taxes, and fosters local added value in the region of installation</td>
</tr>
<tr>
<td>6</td>
<td>Minimize energy-related land use</td>
<td>Since the available land is limited, increasing the land use of the energy system fosters the competition for land use, thus causing rising land prices</td>
</tr>
<tr>
<td>7</td>
<td>Promote competition intensity in the energy market</td>
<td>More competition leads to a better allocation of resources, reduces the market power of market participants, and decreases the energy prices (Flues et al., 2012).</td>
</tr>
<tr>
<td>8</td>
<td>Reduce the costs for measures related to the energy transition</td>
<td>Higher investment and dispatch costs for power plants, and costs for reinforcing the electricity grid increase the expenditures that have to be borne by the citizens</td>
</tr>
<tr>
<td>9</td>
<td>Reduce import dependency</td>
<td>The reason for reducing the energy import dependency is to decrease the dependency on price fluctuations and to increase the security of supply (Flues et al., 2012).</td>
</tr>
<tr>
<td>10</td>
<td>Ensure internationally comparable energy-related political frameworks for the economy</td>
<td>The purpose is to create internationally comparable competition and investment conditions for the economy. This implies that the discrepancy between the German and the international climate protection measures should be minimized</td>
</tr>
<tr>
<td>11</td>
<td>Ensure a fair cost distribution to end-consumer groups</td>
<td>Increasing the electricity prices for small consumers (households, small commerce, trade, and services companies) reduces their buying power and, in the extreme, can lead to energy poverty. Raising the electricity prices for companies that face international competition could threaten their competitiveness, which could affect the economic growth and jeopardize jobs</td>
</tr>
<tr>
<td>12</td>
<td>Protect the countryside and cultural landscape (visual landscape)</td>
<td>Installing dispersed power plants, building new transmission lines, and operating open-cast mining pits change the visual landscape</td>
</tr>
<tr>
<td>13</td>
<td>Enable the participation of citizens in the energy transformation</td>
<td>An organisational participation of the citizens in the planning process of energy infrastructure projects and a financial participation in RES projects can enhance the approval of citizens for such projects</td>
</tr>
</tbody>
</table>
**Table A.3**

Fulfillment scores of the scenarios in each means objective

<table>
<thead>
<tr>
<th>Means Objective</th>
<th>Short Description</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
<th>Scenario D</th>
</tr>
</thead>
<tbody>
<tr>
<td>MO 1</td>
<td>GHG emissions</td>
<td>37.5</td>
<td>95</td>
<td>67.5</td>
<td>67.5</td>
</tr>
<tr>
<td>MO 2</td>
<td>Direct negative effects</td>
<td>36</td>
<td>28</td>
<td>47</td>
<td>38</td>
</tr>
<tr>
<td>MO 3</td>
<td>Pollutant emissions</td>
<td>71</td>
<td>100</td>
<td>89</td>
<td>90</td>
</tr>
<tr>
<td>MO 4</td>
<td>Land use</td>
<td>48</td>
<td>4</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>MO 5</td>
<td>Added value of RES</td>
<td>41</td>
<td>71</td>
<td>48</td>
<td>100</td>
</tr>
<tr>
<td>MO 6</td>
<td>Land use</td>
<td>48</td>
<td>4</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>MO 7</td>
<td>Market competition</td>
<td>65</td>
<td>80</td>
<td>84</td>
<td>81</td>
</tr>
<tr>
<td>MO 8</td>
<td>Overall costs</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>MO 9</td>
<td>Import dependency</td>
<td>37</td>
<td>9</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>MO 10</td>
<td>Political frameworks</td>
<td>81</td>
<td>50</td>
<td>50</td>
<td>64</td>
</tr>
<tr>
<td>MO 11</td>
<td>Landscape</td>
<td>35</td>
<td>23</td>
<td>44</td>
<td>32</td>
</tr>
<tr>
<td>MO 13</td>
<td>Citizens’ participation</td>
<td>28</td>
<td>64</td>
<td>28</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table A.4**

Individual fulfillment scores of the scenarios in MO 11 for FO 3 and FO 4, respectively

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>MO 11 (FO3)</th>
<th>MO 11 (FO4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH 1</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 2</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 3</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 4</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 5</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 6</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 7</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 8</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 9</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 10</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
<tr>
<td>SH 11</td>
<td>100 SC1</td>
<td>100 LC2</td>
</tr>
</tbody>
</table>

1 Small Consumers; 2 Status Quo; 3 Large Consumers
Net Energy Import Dependency (NEID)

\[ NEID = \frac{\sum_i m_i p_i \ln(p_i)}{\sum_i p_i \ln(p_i)}; \quad (A.3) \]

where \( m_i \) is the share of net imports of fuel \( i \) – mineral oil (97.4%), hard coal (100%), lignite (0%), natural gas (93.5%), and PtX (100%) (BMWi, 2018c), and \( p \) is the share of fuel \( i \) on total primary energy supply.

**Table A.5**

Determination of optimal number of clusters based on the Bayesian Information Criterion (BIC)

<table>
<thead>
<tr>
<th>Clusters</th>
<th>Models(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EII</td>
</tr>
<tr>
<td>2</td>
<td>-308</td>
</tr>
<tr>
<td>3(^a)</td>
<td>-300</td>
</tr>
<tr>
<td>4</td>
<td>-284</td>
</tr>
<tr>
<td>5</td>
<td>-265</td>
</tr>
<tr>
<td>6</td>
<td>-277</td>
</tr>
<tr>
<td>7</td>
<td>-263</td>
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<tr>
<td>8</td>
<td>-243</td>
</tr>
<tr>
<td>9</td>
<td>-207</td>
</tr>
<tr>
<td>10</td>
<td>-205</td>
</tr>
</tbody>
</table>

\(^1\) The models are named based on three identifiers: volume, shape, and orientation of the clusters. \( E \) means equal, \( V \) stands for variable, and \( I \) connotes the coordinate axes. Hence VEI defines a model where the volumes of the clusters can vary, the clusters have the same shape, and the orientation is equal to the coordinate axes. 

\(^2\) A large BIC score suggests strong evidence that the model and the corresponding cluster number are most appropriate for clustering the observations.

**Figure A.5**

Group opinions on the impact of reducing GHG emissions (impact function of MO 1)
Group opinions on a fair cost distribution (MO 11) to enhance economic welfare (FO 3) and approval of the energy transition (FO 4)

Table A.6
Mean relative impacts of means objectives on fundamental objectives for each group

<table>
<thead>
<tr>
<th>FO</th>
<th>MO</th>
<th>Socio-ecological group</th>
<th>Socio-economic group</th>
<th>Economic-ecological group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean std. dev.</td>
<td>mean std. dev.</td>
<td>mean std. dev.</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>36.3</td>
<td>42.2</td>
<td>26.2</td>
</tr>
<tr>
<td>4</td>
<td>53.3</td>
<td>24.0</td>
<td>43.2</td>
<td>13.1</td>
</tr>
<tr>
<td>5</td>
<td>65.3</td>
<td>28.9</td>
<td>68.8</td>
<td>40.5</td>
</tr>
<tr>
<td>6</td>
<td>34.7</td>
<td>26.1</td>
<td>36.0</td>
<td>24.1</td>
</tr>
<tr>
<td>7</td>
<td>45.7</td>
<td>33.5</td>
<td>52.8</td>
<td>32.6</td>
</tr>
<tr>
<td>8</td>
<td>75.0</td>
<td>26.0</td>
<td>67.0</td>
<td>40.3</td>
</tr>
<tr>
<td>10</td>
<td>57.1</td>
<td>45.6</td>
<td>48.8</td>
<td>33.0</td>
</tr>
<tr>
<td>11</td>
<td>49.5</td>
<td>21.0</td>
<td>61.2</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Table A.7
Mean relative weights of fundamental objectives for each group

<table>
<thead>
<tr>
<th>FO</th>
<th>Socio-ecological group</th>
<th>Socio-economic group</th>
<th>Economic-ecological group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>mean std. dev.</td>
<td>mean std. dev.</td>
</tr>
<tr>
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<td>95.0</td>
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<td>73.8</td>
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<tr>
<td>2</td>
<td>68.2</td>
<td>31.3</td>
<td>78.8</td>
</tr>
<tr>
<td>3</td>
<td>63.6</td>
<td>24.3</td>
<td>88.5</td>
</tr>
<tr>
<td>4</td>
<td>84.5</td>
<td>14.6</td>
<td>87.2</td>
</tr>
</tbody>
</table>
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