**Robust Assessment of Energy Scenarios from Stakeholders' Perspectives**

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**Robust Assessment of Energy Scenarios from Stakeholders' Perspectives**

Abstract

Using scenarios is vital in identifying and specifying measures for successfully transforming the energy system. Such transformations can be particularly challenging and require the support of a broader set of stakeholders. Otherwise, there will be opposition in the form of reluctance to adopt the necessary technologies. Usually, processes for considering stakeholders' perspectives are very time-consuming and costly. In particular, there are uncertainties about how to deal with modifications in the scenarios. In principle, new consulting processes will be required. In our study, we show how multi-criteria decision analysis can be used to analyze stakeholders' attitudes toward transition paths. Since stakeholders differ regarding their preferences and time horizons, we employ a multi-criteria decision analysis approach to identify which stakeholders will support or oppose a transition path. We provide a flexible template for analyzing stakeholder preferences toward transition paths. This flexibility comes from the fact that our multi-criteria decision aid-based approach does not involve intensive empirical work with stakeholders. Instead, it involves subjecting assumptions to robustness analysis, which can help identify options to influence stakeholders' attitudes toward transitions.

Keywords:

Scenario assessment; MCDA; robustness; transition paths; attitudes

# Introduction

There are many transition paths for decarbonizing energy systems to protect the climate, which, however, may differ, e.g., regarding the technology mix employed and the pace of the energy system transformation. Stakeholders like private households, energy utilities, and industry, amongst others, influence the feasibility of these transition paths through their investment decisions or public protests. Since different stakeholders with diverging interests and goals may prefer different transition paths, there is a risk of conflicts that could affect the success of the energy system transformation. From the individual stakeholder's perspective, 1) ex-ante information on the multiple effects of transformation paths and 2) information on possible support for or hesitance towards individual paths by other stakeholders could help with the implementation or adjustment of measures in advance. The attitude (supportive or hesitance) towards individual paths depends on the multiple effects associated with a respective path.

Usually, surveys, a series of workshops, or expert interviews are conducted to assess the implications of new or modified transition paths (see, e.g., [1-3]). As these approaches can be time-consuming and costly, it is common to consider only a few of the many transition paths. For this reason, a tool capable of assessing ex-ante impacts of a larger number of transition paths with significantly reduced effort compared to existing methods is needed. Due to uncertainty about the future, such a tool should provide information on how modified transition paths affect key outcomes and hence, on the robustness of the findings obtained for modifications of the transition paths.

There are a lot of studies showing that stakeholders' preferences can change over time (see, e.g., [4], [5]). Hence, if a tool is to explore stakeholder acceptance of transition paths covering decades, it must be able to handle the implications of minor or significant changes in the preferences of those stakeholders. Stakeholders might differ with respect to their preferences. Nowadays, modelers of energy scenarios usually forego the explicit consideration of stakeholders' views and focus on developing criteria without discussing whether individual stakeholders will support the presented transition paths (see, e.g., [6]). The tool should be able to deal with several stakeholders to identify possible conflicts at an early stage. Our study presents and employs an easily applicable approach to fulfil these requirements. Hence, our approach aims to

a) assess the implications of modifications in the transition paths

b) systematically incorporate the effects of changes in stakeholders' preferences on their acceptance of transition paths

c) consider a wide range of diverse stakeholder groups.

It allows the assessment of the support or rejection of transition paths by many stakeholders without the need for intensive consultation processes for each new path. Our approach helps to preselect scenarios before putting significant efforts into further analyses. In this sense, it supports further empirical analyses with stakeholders and enables the testing of how stakeholder preferences might be affected by adjustments to transition paths.

Multi-Criteria Decision Analysis (MCDA) is a well-established approach to assess preferences of stakeholders. It has shown its suitability for complex decision-making processes in many applications. Therefore, we employ it as the basis for our approach. MCDA focuses on decision-making processes involving the interpretation of massive quantities of information [7] and conflicting objectives [8]. Decision alternatives are ranked according to their desirability for the stakeholders [9] based on a set of criteria, reflecting the performance of different decision alternatives, and weightings (for one or more stakeholders) which represent the importance of each criterion for the stakeholder(s) [10]. It is possible to handle conflicting criteria and geometrically represent decision alternatives based on these criteria, facilitating the interpretation of the results of the MCDA [11]. MCDA techniques have been applied to decision problems relevant to sustainability, for example, in energy management [12, 13], transport policy [14, 15], green supplier selection [16], as well as in the assessment of scenarios [17, 18]. In addition to a) the specification of the system considered, b) the selection of relevant stakeholders/decision makers, c) the identification of alternatives, d) the selection of criteria, e) the description of the alternatives by using these criteria, and f) the weighting of the criteria by the selected stakeholders, are essential for MCDA.

Depending on the number of criteria and stakeholders, assessing the weightings of criteria by stakeholders can be very costly and time-consuming. Thus, the weightings needed for MCDA are often derived from expert judgments. Some authors assume an equal weighting of the criteria as a starting point for their analysis due to a lack of information (see Tab. 1). The analyses of Hottenroth et al. [17] can serve as an example of a study that tries to strengthen the empirical foundation of the weightings identified by conducting a discrete choice experiment (DCE). However, due to the vast number of criteria, they decided to supplement the DCE with expert judgments. Hence, the example of Hottenroth et al. [17] shows the difficulties of identifying weightings on a broader empirical basis. A reverse MCDA approach, using car sales data from Ball et al. [19], avoids the difficulties of stated preferences and the costly empirical work with stakeholders. Due to the level of effort associated with determining weightings, MCDA-based scenario assessment studies usually prefer to focus not only on the perspective of one representative stakeholder but also on one specific point in time (Tab. 1). This limits the analyses with respect to the range of outcomes (resulting from the stakeholders' heterogeneity) and intertemporal aspects (e.g., limited to greater short-term changes) in the evaluation of decisions.

Tab. 1: Examples of scenario assessments by employing MCDA

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Year of publication | Number of explicit "actor per-spectives" | Criteria | | | | Identification of weightings | Sensitivity analyses | | Time |
| Economic | Social | Environment | Other\* | Modification of Weightings | Variation of MCDA approach. |
| Hottenroth et al. [17] | 2022 | 1 | 2 | 4 | 16 | 1 | DCE, literature review, survey among experts |  | x | 2050 |
| Sahabuddin & Khan [20] | 2021 | 1 | 3 | 6 | 4 |  | Expert judgments | X | x | N.a.\*\* |
| Roinioti & Koroneos [21] | 2019 | 1 | 3 | 6 | 6 |  | Equal weighting | X |  | 2015 |
| Simoes et al. [22] | 2019 | 4x4\*\*\* | 3 | 3 | 3 | 1 | Stakeholder workshops |  |  | 2030 |
| Hussain Mirjat et al. [23] | 2018 | 1 | 3 | 4 | 3 | 7 | Expert judgments | X |  | 2050 |
| Atilgan & Azapagic [24] | 2017 | 1 | 3 | 5 | 11 |  | Equal weighting | X |  | 2010, 2050 |
| Volkart et al. [25] | 2017 | 1 | 2 | 4 | 4 | 2 | Artificial weighting profiles |  |  | 2035 |
| Balezentis et al. [13] | 2017 | 1 | 1 |  | 3 |  | Randomly drawn from a uniform distribution | X |  | 2050 |
| Shmelev & van den Bergh [26] | 2016 | 6\* | 2 | 1 | 3 | 1 | Monte-Carlo fashion, weightings randomized based on priority settings | X |  | 2050 |
| Santoyo-Castelazo & Azapagic [27] | 2014 | 1 | 3 | 4 | 10 |  | Equal weighting | X |  | 2050 |
| Ribeiro et al. [18] | 2013 | 1 | 4 | 1 | 4 | 3 | Expert judgments |  |  | 2020 |
| Rahman et al. [28] | 2016 | 1 | 6 | 4 | 2 | 12 | Stochastic Multi-criteria Acceptability Analysis |  |  | 2020, 2030, 2040 |
| Shaaban et al. [29] | 2018 | 40 | 4 | 2 | 3 | 4 | Equal weightings, expert interviews | x (incl. Monte-Carlo validation) | x |  |

Remarks: \* incl. criteria focusing on technological aspects, \*\* No information provided, \*\*\* Four groups of stakeholders in four different countries

MCDA methods, in general, are subject to uncertainty, as they rely on the perceptions of stakeholders, expressed by criteria weightings [30]. Given this inherent uncertainty, we stress the advantage of systematic, integrated sensitivity analysis for identifying feasible options for increasing stakeholders' support of transition paths. We apply our approach to capturing multiple effects and analyze seven transition paths to achieve Germany's Net Zero emissions target. The scenarios studied involve different levels of expansion of renewable energy technologies, namely wind, Photovoltaics (PV), and biomass power stations, as well as different transformation speeds. The transition paths span three decades, namely 2020, 2030, and 2040. Variants of these paths include negative emissions technologies (i.e., carbon capture and storage technologies). We consider four sets of stakeholders in our study: energy utilities, households, industry, and government. The transition paths are analyzed from these stakeholders' perspectives using the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), a Multi-Criteria Decision Analysis (MCDA) technique [9]. We examine the results' robustness closely by conducting an extensive sensitivity analysis.

The concept of robustness employed in our study reflects the capacity of prioritized pathways to withstand changes in agents' preferences. To put it differently, it reflects the resilience of an option to losing the actors’ prioritization because of their preference changes.

The paper is organized as follows. Section [2](#_Method_:_Multicriteria) introduces MCDA as a methodological approach for use in this paper and presents our approach to assessing robustness. Section [3](#_Assessment_of_technologies) focuses on understanding the assessment of technologies by different stakeholders in our study. This section establishes criteria relevant to the scenario assessment, assigning stakeholder-specific weightings for various criteria. Section [4](#_Assessment_of_technology) provides a complete picture of the assessment of the selected scenarios and compares their overall performances. We conclude in Section [5](#_Conclusions).

# Method

For the method, we employ a two-step approach: firstly, we identify the stakeholders relevant to the transition paths using information from various databases and publications and conduct MCDA analyses employing PROMETHEE II for these stakeholders (Section 2.1). In the second step, we perform a robustness analysis concerning the weightings (Section 2.2). We focus on the weightings because they represent the importance of the individual criteria from the stakeholders' point of view and, thus, the subjective part of the decision-making process. Therefore, they are one, if not the primary source of uncertainty in the MCDA analysis. Exploring the associated parameter spaces using deterministic sampling-based methods suffers from dimensionality, i.e., the exponential growth of the necessary number of weighting samples for the dimension of the parameter space (the number of criteria). It makes that kind of robustness analysis almost infeasible in our case. Instead, our approach exploits the geometric structure of the sets of weightings leading to the same ranking of alternatives and provides a single directly interpretable number as a robustness measure. Moreover, we present a graphical analysis for additional insight (Fig. 1).

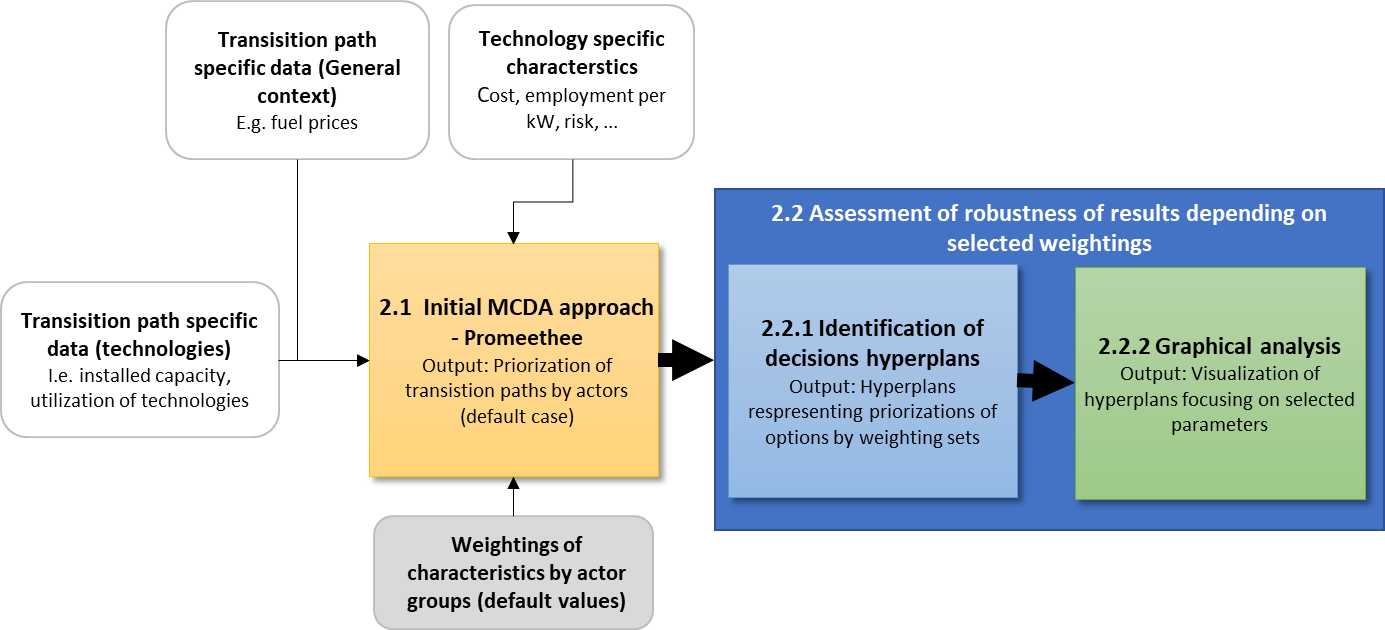


Fig. 1: Methodological approach and data requirements

## PROMETHEE

Since PROMETHEE is a well-established approach (see, e.g., [25], [30], [9]), we selected it as the MCDA method for our analysis. PROMETHEE consists of two steps. The first step establishes an outranking relation on the alternatives, and the second step exploits this relationship to identify the best alternative. PROMETHEE II starts from the performance matrix , whose entries code the objective benefit of alternative with respect to criterion . From , one computes for criterion an auxiliary matrix , where denotes the corresponding non-negative preference function. Brans and Vincke [10] propose 6 preference functions, among of them the ‘linear preference function‘, , the ‘Level Criterion’ and the Gaussian preference function .

For all criteria, the user needs to select preference functions with their respective parameters. The absolute value indicates the strength of the preference of over . The Level criterion suits best for indicators whose performance values are discrete, while a linear preference function suits best for continuous economic variables [16]. As the most of our criteria are connected to continuous quantities, we choose the linear preference function for all criteria.

Based on this, the aggregated performance indices are calculated according to , which compares to with respect to all criteria. Here, the non-negative weightings reflect the importance of criterion from the stakeholder’s perspective and fulfill the normalization condition .

The positive flow

,

then indicates the overall preference of over all alternatives and the negative flow

the anti-preference. PROMETHEE II establishes a ranking of the alternatives according to their net flow aka performance (higher is better). The net flow is a simplification, so relevant information, such as two alternatives being incomparable, can be lost [11].

A straightforward rearrangement of the calculations above leads to an alternative way of computing the net flows as a matrix-vector product: with

|  |  |
| --- | --- |
|  | (1) |

where has the same dimension as and consists of rows . In the analysis, the ideas outlined in [31] are followed. With denoting the dot product of two vectors and , we obtain

|  |  |
| --- | --- |
|  | (2) |

## Assessment of robustness of results depending on selected weightings

### Identification of decision hyperplanes

For our sensitivity analysis for the weightings, we exploit the geometric properties of PROMETHEE II. All non-negative weightings fulfilling the normalization condition constitute the standard simplex in the -dimensional parameter space. We call any such *admissible* and interpret it as a point in a -dimensional parameter space. The given or assumed induces a ranking of the alternatives and indicates, in particular, the most favorite alternative . Let us collect all admissible weightings leading to that -th alternative in the set . We now outline that is a subset of the standard simplex and a convex bounded polytope, where we follow [32]. From two alternatives and , a stakeholder considers , iff . Inserting (2) yields

|  |  |
| --- | --- |
|  | (3) |

With , (2) defines a half-space . All alternatives are inferior to the -th one, leading to the conditions for any alternative .

The side condition translates into with the -th standard unit vector . Thus, enforcing non-negativity for all weightings corresponds to intersecting with additional half-spaces. The normalization condition is with equivalent to and holding simultaneously, corresponding to intersecting with two additional half-spaces. As all conditions on are characterized as intersections with half-spaces, it is an intersection of finitely many half-spaces, bounded due to and, therefore, a polytope. It is convex being the intersection of convex sets (half-spaces are convex). Any half space corresponds here to the decision between alternatives 𝑖 and 𝑗 and divides the set of admissible weightings into two sets. One set of weightings leads to a preference for alternative 𝑖 over 𝑗 and another to the opposite outcome. The boundary of such half-space is a decision hyperplane, the set of weightings for which both alternatives yield the same net flow and are thus of equal value. The boundary of any convex polytope and, therefore, the boundary of any consists of a finite number of facets (subsets of the decision hyperplanes).

One may consider a decision robust for variations in , if is large in some geometrical sense and "somewhere in the middle of ". We, therefore, consider the (Euclidean) distance of to the boundary of a robustness measure for the decision for variations in .￼￼ At the same time, is the radius of the maximal sphere around still inscribed in . Any weighting with a distance of at most to our assumed *w* leads to the same decision outcome. It is well known that the distance to the boundary of a polytope is the minimum of the distances to all facets (for a detailed explanation, we refer to [33]), the decision hyperplanes, which are efficiently computable. The nearest facet, therefore, hints at the alternative decision to expect at first for increasing variations in weightings for that respective stakeholder.

### Graphical analysis

We focus on the weightings of three relevant user-selected criteria for graphical analysis, yielding 2D visualizations. We assume these weightings to be variable, all others to be fixed at their assumed values. While it is common to describe a polytope by enumerating its vertices, any convex polytope can be expressed as the set of all points fulfilling for some matrix and some vector . On the other hand, any set defined by is a convex polytope (see, e.g., [33]). Therefore, *Wi*= . We set , where contains only the fixed weightings and the three variable weightings from above and zeros elsewhere. Then,

|  |  |
| --- | --- |
|  | (4) |

It is straightforward to find a matrix with , where denotes the three-dimensional reduced weighting vector consisting of the three variable weightings only. Inserting this in (4) yields with , such that for the variable weightings only is again a convex polytope and a subset of the standard simplex in the three-dimensional space, which we can visualize as a 2D image. Visualizing four variable weightings as a 3D image is possible analogously. The figures then display slices through the set of admissible weightings parallel to the coordinate hyperplanes corresponding to the fixed weightings and provide oversight over the decision space for these variable weightings. Python implementation of our method is publicly available [34] and used for obtaining our results and figures.

# Specification and application of MCDA

As mentioned in Fig. 1, an assessment of transition paths from different stakeholders' perspectives requires information on the characteristics of the paths and stakeholder weightings. Our study presents a highly flexible approach concerning the selection of transition paths. Therefore, we use publicly available information on technologies in combination with information on the general context being published along with transition paths and path-specific data (including details on installed capacities and their utilization) as starting point. The data is extracted from well-known and reliable sources (e.g., [1]).

Regarding the weightings, we face the challenge that they are only available for specific individual assessments of transition paths and can, in principle, only be used to a limited extent for other studies. In our study, we address uncertainties related to the selection of weighing (taking, e.g., into consideration that they can change over time and stakeholders could have hidden preferences) by conducting a robustness analysis. Hence, weightings derived from survey information should be considered the first starting points for robustness analysis.

The following describes stakeholders and their criteria for assessing transition paths. We then present and characterize scenarios focusing on these criteria.

## Stakeholders and their attitudes

The successful implementation of energy transition scenarios relies on the willingness of stakeholders to champion the transition, which requires an understanding of the benefits and costs of transition paths [35].[[1]](#footnote-2) Stakeholders might differ regarding their weightings for criteria and their relevance to transition processes. In the following section, we emphasize the views of four groups of stakeholders: households (HH), energy utilities (UTI), industry (IND), and government (GOV). Each stakeholder group has a set of priorities, which may overlap with those of other stakeholders.

GOV constitutes the policymakers responsible for setting the regulatory and policy framework for the system transition. GOV, to a greater extent than the other stakeholders, is greatly interested (i.e. it enjoys benefits or prevents costs) in the decarbonization necessary to meet its obligations under the Paris Agreement. However, it must reconcile its decarbonization goals with other priorities, including investment, value-added, and employment, which have high importance and it must also consider factors such as public acceptance.

IND corresponds to energy-intensive sectors, notably iron and steel production [37]. In particular, the industrial sector faces challenges from international competition. Thus, cost aspects (incl. financial risk) are most relevant. Since the industry faces challenges from the obligation to reduce GHG emissions, "GHG emission" is an appropriate criterion for the sector (see, e.g., [38]). Another relevant criterion is (energy) supply security (see, e.g., [39]). Our study considers this point by including import dependency and infrastructure as relevant criteria.

UTI consists of electricity plant operators and investors in generation and storage plants. A successful energy system transformation requires utilities to build new capacities of different technologies and operate the existing power generation capacities. Utilities are primarily concerned with investment and operating costs and the risks (policy, technology-related and financial) associated with technologies [40]. There is increasing debate about the impact of risk and price volatility caused by an expansion of renewable energy technologies such as wind and PV and the need for investment in dispatchable electricity capacity [41].

Households (HH*)* are the residential consumers of electricity. Protests against high electricity prices in 2022 supports the assumption that the cost of electricity is a critical factor for households in supporting transition paths. For households, income effects, induced emissions, participation options, and employment are also significant. In particular, income is strongly and positively related to energy consumption and emissions. Different groups of households manage different income levels, which can affect their acceptance of varying transition paths [35]. Thus, our study categorizes households into six groups according to net household income (Tab. 2).

Tab. 2: Income Groups and Corresponding Net Income Ranges

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Income Group | HH1 | HH2 | HH3 | HH4 | HH5 | HH6 |
| Net Income Range (€ per month) | 0-1300 | 1300-1700 | 1700-2600 | 2600-3600 | 3600-5000 | 5000-18000 |

For stakeholders, a differentiated set of criteria is relevant when making decisions influencing the energy transition. Decision making on projects with complex technical features usually has a large number of criteria, sometimes as many as 100. However, usually, between 6 and 20 criteria are used [42]. Although there is no rule on the number of criteria, it should be as low as possible, whilst covering all essential aspects, therefore leading to a consistent resulting set to facilitate computation and interpretation.

Within the analysis, the values of criteria represent the general performance of each alternative. Covering exclusive and exhaustive criteria is necessary to ensure the investigation is holistic. We limit ourselves to those that are usually mentioned concerning the assessment of energy technologies and energy systems (see, e.g., [43], [35][18]). These criteria are operationalized by criteria that assign a numerical value to the criteria, thus making the assessment possible. All these criteria can be grouped into six overarching categories:

* Economic I: Economic criteria from the point of view of an investor in power generation and storage technologies.
* Economic II: Macroeconomic criteria.
* Ecological: Ecological criteria that are crucial to any energy system analysis.
* Social: These criteria drive the social acceptance of a path essential to its successful implementation.
* Risks & complementarities: These criteria are relevant to the technological change underlying the transition. Examples of risks include policies that hinder the development of technology, the stalling of cost reductions, and an increase in the cost of financing related to particular projects.

We extract criteria from a literature review to describe the categories in more detail. We pay careful attention to the inclusion of criteria that are relevant from the perspective of stakeholders. Fig. 2 lists the criteria we extracted from the literature to assess the different categories.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | | | | | | | | Assessment Criteria | | | | | |  | | | | | | | | | | |
|  |  |  | | | | | | | |  | |  |  |  | |  | | | | | | | | | | |
|  |  | |  | | | |  | | | |  | | | |  | | | |  | | | |  |  | |
|  | Economic I | | |  | Economic II | | |  | Ecological | | |  | Social | | |  | Risks | | |  | Comple-mentarities | | | |  | |
|  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | | |  | |
|  |  | Running costs  [22] | |  |  | Direct income  [18] | |  |  | Share of renewables  [13] | |  |  | Acceptance  [20] | |  |  | Technology risk  [26] | |  |  | Experience  with similar  technologies  [44] | | |  | |
|  |  |  |  |  |  |  |  |  |  |  |  |  | |
|  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | | |  | |
|  |  | Unit cost of electricity (LCOE)  [20] | |  |  | Employment  [20] | |  |  | GHG emissions  [20] | |  |  | Possibility for participation  [28] | |  |  | Financial risks  [26] | |  |  | Dependence on infrastructure  [44] | | |  | |
|  |  |  |  |  |  |  |  |  |  |  |  |  | |
|  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | |  |  |  | | |  | |
|  |  | Investment cost  [20] | |  |  |  | |  |  |  | |  |  |  | |  |  | Policy framework risks  [26] | |  |  | Import  dependency  [25] | | |  | |
|  |  |  |  |  | |  |  |  | |  |  |  | |  |  |  |  |  | |

Remarks: Quoted references are examples of studies that explicitly use the corresponding criteria.

Fig. 2: Assessment criteria

The first group of criteria focuses on economic factors relevant on a microeconomic level. It includes *running costs* and *unit costs*. We are guided by [44] and [18] in selecting the criteria. We assign macroeconomic effects like income and employment to the "Economic II" criteria category.

*Share of renewables* and *greenhouse gas (GHG) emissions* are criteria often used in energy-related MCDA studies [43]. These criteria are particularly relevant for GOV and all other stakeholders. Regarding social aspects, we follow [23, 45] and use *acceptance* and *possibility for participation* as criteria.

Riskcriteria help understand the technologies' risk-related characteristics and are relevant for all stakeholders. Following [23], we select *technology risks*, *financial risks* as well as the *risk of policy framework* as criteria. Complementarities criteria deal with dependencies inherent to each technology in a scenario. UTI and GOV are highly interested in such criteria. From this category, we use *experience with similar technologies*, the *need for new infrastructure,* and *import dependencies*.

Specific criteria can be quantified easily, such as the *share of renewables*, *GHG emissions*, the *unit cost of electricity,* and *investment cost*. In contrast, others are qualitative, such as those in the risk and complementarities categories – these must be measured, for instance, on a Likert scale from worst to best, assigning numbers.

Since we are interested in assessing transition paths and only indirectly in individual technologies, we have to do some pre-processing work. Firstly, we scale up the criteria' technology-specific values by using the information on the installed capacities of the particular technology or the technology-specific utilization rates. Subsequently, for each criterion, we sum up the scaled-up values of all technologies (see Supplementary material). The LCOE, as an example, is assessed by calculating specific costs for producing one kWh of electricity for each technology. Following this, the particular costs are multiplied by information on the utilization of the specific technology. Finally, we sum up the cost of all technologies and compare the resulting cost of the scenarios.

So far, for the assessment of transition paths weighting factors have not been selected and were used uniformly (see Tab. 1). Hence, the weightings vary significantly between studies.

Thus, we decided to derive initial weightings from a few basic assumptions:

1. In principle, economic factors are more important than others.
2. With increasing income, economic factors become less important.
3. Energy utilities are interested in financial aspects linked with investment and operation of power plants and in different risks and GHG emissions.
4. Industry focuses strongly on economic factors (in particular on the cost which determines wholesale prices for electricity) but also pays attention to GHG emissions and the security of energy supply.
5. The government rates each relevant criterion evenly.

Assumptions 1 to 2 are based on research by [5], and assumptions 3 and 4 are based on information provided in [39, 46]. No information on the government's preferences is available; hence we use uniform weightings as a first guess.

In our study, the stakeholders' criteria weightings are measured on a scale of 0 (not relevant) to 3 (highly relevant). Tab. 3 gives the default weightings assigned to each criterion. Weightings derived without empirical testing can only serve as a first starting point. Therefore, we perform a sensitivity analysis (Section 4.3) to check the robustness of our results concerning the estimated weightings.

Tab. 3: Initial criteria weightings

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **HH1** | **HH2** | **HH3** | **HH4** | **HH5** | **HH6** | **UTI** | **IND** | **GOV** |
| (Average) Running cost | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.00 | 3.00 | 0.00 |
| (Average) Unit cost of electricity (LCOE) | 3.00 | 2.75 | 2.50 | 2.25 | 2.00 | 1.75 | 3.00 | 0.00 | 3.00 |
| Investment cost | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.00 | 0.00 | 3.00 |
| Direct Income | 0.50 | 0.35 | 0.20 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 3.00 |
| Employment | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.00 |
| Share of renewables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 3.00 |
| GHG emissions | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 2.00 | 1.00 | 3.00 |
| Acceptance | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 2.00 | 0.00 | 3.00 |
| Possibility for participation | 0.00 | 0.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 | 3.00 |
| Technology risk | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 0.00 |
| Financial risk | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 1.00 | 0.00 |
| Policy framework risks | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 0.00 |
| Experience with similar technologies | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 0.00 |
| Dependency on infrastructure | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 1.00 | 3.00 |
| Import dependency | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 3.00 |

Source: Own estimation

## Scenarios and their characteristics

A primary goal of this study is to develop a template for analyzing energy transition paths from the perspective of multiple stakeholders. A total of seven scenarios have been selected as examples. The chosen scenarios vary in terms of the focal technologies and the speed of change. Thus, the scenarios serve as illustrative examples of countless energy scenarios.

*The Distributed Generation*[[2]](#footnote-3) *(DG)* scenario focuses on decentralized and small-scale electricity generation, with prosumers (consumers who also produce electricity) at the center and a rapid expansion of PV, especially roof-top PV. UTIs only maintain backup electricity generation in this scenario, as PV produces most of the electricity. This scenario requires some level of investment from the households.

*The Global Ambition (GA)* scenario focuses on maximizing the usage of existing infrastructure. The use of centralized generation technologies characterizes technological development. Greater use of offshore wind power and energy imports from competitive sources frame the overall transition process. Natural gas is used as a transition fuel to maximize the utilization of existing power generation capacities.

*Global Ambition with use of CCS (GACCS)* corresponds in principle to GA. However, we assume gas power plants will be equipped with carbon capture and storage technologies.

*The high demand for electricity*[[3]](#footnote-4) *(DLR21)* scenario centers on a significant expansion of wind energy and PV driven by increased electricity demand. By 2030, the installed capacity of wind power will reach 210 GW. For 2040, a total of 170 GW is assumed. There is some development of power-to-gas (hydrogen) technologies in the later years of this scenario.

*The Hydrogen*[[4]](#footnote-5) *(H2)* scenario focuses on renewable energy. Here, a vast amount of hydrogen is generated using surplus wind energy, which is stored and later converted back into electricity to meet electricity demand or to be used for heating. Thus, wind energy plays a dominant role in this scenario.

The scenario *Biomass (BIO)* is a variant of GA. For this scenario, biomass-fired power plants are assumed to replace fossil fuel-fired power plants, in part. Alongside biomass, renewable energy technologies, such as wind and PV, also play a vital role. As with *H2*, *BIO* requires extra investments for the storage and transport of biomass.

For the scenario *Biomass with CCS* *(BIOCCS),* we assumed the same installed capacities as for *BIO*. In contrast to *BIO*, we expected that biomass-fired power plants would be equipped with CCS technologies.

The deployment of technology capacities across the scenarios is given in Tab. 4.

Tab. 4: Installed capacities across scenarios (without "other" power plants)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **GW** | **2030** | | | | | | | **2040** | | | | | | |
| **Scenario** | | | | | | | **Scenario** | | | | | | |
| **DG** | **GA** | **GACCS** | **DLR21** | **H2** | **BIO** | **BIOCCS** | **DG** | **GA** | **GACCS** | **DLR21** | **H2** | **BIO** | **BIOCCS** |
| Gas-fired power plants | 22 | 22 | 20 | 13 | 18 | 17 | 17 | 21 | 21 | 16 | 15 | 10 | 11 | 11 |
| Hard coal-fired power plants | 7 | 7 | 7 | 0 | 9 | 7 | 7 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Lignite-fired power plants | 8 | 8 | 8 | 0 | 10 | 8 | 8 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Wind-onshore power plants | 96 | 79 | 79 | 126 | 72 | 79 | 79 | 110 | 95 | 95 | 164 | 154 | 95 | 95 |
| Wind-offshore power plants | 17 | 20 | 20 | 20 | 11 | 20 | 20 | 20 | 23 | 23 | 46 | 31 | 23 | 23 |
| PV | 110 | 84 | 84 | 141 | 65 | 84 | 84 | 145 | 105 | 105 | 171 | 113 | 105 | 105 |
| Biomass-fired power plants | 7 | 7 | 7 | 16 | 3 | 12 | 7 | 7 | 5 | 5 | 12 | 3 | 15 | 5 |
| Hydrogen-fired power plants | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 0 | 0 |
| Biomass-fired power plants + CCS | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 10 |
| Gas-fired power plants +CCS | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 |

Source: DG, GA; [1], DLR21: [47], H2: [48], scenarios GACCS, BIO, and BIOCCS are modified variants of GA.

Evaluating a scenario requires information about the technologies and their deployment. In general, we distinguish between input data, which are generally not changed in scenario variations, and framework data, which can be easily and quickly modified depending on the focus of the investigation. The input factors generally held constant in scenario variations include costs and efficiencies. Factors like employment per unit of installed capacity, attitudes towards the corresponding technology, technology-specific possibilities for participation, and technological and financial risks can be assigned to this category of input factors. The equations we use for the calculations are presented in the Supplementary material.

Criteria like running costs and emissions strongly depend on the utilization of individual technologies. Correspondingly, we scale the technology-specific factors with the rate of utilization. The nature of characteristics, such as investment costs, acceptance, and dependency on new infrastructure are less linked to the utilization of technologies. Hence, we use installed capacity for scaling these technology-specific figures. The demand for investment and impacts linked to the construction of power plants and infrastructure are evaluated using the information on capacity additions. LCOE, GHG emissions, and share of renewables (REG-Share) are criteria that are usually provided in energy models. In addition to these criteria, risk, acceptance, and import dependency are introduced.

Usually, energy scenarios are provided without detailed information on assumed cost per kW, efficiencies, or risks. A fortiori, no information is provided on acceptance and risk. Missing data hamper an appropriate comparison of scenarios. In order to be able to compare scenarios, we used data from DLR [47], Entso-E [1], Rutovitz et al. [49], and Scheer et al. [50]. Input data (e.g., the cost for power plants and the vintage structure of the power plant stock) are also harmonized, and information gaps (e.g., information on acceptance and risks) are closed. Our study should serve as a pilot study, with the possibility of applying the approach used to the evaluation of forthcoming Net Zero roadmaps. Tab. 5 shows the values we assumed for the different types of input factors and technologies for 2040.

Tab. 5: Assumptions on technology-specific parameters

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Data for 2040** | Unit | Gas-fired power plant | Hard coal-fired power plant | Lignite-fired power plant | Wind-onshore | Wind-offshore | PV | Biomass-fired power plants | Hydrogen-fired power plant | Biomass-fired power plant with CCS | Gas-fired power plant with CCS |
| Technology-specific investment costs\* | Euro/kW | 748 | 1432 | 1175 | 1180 | 2100 | 765 | 2318 | 800 | 4356 | 1175 |
| Technology-specific operation and maintenance costs\* | Euro/kWh | 0.007 | 0.007 | 0.008 | 0.014 | 0.021 | 0.013 | 0.029 | 0.007 | 0.066 | 0.011 |
| Technology-specific efficiency\* | % | 60% | 49% | 44% | 100% | 100% | 100% | 30% | 63% | 22% | 52% |
| Technology-specific employment\*\* | Jobs /MW | 0.14 | 0.14 | 0.14 | 0.30 | 0.30 | 0.70 | 0.14 | 0.14 | 0.14 | 0.14 |
| Acceptance\*\*\*of the specific technology | Scores/MW | 3 | 2 | 1 | 4 | 4 | 4 | 3 | 3 | 2 | 1 |
| Possible participation\*\*\* | Scores/MW | 1 | 1 | 1 | 4 | 3 | 5 | 2 | 2 | 1 | 1 |
| Technology risk\*\*\* | Scores/MW | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 3 | 4 | 3 |
| Technology-specific financial risk\*\*\* | Scores/MW | 1 | 2 | 5 | 5 | 5 | 5 | 4 | 3 | 1 | 1 |
| Policy risk\*\*\* (technology specific) | Scores/MW | 2 | 1 | 1 | 4 | 4 | 5 | 3 | 4 | 1 | 2 |

Sources: \* Own compilation based on [47], \*\* [49], \*\*\* Own compilation based on [50], 5: best, 1: worst

Prices for energy carriers and CO2 allowances usually play a key role in energy scenarios since they determine investment decisions and the use of technologies. Tab. 6 provides an overview of the assumed prices in 2040 for the different scenarios. Furthermore, the table shows the extent to which the technologies are deployed in the scenarios. The utilization and development of the installed capacities are outputs of the model runs and provide scenario-specific information. Hence, both factors are essential for an assessment of the scenarios.

Tab. 6: Scenario-specific factors for 2040

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Unit | DG | GA | GACCS | DLR21 | H2 | BIO | BIOCCS |
| Fuel prices\* (2040) | | | | | | | | |
| Hard coal | Euro/kWh | 0.025 | 0.025 | 0.025 | 0.014 | 0.019 | 0.025 | 0.025 |
| Lignite | Euro/kWh | 0.004 | 0.004 | 0.004 | 0.004 | 0.009 | 0.004 | 0.004 |
| Natural Gas | Euro/kWh | 0.026 | 0.025 | 0.025 | 0.036 | 0.026 | 0.025 | 0.025 |
| Biomass | Euro/kWh |  |  |  | 0.012 | 0.012 | 0.012 | 0.012 |
| Hydrogen | Euro/kWh |  |  |  | 0.088 | 0.110 |  |  |
| CO2 price | Euro/t CO2 | 100 | 80 | 80 | 220 | 148 | 80 | 80 |
| Utilization\*\* (2040) | | | | | | | | |
| Hard coal-fired power plant | Full load hours | 0 | 0 | 0 | 0 | 4224 | 0 | 0 |
| Lignite-fired power plant ­ | Full load hours | 0 | 0 | 0 | 0 | 6202 | 0 | 0 |
| Gas-fired power plant | Full load hours | 1036 | 1036 | 1036 | 2705 | 2269 | 1036 | 1036 |
| Wind onshore | Full load hours | 2767 | 2767 | 2767 | 1500 | 2272 | 2767 | 2767 |
| Wind offshore | Full load hours | 4174 | 4174 | 4174 | 5500 | 4611 | 4174 | 4174 |
| PV | Full load hours | 954 | 954 | 954 | 1000 | 1159 | 954 | 954 |
| Biomass-fired power plant | Full load hours | 5646 | 5646 | 5646 | 4069 | 5328 | 5646 | 5646 |
| Hydrogen-fired power plant | Full load hours | 0 | 0 | 0 | 2960 | 3455 | 0 | 0 |
|  | | | | | | | | |
| CO2 Storage volume | Mill. m3 | 0 | 0 | 2 | 0 | 0 | 0 | 84 |

Remarks: \*Input factor, \*\* Model output, sources: [2], [47], [48]

Based on the figures presented, it is possible to assess scenarios from a specific stakeholder's perspective.

# Results

In this section, we discuss the preferences of different stakeholders for transition paths found by our method. In addition to the results of employing the PROMETHEE II approach using our initial weighting, we provide information on the sensitivity of the results with respect to modifications of the weightings.

## Households

Preferences in households are driven predominantly by the unit cost of electricity, which decreases in relevance as income increases[[5]](#footnote-6) (see Section 3.1). Additionally, factors like employment and household income must be considered as their importance is relatively higher for lower-income households. For higher-income households, participation options are more important than for lower-income households, which impacts the different preferred scenario outcomes. Generally, income is the main determining factor in weighing options differently, as income affects both the unit cost of electricity and employment of households as well. Assuming that households do not bear any investment costs (at least not directly), they prefer both DG and DLR21 scenarios in 2030, favoring DLR21.

However, as DG is focused on roof-top PV, households have to bear some investment costs. Due to this, DG becomes, to some extent, less preferable among households and becomes less dependent on income in 2040. While in 2030, DLR21 seems to be the most preferred scenario across all households; this changes in 2040. According to our calculations, only HH1 and HH2, the household groups with the lowest income, associate a positive value with DLR21 but prefer DG. In our assessment, HH3 to HH6 favor BIOCCS with increasing income (the higher the household income, the higher the preference). This indicates that the benefits (e.g., low electricity costs, low financial risk, low emissions) outweigh the investment costs. Overall, we expect scenario preferences to vary with income in 2030 but much less so in 2040. Thus, the income sensitivity of the scenarios decreases over time as the benefits outweigh the costs. In Fig. 3, we list preferences according to households classified by income resulting from our calculations.

|  |  |
| --- | --- |
| 2030 | 2040 |
|  |  |

*Fig. 3: Performance of scenarios from households' perspective.*

Over time, hesitancy towards scenarios with CCS seems to decline, as these offer feasible and efficient options to reach climate goals and can be understood as income indifferent. In 2040, the households with lower average household income (HH1-HH3) will prefer scenario DG, while the higher income households HH4-HH6 prefer scenario BIOCCS.

## Utilities, Industry, and Government

The various kinds of costs and risk parameters drive utilities. According to our assessment, scenario DLR21 performs best in the first period. In particular, the assumed fast phase-out of coal-fired power plants means that the unit cost of electricity and the running costs are favorable compared to scenarios other than DG. However, DLR21 performs substantially better on financial risk related to prices for fossil energy carriers. Scenario DG shows similar performance as DLR21. In comparison to DLR21, DG results in lower costs. However, the risk advantages will be smaller. From a long-term perspective, DG shows the highest benefits. Since, in all scenarios, coal-fired power plants will be phased out, DLR21 will lose its lead. In particular, utilities' interest in BIO and GA will increase. These scenarios show advantages in cost, technological risk, and experience with similar technologies.

Industry's preferences are mainly driven by the unit price of electricity for enterprises, whereas the level of GHG emissions and aspects of import dependence is of minor importance. Accordingly, the industry will prefer the scenario linked with the lowest cost: based on our cost calculations, this will be DLR21 followed by DG in the first period. In 2040, DG will rank first, followed by GA (Fig. 4).

|  |  |  |  |
| --- | --- | --- | --- |
| Utilities | Industry | | Government |
|  |  | |  |
| For comparision: | | | |
| HH1 | | HH6 | |
|  | |  | |

Fig. 4: Performance of scenarios from the utilities, industry, and government perspectives.

The results indicate that government strongly prefers DLR21 firstly because of employment and income effects, which are driven by the high deployment of wind and solar energy. Considering a longer-term perspective, the scenario BIOCCS becomes the most favorable option for the government since it leads to substantial decreases in GHG emissions while bringing positive employment effects.

GHG emissions and share in REG are, to some extent, linked. Hence, the problem of double-counting criteria could arise. We consider them individually because, from the perspective of, e.g., the government, these are two separate energy policy goals. In our sensitivity analysis, we modified the weightings of the goals. Hence, we can show the possible implications of reducing double counting on the possible prioritization of transition paths.

All in all, our results indicate small differences in the performance scores between the different household groups whereas the differences to the other stakeholder groups are significantly higher. This indicates that in the application we investigate, relatively small differences in weightings count less than modifications in the set of relevant weighting criteria (Fig. 4).

According to our results, rankings in the nearer future are relatively similar, whereas as time progresses, divergences between actor groups’ rankings increase (Fig. 4). This can be due to stronger differences in the scenario characteristics. Resulting challenges or possible conflicts should be addressed timely, e.g., by applying concepts like mediation, co-creation processes, or financial compensation to mitigate adverse outcomes.

## Sensitivity Analysis

## Following section 4.1, we consider the weightings of LCOE, GHG Emissions and Acceptance variable and visualize the corresponding slices through the set of admissible weightings in Fig. 5 and Fig. 6. In these ternary plots, the dashed lines help determine the assumed values of the three variable weightings which here appear as barycentric coordinates. The maximal value of a variable weighting is presented in the corners of the triangles; it is smaller than one due to the fixed weightings contributing to the sum of weightings. The black dot represents the assumed values of the variable weightings; the surrounding white circles with radius (compare Tab. 7) indicate the amount of robustness. Within PROMETHEE II, the linear preference criterion is scaled such that the maximum value that any alternative can have on a given criterion is one.

Tab. 7: and nearest alternatives for all stakeholders in 2030 and 2040

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Stakeholder | HH1 | HH2 | HH3 | HH4 | HH5 | HH6 | UTI | IND | GOV |
| 2030 |  | 0.023 | 0.021 | 0.031 | 0.030 | 0.039 | 0.053 | 0.009 | 0.028 | 0.134 |
| Nearest alt. | DG | DG | DG | DG | DG | DG | DLR21 | DG | DG |
| 2040 |  | 0.001 | 0.006 | 0.002 | 0.011 | 0.023 | 0.036 | 0.059 | 0.24 | 0.066 |
| Nearest alt. | DG | BIOCCS | BIOCCS | DG | DG | DG | BIO | GACCS | BIO |

It seems surprising at first that the circles are significantly smaller than one would expect when looking at the visualizations. However, refers to any simultaneous variation of all weightings, not only to the variation of just the three selected. We interpret this finding as a confirmation of our approach to consider in the robustness analysis all weightings simultaneously, because restricting to selected weightings alone can obviously lead to a considerable overestimation of robustness. Due to the lack of space, we do not address the question of which combination of changes in weightings determines , even though our method allows for this.

It turns out that the households' decision favoring DLR21 is not very robust to variations of weightings for 2030 and not robust for 2040; the robustness increases for increasing household income. We can, however, rule out that changing the weightings for GHG emissions, Acceptance, and LCOE leads to choices other than DLR21 and DG for households in 2030 (Fig. 5) In contrast to households, the government's preference for DLR21 in 2030 and for BIOCCS in 2040 seems to be relatively stable.

|  |  |  |
| --- | --- | --- |
| HH1 | HH6 | GOV |
| 2030 | | |
|  |  | **Ein Bild, das Diagramm enthält.  Automatisch generierte Beschreibung** |
| 2040 | | |
|  |  | Ein Bild, das Diagramm enthält.  Automatisch generierte Beschreibung |

Fig. 5: Sets form a partition of the (scaled) standard simplex, the outcome of the decision depending on the weightings chosen is color-coded; HH1, HH6, and GOV for 2030 and 2040. The black dots indicate the assumed weightings.

The ongoing debate about the continued use of nuclear power shows that technological risks in energy production also play a role for households. Therefore, we now replace Acceptance by Technology Risk as criterion with variable weighting (Fig. 6). For increased importance of Technology Risk, the households opt for DLR21 as before. A 4D-slice of the standard simplex can be rotated in the three-dimensional space, where it appears as scaled regular tetrahedron as shown in Fig. 7. Fig. 6 (left) appears as the slice “Income fixed” in Fig. 7 (left). Unless LCOE dominates, HH1 will favor DLR21 regardless of the importance of Income, in contrast to 2040, where BIOCCS becomes a viable alternative.

|  |  |
| --- | --- |
| HH1 | HH6 |
|  |  |

Fig. 6: The sets for HH1and HH6 and with different variable weightings, 2030.

|  |  |
| --- | --- |
| 2030 | 2040 |
|  |  |

Fig. 7: The sets for simultaneous variations of the weightings of four criteria for HH1.

We, moreover, investigated the robustness of the preferences to the choice of the preference function. Replacing the Linear preference function with the Gaussian one yields comparable results. Further details can be found in the Supplementary Material.

# Discussion and Conclusions

The occurrence of political, economic, and natural extreme events (e.g., the Ukraine-Russia conflict, soaring prices for commodities, floods, and heat waves) highlights the need to upgrade existing energy scenarios. In principle, developing new scenarios considering stakeholders' perspectives, whose support is critical to implementing paths, is time-consuming and costly. Hence, there is a need for approaches that provide information on the impacts of proposed changes in transition paths resulting from energy scenarios, stakeholders' support for paths, and how transition paths should be designed to align with stakeholders' preferences. Our approach addresses this need. In addition, the study aims to show the effects of changes in stakeholders' weightings of selected decision criteria on possible support of transition paths. By providing information on weightings and their implication, we can identify critical weighting constellations that might favor changes in attitudes towards transition path levels. These constellations should receive special attention if a transition path is desired by, e.g., the government. In addition, the analysis enables the assessment of implications from preferences changes.

In the past, MCDA has proven its potential for assessing stakeholders' attitudes. Hence, we decided to employ an MCDA approach. Using a set of heterogeneous stakeholders and examples for energy scenarios, we emphasize that MCDA is a suitable tool for assessing stakeholders' perspectives on a flexible number of energy scenarios. Crucially, it allows this assessment to be carried out without having recourse to complex stakeholder consultation processes in response to each scenario modification.

Using the PROMETHEE II technique, the study assesses the scenarios for achieving Net Zero emissions by the year 2050 from the perspective of the relevant stakeholders. It breaks this down across years (2020, 2030, and 2040) and regions of Germany so support for and hesitance towards transition paths can be identified in advance. This information can be helpful for the preselection of scenarios likely to be supported by most stakeholders.

According to our results, stakeholders' mindsets towards a scenario can shift with changes in the time horizon. Under possible techno-economic constellations for the year 2030, most stakeholders prefer DLR21. Regarding the situation in the year 2040, their preference shifts to scenario DG.

The results show that:

1. Heterogeneity matters because not all stakeholders prefer the same scenario and, thus, might not support the same policy strategy.
2. Attitudes towards a scenario depend on the time horizon. Therefore, raising awareness of the long-term effects can be necessary.
3. Robustness checks provide information on the potential for influencing the mindsets toward specific scenarios. These checks could help to identify measures to foster the support of transition paths.
4. Personal benefits and costs drive support for transition pathways – for example, the unit cost of electricity is crucial to household preferences towards scenarios. Employment and income have a powerful influence over government preferences. Regarding reduced emissions, the public benefit only shapes part of the preference. Ancillary benefits can, therefore, be seen as a motivation for a successful transition and can increase acceptance of such a transition.

Our results stress the vital role that heterogeneity in the stakeholders' priorities plays in evaluating scenarios. Furthermore, we highlight the influence of the chosen time horizon on the analysis and its results. It has to be pointed out that the results should not be interpreted as trends, as our study does not employ a dynamic time series. Instead, the results can underline the meaning of information for the mid-and long-term impacts of transition paths. Focusing on long-term consequences might result in other support regimes than focusing on mid-term effects.

It should be noted that the results are based on certain assumptions and simplifications. This applies to the selection of scenarios, the data sources used, and methodological aspects. Other scenarios could be preferred to the examined scenarios. Providing more comprehensive and comparable information on, e.g., scenario-specific technology mixes can help improve the evaluation. The normalization approach assumed in PROMETHEE for comparing criteria or preference functions are based on simplified assumptions. Possible implications of variations in the preference functions have been presented in this study. Further analysis and the use of alternative MCDA approaches are beyond the scope of this study. In principle, our approach can accommodate any number of scenarios, which means new scenarios can be added to the set of possible developments being assessed from stakeholders' perspectives without significant additional effort. Furthermore, the number of stakeholders can be expanded. In principle, an extension of criteria or criteria categories can be undertaken. Then, weightings for the new criteria have to be specified, and additional information might need to be extracted from the scenarios.

Our work is an exploratory study to gain information on the approach's applicability. While an empirical there is currently no cross-evaluation of our approach, this should be one of our future tasks. Furthermore, as we focus on the electricity supply system, it will be necessary for us to extend our analysis to capture other parts of the overall system.

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1. A strand of the environmental economics literature distinguishes between primary and ancillary benefits resulting from the multiple effects of climate policy (e.g. [36]). Primary benefits accrue from climate protection, i.e. from climate policy’s primary goal, and ancillary benefits comprise the benefits from all other effects, namely so-called ancillary effects like reduction of local air pollution, emerging due to the respective policy. In the present study however, it is not clear per se what goals individual stakeholders consider to be primary and ancillary, i.e. the priority of goals will differ among stakeholders. [↑](#footnote-ref-2)
2. Both DG & GA scenarios correspond to scenarios published by Entso-E [1]. [↑](#footnote-ref-3)
3. DLR21 scenario correspond to the scenario presented in [47]. [↑](#footnote-ref-4)
4. Scenario H2 bases on a scenario developed by [48]. [↑](#footnote-ref-5)
5. Income and employment (measured in fulltime equivalents) are highly correlated. In order to avoid double accounting, we focus on income. [↑](#footnote-ref-6)