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Sustainability assessments of energy scenarios: citizens' preferences for and assessments of sustainability indicators

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Abstract

Background: Given the multitude of scenarios on the future of our energy systems, multi-criteria assessments are increasingly called for to analyze and assess desired and undesired effects of possible pathways with regard to their environmental, economic and social sustainability. Existing studies apply elaborate lists of sustainability indicators, yet these indicators are defined and selected by experts and the relative importance of each indicator for the overall sustainability assessments is either determined by experts or is computed using mathematical functions. Target group-specific empirical data regarding citizens' preferences for sustainability indicators as well as their reasoning behind their choices are not included in existing assessments.

Approach and results: We argue that citizens' preferences and values need to be more systematically analyzed. Next to valid and reliable data regarding diverse sets of indicators, reflections and deliberations are needed regarding what different societal actors, including citizens, consider as justified and legitimate interventions in nature and society, and what considerations they include in their own assessments. For this purpose, we present results from a discrete choice experiment. The method originated in marketing and is currently becoming a popular means to systematically analyze individuals' preference structures for energy technology assessments. As we show in our paper, it can be fruitfully applied to study citizens' values and weightings with regard to sustainability issues. Additionally, we present findings from six focus groups that unveil the reasons behind citizens' preferences and choices.

Conclusions: Our combined empirical methods provide main insights with strong implications for the future development and assessment of energy pathways: while environmental and climate-related effects significantly influenced citizens' preferences for or against certain energy pathways, total systems and production costs were of far less importance to citizens than the public discourse suggests. Many scenario studies seek to optimize pathways according to total systems costs. In contrast, our findings show that the role of fairness and distributional justice in transition processes featured as a dominant theme for citizens. This adds central dimensions for future multi-criteria assessments that, so far, have been neglected by current energy systems models.

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Background

The transition of energy systems towards more sustainable forms of energy production and consumption continues to be a key challenge for politicians, stakeholders and societies worldwide. Assessing the sustainability of national transition pathways thereby constitutes an important decision-support for governments [1, 2] and has resulted in scholarly efforts to systematically assess energy scenarios with regard to their ecological, economic and social effects [3–6]. Such sustainability assessments can serve different purposes: they support the comparability of often very complex scenarios and explicate (un)desired effects of transition processes that are not explicitly included in the scenario studies. This enables decision-makers to better understand and monitor sustainability trade-offs within and across different pathways and, thus, to select suitable alternatives and implement policies that guide the transition process [7–9]. When assessing the sustainability of energy scenarios, a broad spectrum of often conflicting environmental, economic, technical and social criteria needs to be considered [10]. Multi-criteria decision analysis (MCDA) has the potential to consider the multidimensionality of sustainability and, therefore, has emerged as a popular method for assessing energy technologies and systems [9–16].

While existing studies have significantly advanced multi-criteria assessments by defining and applying elaborate lists of economic, ecologic, technical and even social indicators [8, 9, 11–14, 16–18], two observations are notable: first, the sustainability indicators to be used for assessments are selected and defined by researchers and decision-makers, or are based on literature reviews. Second, the indicator weights showing the relative importance of each indicator in the final assessment are either determined by researchers/experts or are computed using different mathematical functions as part of the multi-criteria assessment. Few exceptions have discussed sustainability assessments with a wider group of stakeholders in transdisciplinary settings [19]; yet, target group-specific empirical data regarding preferences, priorities and trade-offs of sustainability indicators remain widely missing.

By definition, the *Leitbild* of sustainable development is designed to guide today's decisions about future energy systems [7] even though the concept of sustainability does not specify indisputable sets of indicators, let alone proposes solutions for indicator conflicts and trade-offs [20]. On the one hand, this means that scientists need to provide definitions and sets of indicators underpinned by valid and reliable data. On the other hand, reflections and deliberations are required regarding what societal actors, including citizens, consider as justified and legitimate interventions in nature and society, and what considerations they include in their own assessments [21]. We therefore argue that sustainability assessments of energy systems need to reflect the perspectives and preferences of citizens for energy systems and technologies. Yet, to date, empirical studies remain scarce, because citizens often lack the necessary background knowledge to discriminately assess different energy technologies and systems [17]. Authors have thus called for the disclosure of complete life-cycle information on energy technologies in order to allow for more informed assessments [22].

Based on this, we present an empirical approach to address the following research question: *What are citizens' preferences for sustainability indicators when assessing future energy systems and what is their reasoning behind their choices for indicators?*

The research presented in this paper is part of the interdisciplinary research project InNOSys[1] which sought to assess and optimize pathways for the future German energy system by integrating economic, ecologic and social sustainability indicators into a multi-criteria decision analysis. In the project, a list of sustainability indicators was derived to assess existing scenarios for the German energy system in 2050 with GHG emissions reductions of 80–90% and of more than 90%.[2] The indicators used resemble lists of previously reviewed studies [9–11, 13, 14, 18] and pertain to economic, ecological and social dimensions.[3] As part of the project, we conducted a discrete choice experiment (DCE) that allowed us to analyze the relative importance of different sustainability indicators for citizens' decisions regarding their preferred future energy systems.

[1] For more information on the project, please consult https://www.innosys-projekt.de/en (last accessed 06/09/2022).

[2] The scenarios were remodeled to harmonize underlying assumptions. The harmonization was done using the models MESAP and flexABLE (for more details, see [16]) and included, among other, assumptions on energy demand, energy prices, technology prices, population and GDP.

[3] Data from the Framework for the Assessment of Environmental Impacts of Transformation Scenarios (FRITS) 4 and PANTA RHEI 23 was used to determine the values of indicators for each scenario.

In the discrete choice experiment, citizens had to choose among different future energy systems in Germany. The choices were underpinned using the derived sustainability indicators. Indicator values displayed full life-cycle data and were presented in a transparent and approachable fashion. The integration of all sustainability indicators in the display of the choices ensured that citizens were able to express their preferences for certain future energy futures but at the same time were made aware of the possible ecological, economic and social consequences of their choices.

While the involvement of citizens in the assessment of sustainability indicators presents an important step towards more participatory sustainability assessments, we also acknowledge another form of citizen involvement—that is, the selection of suitable sustainability indicators. In previous MCDA sustainability assessments, indicators have been selected based on the availability of valid data in order to ensure measurability and comparability of assessments [10, 11, 13, 18]. As a result, particularly indicators on social sustainability revolve around a handful of semi-measurable factors, including for instance social acceptability, job creation, human health and energy costs [9–11, 14, 18]. In our research, we sought to find out what aspects and indicators citizens associate with the sustainability of energy scenarios that go beyond currently used indicators. For this, we present qualitative findings from six focus groups.

Our paper seeks to make three contributions to the existing literature on sustainability assessments of energy scenarios: first, we document how discrete choice experiments (DCE) can be made fruitful for studying citizens' preferences for indicators of sustainability and their assessments of sustainability trade-offs when it comes to deciding upon future energy systems. In the past, DCE have been typically used in marketing research to detect consumer preferences; yet, it is increasingly emerging as a research method for gathering individuals' preferences for a variety of sustainability- and energy-related issues. As we argue in our paper, DCE is particularly suitable because the quantitative data it reveals can be used as inputs for multi-criteria sustainability assessments, as was done by the research team [15]. Second, the actual findings of our DCE suggest indicators on climatic effects and resource consumption to have the strongest effect on whether citizens preferred one energy scenario over another. In contrast, economic-related indicators were regarded as the least relevant ones. As we will discuss, this presents a significant difference to results of existing MCDA analysis that use expert assessments and modeling [9, 11]. Third, insights from our explorative focus groups reveal a discrepancy between what (mostly quantitative, indicator-based) assessment models can capture, and what citizens seem to value most when assessing future energy systems; that is, the role of fairness and distributional justice. We discuss how these aspects can be considered for future sustainability assessments of energy systems.

The paper proceeds as follows: the next chapter briefly reviews existing approaches to sustainability assessments of energy systems. It then discusses how the methods DCE and focus groups have previously been applied to capture citizens' preferences and perspectives on sustainability and energy systems. This is accompanied by our methodology and data collection processes. The following chapter presents key results. We close with a discussion of the relevance of the findings for decision-makers in transitions and energy systems modelers.

Methods

This chapter is sub-divided into three main sections: the first section starts with a review of existing studies on sustainability assessments of energy systems followed by a description of our own research approach. The next two sections, respectively, address focus groups and discrete choice experiment, again including a literature review on the methods' previous applications in energy contexts and a specification of our own approach.

Sustainability assessments of energy systems

Literature review

The goal of *sustainable* energy transitions can be defined as establishing a secure, affordable energy system that spares non-renewable energy sources as well as environmental resources and that meets the needs of both present and future generations [23, 24]. Sustainability has been notably shaped by the Brundtland Report that called for sustainable development processes that satisfy "the needs of the present without compromising the ability of further generations to meet their own needs" [25, 26]. In the aftermath of the report, sustainability has been operationalized using multiple frameworks that differ in the dimensions they incorporate and in how these dimensions relate to each other [20]. While concepts that prioritize ecological preservation historically constitute the oldest [24, 27], the 'three-pillar concept' that jointly considers ecological, economic and social aspects prevails in sustainability assessments of energy systems and technologies [11, 13]. Newer concepts, e.g., the Sustainable Development Goals by the UN [28] or the Integrative Concept of Sustainable Development [29] move away from the pillar-logic and emphasize elements like "securing human existence", "maintaining society's productive potential" and "preserving society's options for development and action"; these concepts have also been applied for sustainability assessments of energy systems [8, 23].

Given the multidimensionality of sustainability and the availability of various concepts, no standardized methodology exists for sustainability assessments of energy systems and technologies [13]. Existing studies vary in terms of two critical steps in sustainability assessments [11, 24]: (1) the selection and definition of indicators suitable to comprehensively assess future system options as well as the gathering of reliable information about the indicators' performances in different system futures, and (2) the application of methods to determine indicator weights showing the relative importance of each indicator for the final assessment.

As for the first step, the assessment of energy systems is mostly guided by ecological footprints, systems costs and technological feasibility [30, 31]. In the last years, Life Cycle Sustainability Assessments (LCSA) have also been applied to assess ecologic impacts and life cycle costs for parts of energy systems and individual technologies using diverse sets of indicators backed up by large datasets [12, 13, 16]. Hence, with the usage of LCSA, a more systematic application of economic and ecologic indicators for assessing future energy systems is emerging (see [16] for a review). In the past years, also social sustainability indicators are receiving increasing attention. In sustainability assessments using MCDA, the "social" dimension is incorporated by using qualitatively and/or quantitatively measurable indicators including *social acceptance, job creation, social benefits, human health,* or *energy costs* [9–11, 13, 14, 18]. Sustainability assessments without MCDA have developed elaborate lists of social indicators [19, 23]. Again other studies have used empirical data from social LCA databases to assess the social sustainability of energy technologies [32]. However, data on the social sustainability performances is criticized for its methodological shortcomings and the resulting lack of reliability and validity [32–34]. In sum, social sustainability is designed as a normative function, i.e., what are acceptable technologies or policy measures for citizens. In this context, some studies also collect data on individuals' overall attitudes, emotions and perceptions of the technologies [17]. At the same time, the majority of social indicators are defined and assessed exclusively by experts, and in many cases, they also assess the relative importance of the social sustainability indicators compared to ecologic and economic ones as part of multi-criteria assessments. Table 1 provides a non-exhaustive overview of the different kinds of indicators, how they were selected and assessed in previous studies.

Our approach

Citizens' preferences for and their perspectives on the sustainability of energy systems and technologies can be analyzed using qualitative and quantitative methods. On the quantitative side, surveys have proved useful in collecting aggregated data on public attitudes towards (sustainable) energy technologies, often with a focus on climate change awareness [35–37]. These surveys mostly cover a broad range of sustainability-related topics without zooming in on different sustainability indicators. Only few surveys specifically address public perceptions of social sustainability aspects [38] and the public's perceived importance of the Sustainable Development Goals and their indicators [39]. In recent years, discrete choice experiment (DCE) has emerged as a popular quantitative research method to study individuals' preferences for a variety of sustainability- and energy-related technologies, services and policy measures [40–42].

In our approach, we aimed to enable citizens to rank the importance of different indicators of social sustainability while considering information provided by LCA when opting for their preferred future energy system. Therefore, we designed a DCE based on LCA-results for different energy scenarios. Naturally, this approach limits the choice of indicators to be ranked to indicators for which such information is obtainable and might ignore dimensions which are more important to the public, but for which such data are not available. In order to capture such dimensions and to better understand the reasoning behind citizens' choices, we also conducted focus groups, where citizens could discuss their understanding of social sustainability without being restricted to dimensions for which quantitative information is available. To gain qualitative insights on public perceptions, interviews are suitable but time-consuming and therefore mostly replaced by the use of focus groups. Focus groups present a form of group discussion to systematically access perceptions about and attitudes towards energy issues.

In the best case, the focus groups would have been conducted prior to the DCE and quantitative results for the dimensions that matter the most to the public would have been provided for the DCE. However, given the complexity of the quantitative models involved this was not feasible in the scope of this research project. In our research, 124 citizens participated in the discrete choice experiment while 65 of them also participated in one of six focus groups. Participants for both methods were recruited through a market research company. The recruitment was guided using the following selection criteria: (1) participants needed to live in either Stuttgart or Osnabrück,[4] (2) an equal distribution of gender, (3)

[4] North Germany is heavily affected by the expansion of wind power generation and regularly produces more renewable energy than it needs while the industrialized centers in the south still lack renewable capacities. The emerging need for powerlines creates diverging patterns of acceptance in the German regions [43]. The cities Osnabrück (in Lower Saxony, northern GER) and Stuttgart (in Baden-Württemberg, southern GER) represent these dynamics.

Table 1 Overview of selected sustainability assessment studies of energy technologies and systems

Selection of indicators	Assessment of indicators	Social indicators used	Total number of indicators	References
Selection based on the following principles: - Systemic - Consistency - Interdependency Measurability - Comparability -Delphi method with experts	Procedures to obtain Weights of indicators: - the variance degree of criteria - independency of criteria - subjective preferences decision-makers	- Social acceptability - Job creation - Social benefits	- Technical: 7 - Economic: 9 - Environmental: 9 - Social: 4 - Total: 29	[11]
Literature review	- Multi-attribute value theory - Equal weighting - Different preferences for sustainability indicators using three indicators; different runs where each indicator is given a different preference	- Security and diversity of supply - Acceptability - Health and safety - Intergenerational issues	- Environmental: 10 - Economic: 3 - Social: 4 - Total: 17	[9]
Literature review based on following criteria: - Reflect sustainability concept - Measurability with respect to specific sustainability goals - Availability of timely information - Availability of reliable information - Reflection of a strategic view - Offer references on systems optimization - Reflects longevity of system design	Fuzzy analytical hierarchical process, including pairwise comparisons of alternatives with respect to attributes in a matrix	- Job creation - Benefitted residents	- Environmental: 5 - Economic: 3 - Social: 2 - Total: 10	[18]
- Literature review - informal discussions with stakeholders - Final selection by researchers based on following criteria: - Systemic - Independency - Consistency - Measurability - Comparability	Weighted sum multi-attribute utility method. Indicator weights were established through a survey of 62 academics	- Job creation - Human health - Social acceptability - External supply risk	Economic: 1 Technical: 3 Environmental: 2 Socio-political: 4 Total: 10	[13]
- Literature review - Inclusion of decision-makers - Final selection based on availability of qualitative and quantitative data	Linear preference functions as part of the method Prometee	- energy costs - contribution to economy - social acceptability	Technical: 3 Environmental: 3 Socio-economic: 3 Total: 9	[10]

an even number of participants that represent three age groups (students/working/retired), and (4) a good mixture of educational background and professions.

Focus groups

Literature review

Focus groups have a long history as a method for gaining data in a variety of sciences, starting from psychology, economics and market analysis; it is one of the most known explorative and qualitative methods in sociology and its assigned research fields [44, 45]. Focus groups are a form of group discussion to systematically access arguments on, perceptions about and attitudes towards a given topic. Moderation constitutes a core requirement to provide guidance during the discussion, to ensure that discussions do not get off topic or that single participants dominate and restrain others from voicing their opinion. This way, the group discussion follows the ideal of Habermas [46] to include as much diverse opinions as participants offer and are willing to share. These characteristics do not only make focus groups more time efficient than interviews; it also reveals the inherent social component of the method: individuals' statements are always carried out in the presence and awareness of a group. This dynamic alters the entire communication process as statements are checked, agreed or countered immediately by the other participants and, thus, it can foster the depth of insight into a field as previously untapped sources of (civil) knowledge are activated [47].

As of today, focus groups were used to shed closer light on single aspects within social sustainability, like addressing the social side of rebound effects in energy use [48]. In those studies, focus groups mostly serve as an exploratory method to gain insights into new, previously uncharted aspects of social sustainability, yet without the ambition to triangulate results with existing ecologic or economic data. Others focus on subtopics like the connection between urban lifestyles and sustainability from a social standpoint, like the "Ulysses" project [49]. Holistic scientific programs as the "Nachhaltigkeitsbarometer" [38] that include a complex multidimensional view on sustainability conduct focus groups almost exclusively among professionals (here working in the energy sector), not lay people, like our study.

Challenges related to the mitigation of climate change and the resulting need to transform energy production and consumption patterns provoke fundamental changes in individuals' lifestyles and their autonomy. In this context, focus groups have provided great potential for tapping citizens' local knowledge as explorative data sources [50–52]. In reviewing the role of focus groups within energy transition research projects, Gailing and Naumann [53] state that focus groups do not only reproduce and surface already existing perspectives of individuals'. The methodological setup also creates 'spaces' in which the group discussion creates and produces social realities. According to the authors, this can help change social disparities in that participants gain the power to not only respond but to steer the discourse itself. Following this constructivist perspective on focus groups, these effects potentially transcend the protected spaces of the focus groups in that participants have the possibility to participate in a more direct way and with greater power in decisions on energy transition processes [54].

Our approach

To explore citizens' perspectives on the sustainability of future energy systems beyond a set of expert-based indicators, six moderated group discussions were conducted. Our sample ($n = 65$) consisted of three evenly sized subsamples of seniors, working citizens and students. Both genders were over all equally participating, though in the subsamples the ratio oscillates ± 5% around the aspired 50%. To account for local differences in Germany, three focus groups were conducted in Osnabrück (Lower Saxony) and three in Stuttgart (Baden-Württemberg).[5] Prior to the focus groups, participants were sent an information package containing descriptions of presently discussed energy technologies for the German energy system (the technologies that were also used later in the DCE) as well as data on their ecological and economic life-cycle effects. This information served as a starting point for the group discussion; see Fig. 1. During the focus groups, participants were guided to discuss beyond this information in that the moderators provoked discussions around the perceived advantages and disadvantages of the technologies as well as their potential consequences for participants' environment and lifestyle. The auto records of each focus group were transcribed and analyzed using the software *MaxQDA*. Given the explorative nature of our research, we followed an inductive coding process. From our data, we derived codes to represent single aspects, e.g., technologies, thoughts or entire arguments that were mentioned by participants. During this process of developing a very fine-grained coding scheme, we synthesized thematic clusters and structure our data. For example, within discussions about the dangers and personal consequences of climate change, participants focused on very diverse dimensions that centered around topics such as lost chances for future generations, the need to save ecosystems or the causality between human action and climate change. The aspects were hence aggregated into the codes 'generational fairness', 'ecosystem preservation' and 'deny of human climate change'. The interpretation and systematization of qualitative data also depends on the researcher. Thus, the coding process was repeated independently by three trained social scientists to create a complete set of codes. Subsequently, the researchers united their different code systems in iterative steps into a coherent one. The objective was to generate an intercoder-reliability to minimize individual differences in the interpretations. As a last step, the codes were revisited and tailored to our research question in terms of what participants associate the social sustainability of future energy systems.

Discrete choice experiments

Literature review

Discrete choice experiment (DCE) has emerged as a popular quantitative research method to study individuals' preferences for a variety of sustainability- and energy-related technologies, services and policy measures [40–42]. The basic idea of the method is that instead of *revealing* preferences through empirical observations, researchers have individuals' explicitly *state* their preferences regarding a set of predefined options. Through an experimental setup, researchers predefine options with varying attributes and levels so as to analyze what relative value the different attributes [55]. This way, the method

[5] The recruitment of participants was guided using the following selection criteria: i) participants needed to live in either Stuttgart or Osnabrück, ii) an equal distribution of gender, iii) an even number of participants that represent three age groups (seniors/ working/ students), and iv) a good mixture of educational background and professions. While the first criterion stems from the consortium institutes' background, the other three were introduced to gather a stratified random sample.

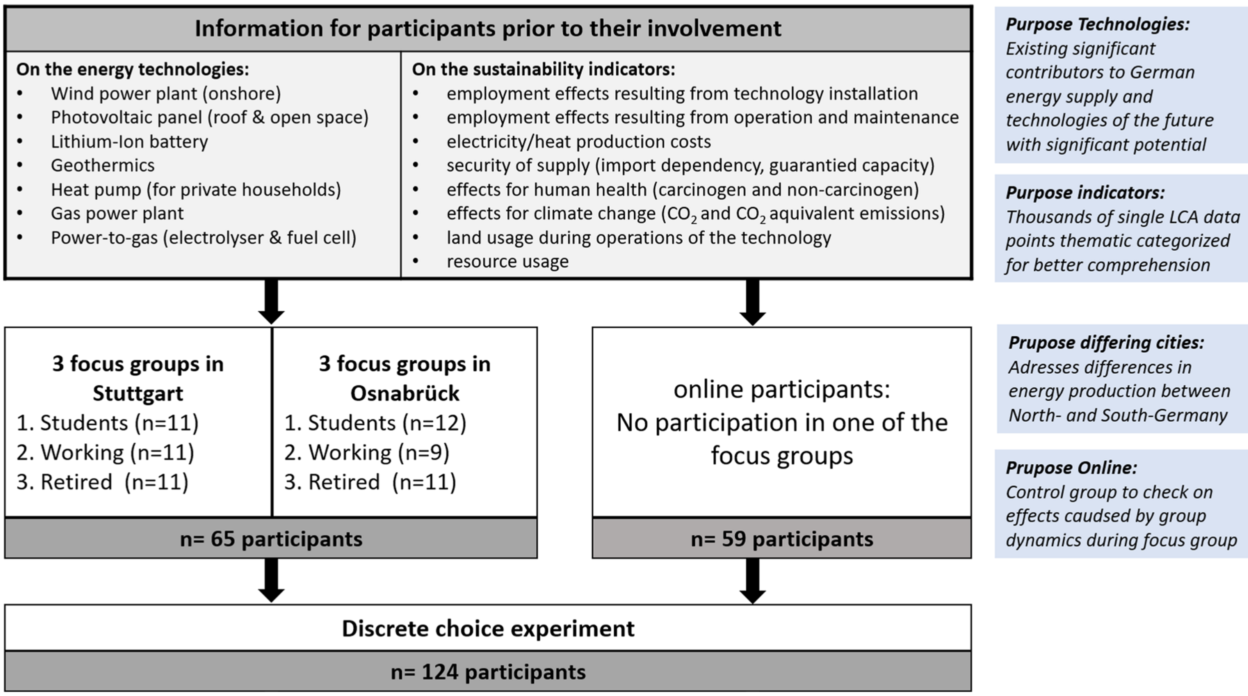


Fig. 1 The empirical research design

takes into account that in complex decision situations, preferences are not one-dimensional but involve trade-offs between underlying, or 'latent' preferences [56]. The methods have, thus, proven to be more reliable than direct questions regarding the importance of specific attributes for individual choices [56] and demonstrate a high external validity [57]. DCE and conjoint analysis have often been used synonymously in social science applications.[6] While we acknowledge the different traditions and theoretical foundations of both methods, the following review includes applications of CA and DCE in the context of energy and sustainability. As the purpose is to situate our study among the existing approaches to a better understanding of citizens' preferences for energy technologies and sustainability measures, we emphasize the common features of CA and DCE: the setup of a hypothetical decision situation in which individuals have to choose among a discrete number of options with different attribute levels, the use of attributes as explanatory variables using regression models [59, 60] as well as similar procedures on data collection. Table 2 presents a non-exhaustive overview of the different perspectives researchers in the areas of energy and sustainability studies have adopted in using stated preference elicitation methods.

As illustrated in the table, individual energy technologies are used as a basis for the experiments. To our knowledge, no previous study has been underpinned by different energy systems or combinations of energy technologies. Among these reviewed studies, costs and citizens' willingness to pay for environmental protection measures are the dominant attributes tested in combination with other environmental factors. In the study by Alvarez-Farizo and Hanley [61], three environmental-related attributes are highly significant, with the impact of wind farms on flora and fauna being the most important factor for citizens. The cost attribute thereby showed comparatively weak effects. This can also be observed in

[6] Both methods have their origins in psychology and have been typically used in marketing to detect consumer preferences. In line with Green and Srinivasan [58], we acknowledge conjoint analysis as an umbrella term that includes a broad spectrum of approaches that "(…) estimate(s) the structure of a consumer's preferences (e.g. part worth's, importance weights, ideal points) given his/her overall evaluations of a set of alternatives that are pre-specified in terms of levels of different attributes." While some authors suggest that discrete choice experiments present a subcategory of conjoint analysis [55], Louviere et al. [56], however, argue that subsuming DCEs under the header of CA does not do justice to the theoretical underpinnings of DCE: Whereas CA is founded on mathematical principles of 'conjoint measurements', DCE is based on random utility theory that offers (better) insights into the choice behavior of individuals. It assumes that the latent utilities can be summarized by two components, a systematic (explainable) component and a random (unexplainable) component. Systematic components comprise attributes explaining differences in choice alternatives and covariates explaining differences in individuals' choices. Random components comprise all unidentified factors that impact choices." Due to the involvement of a random component, with DCE, researchers can only determine the probability that an individual will prefer one alternative over the other.

Table 2 Overview of previous CA/DCE applications in energy and sustainability studies

Specifications of the studies	Variations across the literature
Individuals being interrogated…	• Citizens as consumers/private households [84, 85] • Citizens as potentially affected by an energy technology [62, 61] • Citizens as private investors [86–89] • Stakeholders involved in technology installation and operation [90, 91]
…concerning the objects of investigation…	**Single energy technologies**: • Economic and ecologic effects of wind energy [64], including onshore [61] and offshore [63], siting decisions of geothermal power plants [92], nuclear waste [65], photovoltaics, hydro schemes, biomass, waste combustion, natural gas [62] **Policies, programs, products**: • Climate change mitigation policies for residential energy use [84] • Private investments in technologies [89], e.g., wind [87], solar thermal [93] • Electricity products [94], load control management/domestic appliance curtailment contracts [95] • Smart meters [96], electricity saving products [97], energy pricing programs for demand side management [98]
…testing the value of the attributes…	**Environmental aspects:** • Impacts on landscape, wildlife, air pollution [62], and landscape, habitat and fauna in combination with costs of technologies [61] • Marine species abundance and diversity with artificial reefs, wind farm ownership, esthetic impacts [63] **Economic/social aspects:** • Employment in local community, price for electricity [62] • Town location, distance from respondents' home, monetary savings, tax revenue of community [64] • Willingness to pay for energy efficiency versus CO_2 reduction measures [84] • Return, risk, duration and field of private financial investments [88, 89] **Level of information/personal involvement** • Environmental labeling, disclosure of information about life-cycle [85, 99] • Transparent information on energy sources for electricity products [94], feedback provision on energy saving-programs [97, 100] • Level of engagement in the technology/control over the technological features [96, 98] • Procedural fairness and distributive justice in policy decisions [65] • Personal convenience: type of curtailment contracts, frequency of curtailment, opt-out, advance notice, compensation [95]
…accounting for differences across individuals due to…	• Age [85, 87], gender [96] • Income [84, 62, 88] • Urban vs. rural communities [62] • Environmental attitudes & behavior [87, 95] • Trust in electricity suppliers [95]
…using methodological variations	• Comparison of contingent rating and choice experiment [61], CA and self-explicated method [101] • CA to improve communication between LCA analysts and stakeholders [91] • Combination of CA with field experiment [98]

The review is based on an advanced search in the Science Direct database using the terms 'conjoint analysis' and 'discrete choice experiment'. Results showed a large number of studies using CA and DCE in the area of transportation and sustainable mobility. Since our project only focuses on the electricity and heat sector, the studies are not included here

a study by Bergmann et al. [62] that uses a similar experimental setup for different energy technologies. Effects on landscape and wildlife are valued the highest by the respondents. The study by Klain et al. [63] looks at offshore wind farms and demonstrates that impacts on reef habitat—among the other indicators capital costs, ownership structure and visual impacts—are the most salient factor in citizens' decisions. Like many other studies, e.g., [64], they assessed citizens' willingness to pay (WTP) for measures that improve environmental conservation and found particularly high rates for measures on biodiversity. Another set of attributes that resonate with our research design is the role of transparent information for citizens' assessments. Assefa and Frostell [17] found that citizens lack knowledge to discriminately assess different energy technologies while other studies [22] have argued for more transparent and complete life-cycle information of technologies for lay people. The study by Krütli et al. [65] investigates the role of perceived fairness in policy decisions on siting nuclear waste. Testing the attributes procedural justice, distributive justice and outcome valence, the authors find that procedural justice, i.e., the involvement of citizens and the transparency of the decision-making process is highly valued by respondents.

In sum, while the combination of tested attributes in various studies reflect environmental, economic and social dimensions, none of the reviewed studies have explicitly utilized DCE or CA for understanding social sustainability aspects nor for multi-criteria assessments in which the empirical results are utilized as weighted inputs for further, quantitative modeling. Similarly, focus groups that empirically complement, validate and contextualize DCE/CA findings have not been found in the literature. Louviere et al. [56] merely suggest that qualitative research, including focus groups, could be used ex ante to identify possible attributes.

Our approach

As a basis for the discrete choices, we decided upon the technological systems, i.e., the different options participants needed to choose between. Model-based energy scenarios are complex 'if…then' statements derived from multiple assumptions and parameters [66] and are difficult for non-modelers to interpret [67]. Therefore, it was not a suitable option to present participants with such complex scenarios. Likewise, presenting individual technologies would have given the impression that decisions about future energy systems are a matter of single solutions and would have deflected attention from the fact that individual energy technologies are in complex interaction with the overall energy system. To highlight the necessary complementarity of technologies for electricity and heat consumption, conversion and storage, we used reduced scenarios containing two technologies each (e.g., *photovoltaics + battery storage*). For the composition of the scenarios, seven energy technologies were used (the same that were used in the information sheets for the focus groups; see Fig. 1)[7] and combined into 12 meaningful and consistent scenarios (6 focusing on power generation, 6 on power and heat generation). Subsequently, the sustainability indicators, i.e., the attributes and the levels presented for each scenario were selected based on a desk research on sustainability criteria, conducted as part of the research project [15].[8] Data for all indicators included effects regarding the technologies' full life-cycle (installation, operation, disposal).[9] Traditionally, discrete choice experiments fully randomize the levels of attributes across choices. In our case, however, LCA datasets prescribed exactly how each scenario scored with regard to the different sustainability indicators (see [57] for previous applications of non-randomized, predefined vignettes).

Participants were presented with two scenarios at a time and asked to choose the most preferred (paired comparison design). As a basis, the 12 scenarios were paired forming 30 different choices for 'electricity' and 'electricity and heat', while for each scenario all eight sustainability indicators were shown. Given this large number of choices and their complexity, a full factorial design (each participant receives *all* choices) was not adopted as we sought to minimize fatigue effects; therefore, we confronted each participant with 12 choices.[10] Figure 2 presents an overview of how the choices were constructed based on the seven technologies. It also shows how the choices were presented to participants in a pseudo-random pattern. Given the complexity of the scenarios we paid special attention to the presentation and visualization of the data. The scenarios entailed verbal descriptions along with small icons of the involved technologies to facilitate quick recognition during the choice situations. Every sustainability indicator was displayed as a colored percentage: the percentages state how much the scenario's performance deviated from average performance of all considered scenarios. For the example shown in Fig. 3, security of supply for the scenario *wind + photovoltaics* is 19% below the average performance, whereas for *gas + geothermics* the security of supply is 40% above average. The colors indicate the scenarios' contributions to sustainability (green—more sustainability, red—less sustainability).[11] A pre-test showed that a display without any visualization and color results in a lack of understandability for participants.

[7] The decision was based on a meta-analysis of existing energy scenarios [16] and the assumed future relevance of different technologies for the overall energy mix as described in these scenarios. For instance, we refrained from integrating coal or nuclear power plants into the design since all major scenario studies assume their phase out by 2050 (the most common reference point of the scenario studies).

[8] For the multi-criteria assessment of the project, a total number of 22 indicators were used. This large number, however, would have not been manageable for a DCE. Therefore, we limited the analysis to the seven indicators that were most commonly used in existing assessment studies, see section "Sustainability assessments of energy systems: Literature review".

[9] The first four indicators were derived from the life cycle impact assessment method (ILCD midpoint 2.0), which is integrated in the life cycle inventory database *ecoinvent* v3.3 [68] while the employment indicators were derived from research studies on job creation [69] and electricity production costs (based on [1, 70–73]) and formed expert-based assessments (security of supply).

[10] A review of conjoint analyses on environmental issues [55] shows considerable differences among studies regarding the number situations per participant, ranging from 12 to 120.

[11] While we acknowledge the normative nature of the concept of sustainability, the 'sustainability triangle' nevertheless is publicly discussed, widely accepted and points to a clear direction of what is *more* and what is *less* sustainable. For the present case, *higher* sustainability means *higher* job effects, *lower* energy costs for households, *higher* security of supply, and *lower* effects on human health, emissions, land and resource usage. From our perspective, these methodological choices are legitimate since the research objective was not to identify what constitutes sustainability per se, but which indicators contribute most to citizens' preferences for future energy systems.

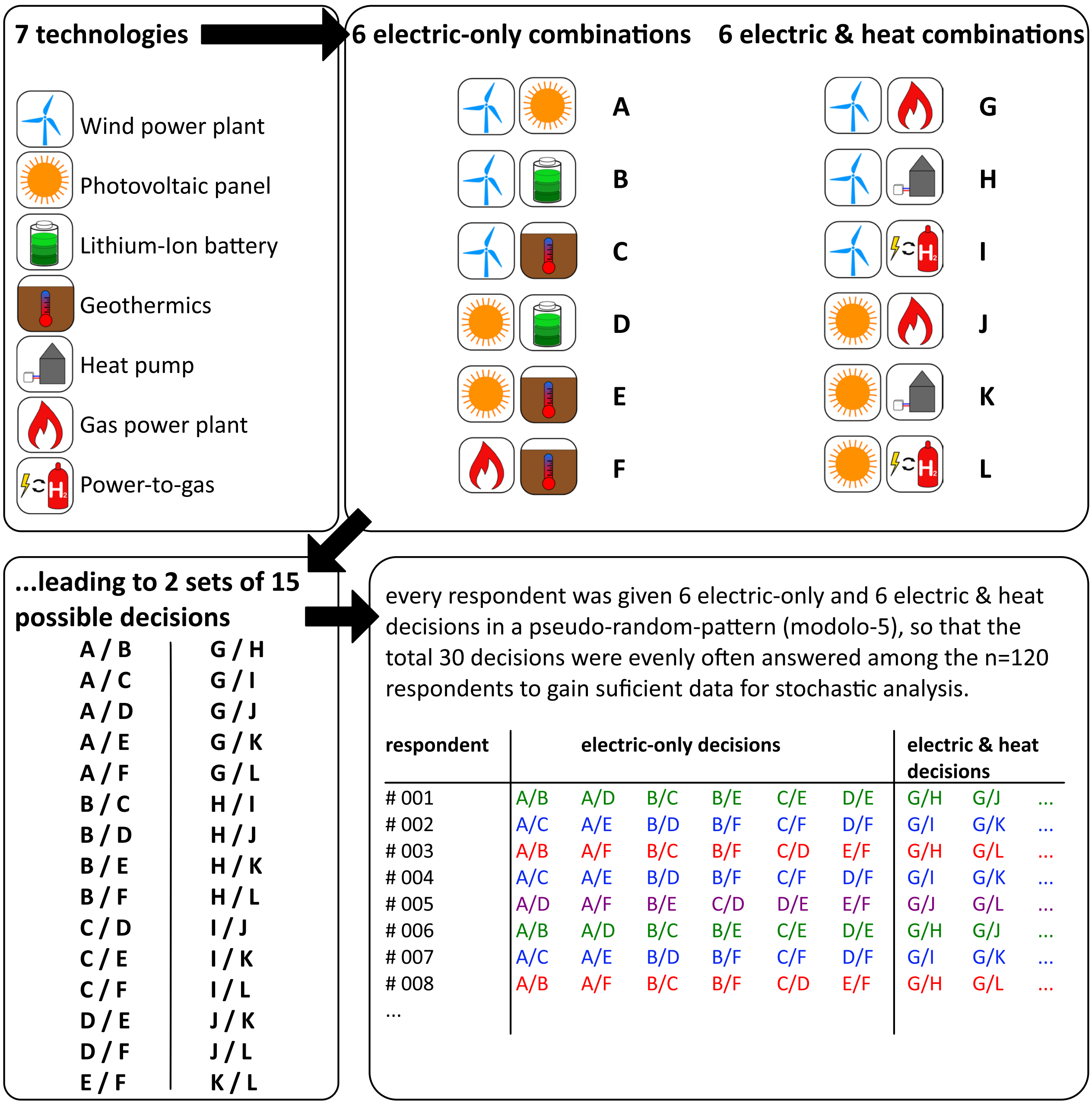


Fig. 2 Constructing combinations for the discrete choice experiment based on seven technologies

To aid understandability, descriptions and a glossary of the energy technologies used in the scenarios and the sustainability indicators were handed out to participants prior to the experiment. Participants had the opportunity to view the information again via a 'mouse over feature' during the experiment. To explain the data visualization and to reduce the risk of misinterpretations, an example was shown to participants at the beginning. Participants completed the experiment online through the survey platform *Qualtrics*. They were sent a personalized link so that they were able to complete the survey in their own time within a period of four weeks.

Responses were analyzed by determining participants' preferences as the part-worth for each level of the attribute [55]. The classic approach to analyzing discrete choice data—published by McFadden [74]—is fitting a conditional logit regression model (also referred to as multi-nominal logit model (MNL) [75]) on the data.

	A: Wind turbine + Photovoltaics	B: Gas power plant + Geothermics
Employment - Installation & Construction	-7%	-7%
Employment - Operation & Maintenance	-24%	+35%
Production Costs	-35%	-21%
Security of Supply	-19%	+40%
Effect on Human Health	-55%	+11%
Impact on Climate Change	-84%	+274%
Land Consumption	-91%	-62%
Ressource Consumption	-25%	-81%

Fig. 3 Exemplary choice as appeared in the DCE. The figure shows just two exemplary choices. For a full overview of all choices and their respective data, please see Appendix B

This approach has two drawbacks: (1) the underlying assumption of independence-of-irrelevant-alternatives (IIA) which is at least questionable in most settings, (2) the inability of accounting for unobserved heterogeneity [75]. Several advancements to the MNL are able to overcome this: Latent-Class MNL, Random Parameter/Mixed MNL and Hierarchical Bayesian MLN [75]. We applied a Random Parameter/Mixed MNL because it allowed to model the nested structure of our data (each participant made several pairwise choices) better than a Latent-Class MLN, and because we were not focused on obtaining individual-level-coefficients (an advantage of Hierarchical Bayes MLN). In contrast to MNL, Mixed MNL estimates a mean effect *and* a standard deviation of that effect over the sample, as well as testing if the variation in effect size is normally distributed in the sample. If the latter is not the case, it can be assumed that factors not included in the model have a significant impact on effect size (unobserved heterogeneity) [75].

Scenario attributes were not presented by absolute values, but by percentages depicting their performance relative to all scenarios in the sample. Since all attributes thus had the same range, their coefficients can be interpreted as attribute weights in the choice of a scenario [59]. The analysis was implemented in the statistical program *stata* using mixlogit [60].

Results

Focus groups

During the group discussions, participants were asked what they understood to be a social sustainable energy transition in order to measure the broadness of the opinions. Participants' perceptions centered around three clusters, marked in different colors in Fig. 3. Connected with the cluster 'lifestyle preservation', arguments highlighted conservative and liberal positions on the future of energy systems: the prioritization of personal freedom over restrictions in energy use, the rejection of technology-related noise and the fear of a destruction of landscape esthetics as well as concerns about the security of supply were typical narratives presented for this type of argument. Our analysis also revealed an opposed cluster around 'lifestyle change': here, participants focused on the perceived injustice in resource and energy use and pointed to discrepancies between national and international conditions and between present and future generations. Although concerns about a failing security of supply of renewable energy technologies also prevailed in this cluster, the argumentation structures led to a different conclusion as opposed to the first cluster, which is the necessity to reconsider present lifestyles and to reduce personal impacts on the environment through own conscious sacrifices in consumption patterns. For a selection of quotes on these topics, see Table 3. Such an inner negotiation process that seeks to balance one's own habits and a more sustainable lifestyle constitutes the core of this type of argument: participants accepted that major changes will be necessary and that these changes will affect all individuals—including themselves. Along with surfacing this inner conflict, participants also proposed different societal guidelines and new approaches towards the use of energy and natural resources (Fig. 4).

While these two clusters seem to be opposing in nature, it is important to note that they present different types of arguments that we observed not only *across* but also *within* participants: some participants used both kinds of arguments (lifestyle changes *and* lifestyle preservation) which underlines the inner conflicts and trade-offs citizens are exposed to when dealing with the concept of sustainability [76]. The third and biggest cluster consisted of arguments pertaining to the balance between individualism over collectivism. Similar to the second cluster, statements about the need for conscious, individual sacrifices were present. However, the cluster also revealed the broadest variety of arguments when negotiating the conflicting positions on sustainability. The arguments circled around different options to maximize energy efficiency, the dangers to human health and ecosystems and the distribution and allocation of risks and burdens among society. The discussions were directly connected with an urgent request to policy-makers to balance the effects of energy transitions in a way the participants deemed just.

During the focus groups, aspects of distributional justice were intensively debated and emerged as one of the topics that showed the most variety in answers and had major potential for dispute. Our analysis also showed that most of the other arguments presented above and beyond were mental link to distributive justice (Fig. 5). Participants' responses in relation to distributional justice circled around who suffers what consequences of future energy production and who gains what benefits of it, with a major emphasis on negotiating different needs among societal groups.

As over twelve hours of conversation transcripts in German and their translation in English would overwhelm the appendix of this article, we decided to present selected ones in both versions in a short overview to leave more space to the results' discussion.

The participants did not limit their considerations to national conditions but also covered global facets of energy justice. Hence, they do not follow political measures to combat climate change and achieve social balance that limit themselves on their home country. They demand more extra-national measurements from politics, as they understand the interconnectedness of the underlying matter.

The arguments on ubiquity of climate change demonstrate that participants are aware of the interconnectedness of international commodity flows and its social outcomes. For example, among several of the focus groups, lithium mining processes in South America were criticized by participants as a particularly unjust side-effect of Germany's investment in battery technologies. Such mining processes were not only discussed with respect to ecological damages but also in terms of the potential social exploitations and the moral (ir)responsibility of importing countries. Participants also reported a perceived distributive injustice between private companies and civil society. Participants were disapproving of benefits being accumulated by or granted towards private investors while damages or losses being transferred to the public domain or leading to price increases for end users.

Overall, the argumentations clustered around the need for lifestyle changes appeared to be more interconnected: here, arguments strongly built on each other (green). The argumentations that tended to lifestyle preservation were presented mostly without connections to each other (orange). Although the topics of employment and energy affordability were also addressed in all focus groups, they had a different status in the groups in Osnabrück compared to in Stuttgart: citizens from Osnabrück placed more emphasis on employment whereas in Stuttgart citizens focused on energy affordability. However, both strands of arguments were clearly subordinate to the debates on distributive and intergenerational justice and appeared to be given as "But what about…"- responses.

Finally, aspects of intergenerational justice emerged as part of the discussion in the focus groups. Participants shared their expectations and—above all—their fears regarding the living conditions of future generations. In this context, arguments on the disposal of residual and waste materials and their avoidance through resource conservation and recycling played a dominant role. Likewise, cross-references to adverse health effects of energy production were drawn and integrated into the discussion.

A deeper analysis is provided in Fig. 5. Here all found arguments are presented in a (original three-dimensional) graph that shows the proximity within the discussion. Meaning the closer arguments are printed, the more immediate they are spoken off or referred to in the respondents' speech acts. This way it is possible not only to identify the large clusters, but also to compare the connectedness of the clusters. As we excluded all below three direct connections it is clear to see that the green cluster,

Table 3 Selection of original and translated quotes from the focus groups

Dimension/aspect	Quote original	Quote translated
Social distribution of costs [Ren_S_#172]	Also man müsste schon irgendwie eine Mitte finden, so dass einige denen was geben, was die brauchen und für die anderen, die es weniger haben	So, you would have to find a middle ground somehow, so that one gives something to those who need it and for the others who have less
Ubiquity of climate change [Stu_OS_#90]	Letztlich ist davon auch die gesamte Menschheit betroffen und nicht einzelne Leute, die ihren Job verlieren oder Probleme mit der Gesundheit haben, sondern es geht ja darum, uns alle zu retten	At the end of the day, it's the whole of humanity that's affected, not individuals who lose their jobs or have health problems, but it's about saving us all
Lifestyle preservation [Ber_OS_#66]	Ich kann auch nicht gutheißen, wenn mir jemand von außen suggeriert wie ich zu leben habe, wenn mir jemand etwas aufdrücken möchte, was überhaupt nicht zu meinem Lebensstil passt	I also cannot approve of someone suggesting to me from the outside how I have to live, if someone wants to impose something on me that does not fit my lifestyle at all
Lifestyle change [Ber_OS_#52]	Dann muss man auch sein Leben umstrukturieren. Das ist die Frage wem mutet man das zu und wer ist bereit was zu tun dafür. Man braucht radikalere Schritte und kann dabei nicht warten, bis jemand die Entscheidung für einen trifft, sondern man [muss] selbst die Schritte gehen. Da stelle ich mir die Frage: Was brauche ich dafür wirklich und dann merke ich, das ist vielleicht gar nicht so viel	Then you also have to restructure your life. That's the question of who you expect to do that and who is willing to do what for it. You need more radical steps and can't wait for someone to make the decision for you, but you [have to] take the steps yourself. I ask myself the question: What do I really need for this and then I realize that maybe it's not so much
Quality of life [Ren_S_#161]	Lebensqualität ist, wenn ich das habe, was ich benötige. Jeder mittelsituierte Mensch hat hier alles bestens. Komfort ist für mich, wenn ich die Garage vor der Tür und das Auto hole, um die Ecke zu gehen um die Zeitung zu kaufen und Brötchen zu holen. Das ist für mich Komfort, der die Umwelt belastet und nicht nötig ist, usw. Es gibt Leute, die meinen das ist notwendig, ja? Lebensqualität ist, wenn ich um die Ecke laufe und saubere Luft habe	Quality of life is when I have what I need. Every middle-situated person has everything here in the best possible way. Comfort for me is to have the garage in front of the door and to get the car, to go around the corner to buy the newspaper and to get rolls. That is comfort for me, which pollutes the environment and is not necessary, and so on. There are people who think that is necessary, yes? Quality of life is when I walk around the corner and have clean air
Human health [Ren_OS_#130]	Die menschliche Gesundheit ist am Wichtigsten. Was nützt uns alles andere. Klimawandel hat es immer schon gegeben. [Einwurf: Aber es geht dann ein wenig fixer, wenn nicht nichts dagegen tun]. Dann ist das ebenso. Aber es wird auf jeden Fall kommen. Wir hatten eine Eiszeit und alles Mögliche. Wenn wir aber nicht gesund sind, nutzt uns alles andere nichts	Human health is most important. What good is everything else. Climate change has always existed. [Interjection: But it goes a little bit faster then, if not do nothing about it]. Then it's the same. But it's definitely coming. We've had an ice age and all kinds of things. But if we are not healthy, everything else is of no use to us

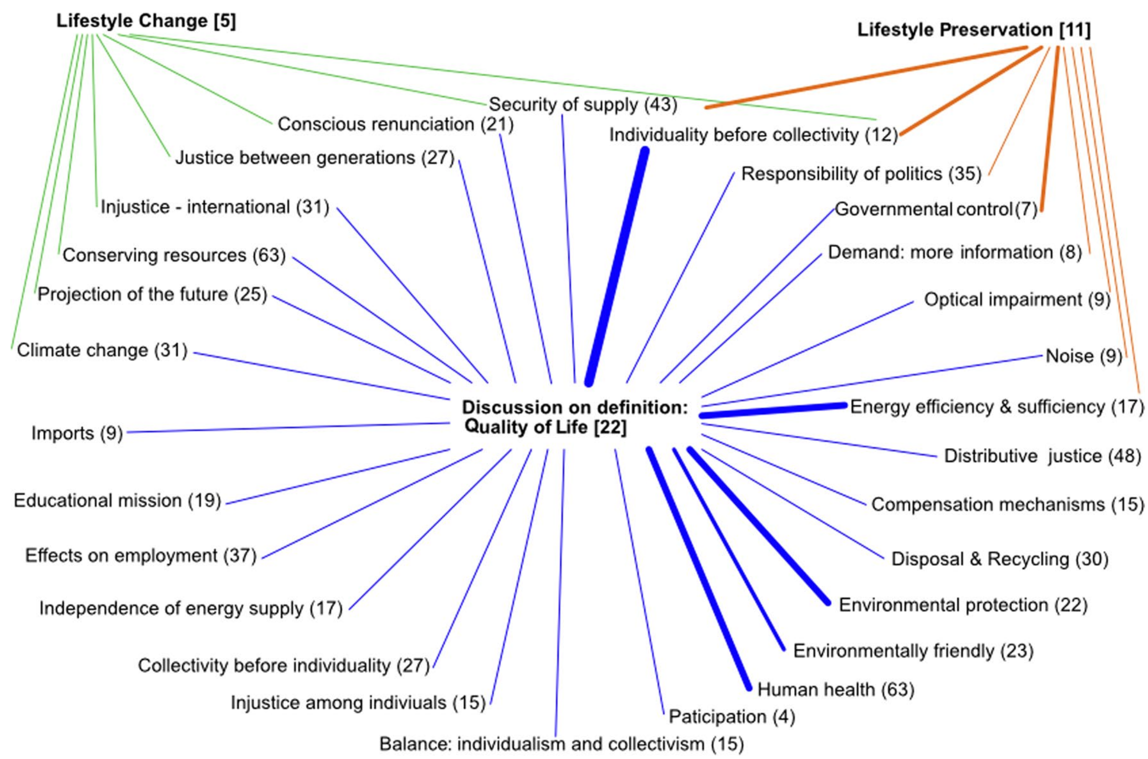


Fig. 4 Argument network and discussion clusters. The picture shows the identified thematic statements and their counts (in brackets) found in all focus groups. The statements are connected to clusters in which several arguments interacted, meaning that arguments related to different clusters. Square brackets denote the frequencies of exchanges of arguments connected to the discussion clusters in all six focus groups. The figure presents all arguments that occurred at least once (thin/1pt lines) connected with each other during the focus groups. Thicker lines (up to 7pt) represent more (up to 11) connected speech acts

lifestyle change, shows more interconnections than the preserving counterpart.

The blue cluster represents the actual debate on distributive justice and its main dimensions on a rational, fact-oriented manner. Here the arguments circle around knowledge: what are the costs of a given technical energy technology and consequences and costs currently allocated.

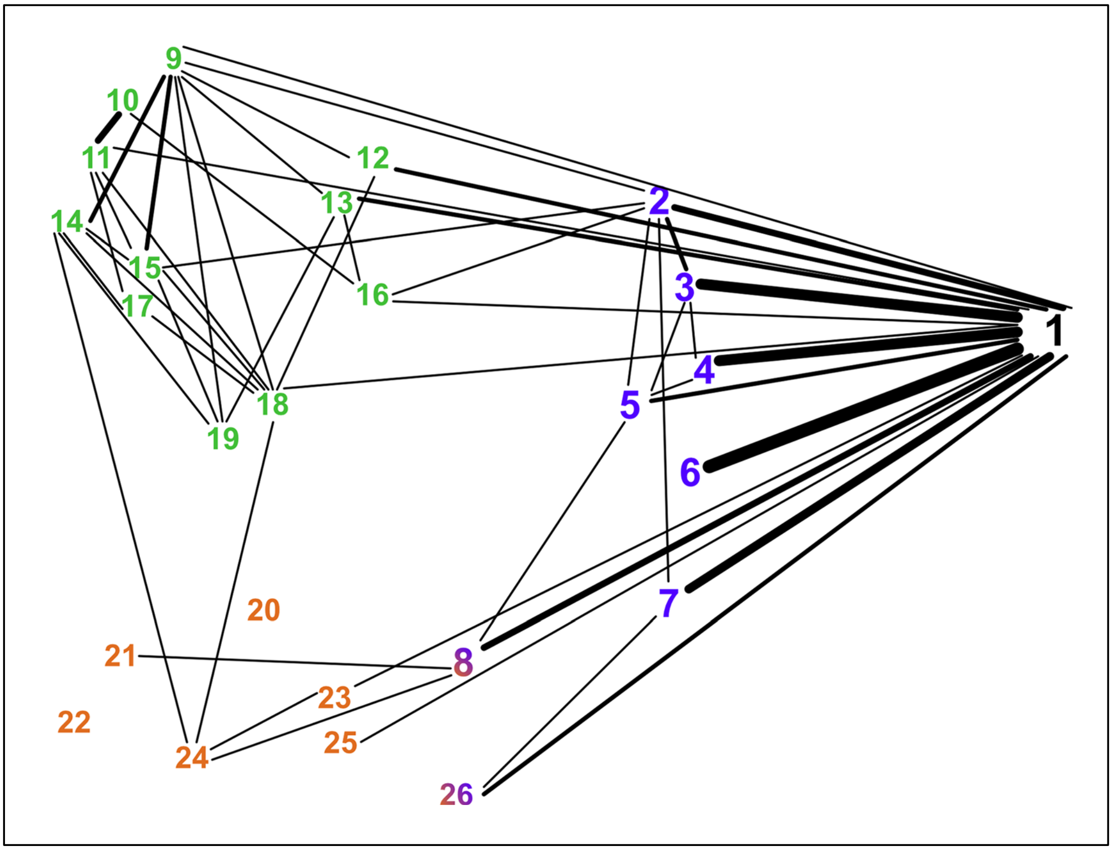
The green cluster represents the individuals using arguments on how to change their (and general) lifestyle to adapt to the perceived new reality surrounding the climate change. These "changers" use similar arguments while reasoning. They agree on a common notion that change is necessary and start debating how where and who should take what political steps. The lifestyle preservers, or conservatives, mostly agree on demanding more (sure, or irrefutable) information before meeting a decision or that they as private people are not the first address to make change but nations and industry. This bypasses the question on social sustainability by a tendency to shift the discussion to responsibility and blaming of other societal actors.

Discrete choice experiment[12]

The model chosen for the analysis of the DCE is significant on a very high level and has a McFadden Pseudo-R2 of 0.49, meaning that almost half of the variance in choices can be explained by the sustainability indicators included in the regression. Most of the indicators selected for the DCE showed a significant effect ($p > 95\%$) on scenario choice, with the exception of the indicator regarding *temporary employment effects.* Since this indicator was also highly correlated with *permanent employment effects*, and the latter had a higher significance as well as a higher effect on scenario choice, the *temporary employment effects* were excluded from the model.

Of the remaining indicators, four showed significant preference heterogeneity and were, thus, modeled as random effects: *climatic effects, health effects, land usage*, and *resource depletion*. Among these, the importance of *health effects* is influenced the most by unobserved

[12] Some of the results presented in this sub-chapter have been published in a previous paper as part of the multi-criteria assessment approach developed in [16].



Legend of arguments:

1 ***Distributive justice***	*9 Conscious renunciation*	*18 Educational mission*
2 Affordability	*10 Projection of the future*	*19 Human health*
3 Injustice among individuals	*11 Justice - Intergenerational*	*20 Employment*
4 Collectivity before individuality	*12 Individuality before collectivism*	*21 Demand for more information*
5 Compensation mechanisms	*13 Quality of life*	*22 Security of supply*
6 Injustice - international	*14 Energy efficiency & sufficiency*	*23 Citizen participation*
7 Injustice – Individuals vs. Companies	*15 Environmental protection as a matter of course*	*24 Own contribution*
8 Balance: Individualism & Collectivism	*16 Environmentally friendly*	*25 Global conflicts*
	17 Conserving resources	*26 Injustice – individuals vs. nations*

Fig. 5 Argumentative network connected to distributive justice. Placement of numbers with respect to the proximity of statements in the transcript. Lines represent at least 3 direct connections in the discussions, thicker lines equal more connections (the thickest lines represent 31 connections)

heterogeneity: the standard deviation is even higher than the estimated mean of the coefficient. The importance of *health effects* seems to vary more than the importance of all the other indicators between citizens; a plausible reason for this variation could be that their impact on an individual's personal health also varies very strongly depending on their personal health status, which is not captured by the model. The importance of *climatic effects* is least influenced by unobserved heterogeneity: in relation to its mean value, it has the smallest standard deviation of these regressors; see Table 4.

Since all the regressors have been normalized before the estimation, coefficients can be compared directly and represent the importance of a regressor for the choice between different scenarios, or preference weights. Overall, the *climatic effects* of the scenarios presented in

Table 4 Results discrete choice experiment

	β [Beta]	Stand. error	$P>\|z\|$	95% Conf.	Interval
Mean					
Climate	0.0581***	0.0081	0.000	0.0421	0.0743
Resources	0.0299***	0.0071	0.000	0.0161	0.0438
Health	0.0252**	0.0092	0.006	0.0073	0.0432
Security	0.0229***	0.055	0.000	0.0121	0.0338
Land use	0.0189***	0.0031	0.000	0.0128	0.0251
Costs	0.0138*	0.0066	0.037	0.0008	0.0268
Employment	0.0137**	0.0050	0.006	0.0039	0.0236
SD					
Health	0.0407***	0.0061	0.000	0.0288	0.0527
Climate	0.0322***	0.0061	0.000	0.0203	0.0441
Resources	0.0320***	0.0055	0.000	0.0212	0.0428
Land use	0.0141***	0.0040	0.000	0.0063	0.0220
N	2976				
$P>x^2$	0.0000				

the DCE had the strongest effect on whether a scenario was preferred over another. *Climatic effects* are seen as almost twice as important as the second most important regressor—*resource depletion*. Surprisingly, both economic-related regressors in the DCE (*total system costs* and *employment effects*) were regarded as the most non-relevant indicators by participants when assessing the social sustainability of the scenarios. Considering the importance of system costs and economic effects of energy transition pathways in media, politics and science [11], their relative unimportance in our DCE was rather surprising to us.

Group differences cannot be modeled directly in mixed-logit models [77], so we looked for them by analyzing interaction terms. Along with the DCE, information about age, gender, occupation and knowledge about the energy system of the participants were collected. For each of these variables, interaction terms with any of the regressors have been tested, but none of them could significantly enhance our model. This result implies that age, gender, occupation, and knowledge about the energy system do not significantly influence preference weights, as well as that the importance of *climate effects*, *health effects*, *land use* and *resource depletion* when classifying a scenario as more or less socially sustainable is affected by other attributes than these.

Discussion

Our empirical research provides insights into what citizens value most when assessing future energy systems—with respect to available, scientific sustainability indicators and beyond.

When assessing the results of our discrete choice experiment, it should be noted that we could not realize a true random sampling of participants that meets the requirements for representativeness. It cannot be ruled out that participants in our sample cared differently about the future energy system than the overall German population. As a result, these findings have to be interpreted with caution.[13] Nevertheless, to our knowledge, this has been the first DCE on citizens' preferences with regard to national energy scenarios, as opposed to single energy technologies, and thus, provides valuable insights: all but one of the sustainability indicators that we derived from current sustainability assessment models showed a significant contribution to participants' choices; only temporary employment effects did not contribute significantly to the model. One of the somewhat counter-intuitive results of preference weights is the relative unimportance of production and total system costs which ranked last but one regarding preference weights. Even if the exact values of preference weights may differ in a representative sample, this result raises the question if costs that emerge from the transition towards renewables have the same importance for citizens as implied by their omnipresence in science, media and politics [11]. In this regard, two previous DCEs on preferences regarding local energy projects present comparable settings. Like in our study, Alvarez-Farizo and Hanley [61] found that environmental attributes were highly significant while the importance of costs of local wind farms ranked significantly lower in citizens' perceptions. On the contrary, in a study of 2006 [62], costs had the highest level of significance and—in contradiction to our results—employment effects did not significantly influence vignette choice. One reason for this discrepancy might be the declining prices for renewables in the last decades; another reason could be that the environmental and social implications of climate change have been getting ever clearer in the meantime.[14] One central implication of our findings is that it underlines increasing concerns of social scientists [78] whether economic incentives have the potential

[13] This is also one of the reasons for us to not compare respective preference weights for subgroups of the sample or calculate the willingness to pay for the other indicators.

[14] Furthermore, Bergmann et. al showed a significant effect of higher education and age, which proved insignificant in our case. This might be an effect of their higher sample number. Similar to our results, Bergmann et al. did not find many sociodemographic variables with significant influence, although they tested the influence of employment in the energy sector, being a parent, membership in a conservation group, and the amount of last electric bill. However, they found a significant difference regarding preference weights between urban and rural populations. Since our sample consisted mainly of urban citizens, we could not test for these differences. Since we included more vignette attributes than the two studies, it comes as no surprise that our pseudo-R2 is higher.

to increase the acceptance and social sustainability of technologies and transition processes in the long-term. In contrast, it suggests that particularly environmental externalities (including those beyond citizens' immediate environment, e.g., resource depletion) will need to be taken up by policy measures.

Another central issue highlighted by the results of the DCE and the focus groups is that citizens balance many different sustainability aspects when choosing their preferred scenarios on the future of energy systems (see Table 5). Diverse contradictions and dilemmas inherent in the concept of sustainability have been taken up from a scholarly perspective and with respect to its policy implications, for instance the weighting of the three sustainability pillars [76] or the possibility of 'green growth' [79]. From the perspective of citizens, however, their inner conflicts and the process of considering diverse trade-offs between sustainability objectives when assessing future energy systems has not been acknowledged or discussed. So far, inner conflicts of individuals with respect to sustainability have mostly been tackled through the lens of 'rebound effects' [80]. The relevance of these aspects is further amplified by the results of the focus groups. The analysis reveals a contradiction between two different kinds of arguments. On one side, citizens expressed their intention to adjust their personal lifestyles towards a more climate stabilizing and sustainable manner. On the other side, citizens also seemed to be more reluctant in changing their everyday life and use of resources. The latter cluster of arguments demonstrated a less coherent set of arguments pointing to the co-responsibility of private sector enterprises as well as a fair balance of burdens between Germany and other actors on the international stage. Here, citizens raised questions about employment and affordability of electricity and heat more often. The lesser interconnectedness of the arguments illustrate that this fraction does not underlie a unifying, clear ideology like the one of the more environmentalist-driven arguments.

A central finding of the focus groups has been the dominance of aspects on distributional justice citizens mentioned in connection to social sustainability. To the participants of the focus groups, it presented more or less a given that the transition of the energy system will be costly; they worried not about having to pay for the transition but expressed their concerns about whether everyone will have to pay a fair share. Especially the balance between private and public sector as well as private sector and citizens were perceived as problematic. To many, burdens connected with the energy systems change were perceived to be externalized towards civil society. Energy justice within processes of energy transitions has received growing scholarly attention in recent years. From a conceptual perspective, previous studies have raised aspects such as possible negative effects for fossil-intensive employment or an outsourcing of emissions from one focal country to another [81]. Particularly, the latter point has been underscored by our empirical research as a key theme in the eyes of German citizens. Here, our findings are in line with insights from other industrialized countries that argue for the importance of distributional and procedural justice [65, 82]. Following newer frameworks that account for distributional and procedural inequalities [83], our research suggests that policies need to move beyond tackling inequalities in transition processes in a selective manner (e.g., by focusing only on effects of single technologies or job effects resulting from the decline of an industry). As our research shows, citizens are concerned about the *systemic* effects and *multiple* externalities of transition processes which need to be reflected and tackled on a system's perspective in the development and implementation of transition pathways.

Table 5 Ranking of indicators based on DCE and focus group results

Factors identified and ranked as part of DCE analysis			Factors raised in the focus group ranked by frequency of mentions	
Factor	**β [Beta]**	**Stand. Error**	**Factor**	***N***
Climate	0.0581***	0.0081	Distributional justice	85
Resources	0.0299***	0.0071	Justice—international	31
Health	0.0252**	0.0092	Waste/Recycling	30
Security	0.0229***	0.055	Justice—intergenerational	27
Landuse	0.0189***	0.0031	Quality of life	23
Costs	0.0138*	0.0066	Conscious renunciation	21
Employment	0.0137**	0.0050	National independence	17

Significance levels: *95% **99% ***99.9% Rank 1 = best 7 = worst

Conclusions and outlook

Our research has been conducted with the purpose to close the gap of social sustainability insights on energy transition pathways and to inform sustainability assessments and multi-criteria decision analyses (MCDA). Our focus groups allowed for an explorative perspective on what citizens value in terms of the *social* sustainability of energy systems and thereby moved beyond (often entrenched) conceptual and indicator-based understandings of the concept in the literature. The discrete choice experiment—as a stated preference method—has proven to be viable option for quantifying and parametrizing citizens' preferences regarding environmental, social and economic implications of future energy systems.

Overall, the combined empirical methods provided two main insights with strong implications for future energy research: (1) While environmental and climate-related effects of future energy systems significantly influenced citizens' preferences for or against certain energy scenarios, total systems and production costs were of far less importance to citizens than the public discourse suggests. (2) The role of fairness and distributional justice and, thus, the sharing of burdens among members of society in transition processes featured as a dominant theme in all six focus groups.

When coordinating the results of the DCE and the focus groups with energy system models and macroeconomic models as part of an integrative assessment of energy scenarios (the overall objective of the research project), it became clear that current energy system models cannot quantify aspects of distributive justice of the calculated scenarios. The only indicator related to distributive justice that the applied models could calculate was the economic regional disparity [15]. However, participants in our focus groups were not only discussing regional inequalities; for them, intergenerational distributive justice, burden sharing between state, firms, and citizens, as well as between different income and lifestyle groups was far more important. In order to tackle the energy transition on the policy level, facing these observed cleavages within society must be addressed to negotiate durable solutions. This field should not be overlooked by future research on citizens' preferences and social sustainability indicators. Future energy scenarios, therefore, face the challenge to adapt to this demand and include statements about the burdens a respective scenario is placing on different actors and societal groups. This claim is far-reaching since many of the models are by design unable to provide this information and would need substantial modifications in order to calculate indicators of social sustainability as sophisticated as they calculate emissions or economic costs. Furthermore, our results not only advocate the enhancement of the scope of such models (1), but also call for a finer resolution in order to understand what implications different energy scenarios hold for different groups in society (2).

Appendix A: Raw data used for calculating performances of the discrete choices

DCE electric-only combinations (balanced to 1 kWh each partner)	**A1 Wind and PV (roof)**	**A2 Wind and PV (ground)**	**B Wind and Li-battery**	**C Wind and Geothermics**	**D1 PV (roof) and Li-battery**	**D2 PV (ground) and Li-battery**	**E1 PV (roof) and Geothermics**	**E2 PV (ground) and Geothermics**	**F Gas (elec.) and Geothermics**
Climate change, GWP 100a	5,60E-07	8,66E-07	2,10E-06	2,19E-06	2,66E-06	2,71E-06	2,46E-06	2,49E-06	1,28E-05
Freshwater and terrestrial acidification	2,67E-07	3,97E-07	1,41E-06	7,60E-07	1,70E-06	1,67E-06	9,06E-07	8,90E-07	1,54E-06
Freshwater ecotoxicity	6,48E-06	6,60E-06	7,95E-06	3,88E-06	1,33E-05	8,20E-06	6,54E-06	4,01E-06	2,31E-06
Freshwater eutrophication	2,67E-07	3,62E-07	8,25E-07	6,14E-07	1,14E-06	1,01E-06	7,70E-07	7,09E-07	6,22E-07
Marine eutrophication	1,59E-07	2,32E-07	5,09E-07	4,75E-07	6,59E-07	6,54E-07	5,50E-07	5,47E-07	1,19E-06
Terrestrial eutrophication	8,18E-08	1,21E-07	6,99E-07	2,64E-07	7,72E-07	7,77E-07	3,00E-07	3,03E-07	6,86E-07
Carcinogenic effects	7,71E-06	7,51E-06	3,53E-05	2,12E-05	3,40E-05	3,49E-05	2,06E-05	2,10E-05	2,02E-05
Ionizing radiation	1,11E-07	1,79E-07	6,89E-07	5,77E-07	8,27E-07	8,25E-07	6,46E-07	6,44E-07	6,02E-07
Non-carcinogenic effects	2,13E-06	2,61E-06	5,43E-06	2,36E-06	7,63E-06	6,39E-06	3,46E-06	2,84E-06	2,28E-06
Ozone layer depletion	2,84E-09	4,62E-09	4,57E-07	5,32E-09	4,60E-07	4,60E-07	7,04E-09	7,10E-09	1,07E-07
Photochemical ozone creation	8,86E-08	1,26E-07	2,43E-07	2,54E-07	3,17E-07	3,18E-07	2,91E-07	2,91E-07	7,54E-07
Respiratory effects, inorganics	5,21E-07	7,65E-07	1,76E-06	1,80E-06	2,24E-06	2,25E-06	2,04E-06	2,05E-06	2,19E-06

DCE electric-only combinations (balanced to 1 kWh each partner)	A1 Wind and PV (roof)	A2 Wind and PV (ground)	B Wind and Li-battery	C Wind and Geothermics	D1 PV (roof) and Li-battery	D2 PV (ground) and Li-battery	E1 PV (roof) and Geothermics	E2 PV (ground) and Geothermics	F Gas (elec.) and Geothermics
Resources, land use	2,13E-08	5,62E-07	6,26E-08	6,61E-08	4,06E-08	1,14E-06	5,51E-08	6,07E-07	8,87E-08
Resources, mineral, fossils and renewables	6,44E-06	1,06E-05	1,94E-05	2,77E-06	2,61E-05	2,77E-05	6,12E-06	6,91E-06	1,60E-06

Impact category ILCD 1.0.8 2016 midpoint, electric-only combinations.

Notes: ILCD as implemented in ecoinvent v.3.4.

PV = photovoltaic panels, data in ILCS is split between open ground PV and on-roof PV. Data presented to participants are mean of both.

Gas (electric)—electricity production, natural gas, combined cycle power plant [DE]/electricity, high voltage.

Normalization according to: Sala S, Benini L, Mancini L, Pant R (2015) Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalization factors. Int J Life Cycle Assess 20: 1568–1585, https://doi.org/10.1007/s11367-015-0958-8.

DCE electric and heat combinations (balanced to 1kWh each partner)	G Wind and gas (heat)	H Wind and heat pump	I Wind and power-to-gas	J1 PV (roof) and gas (heat)	J2 PV (ground) and gas (heat)	K1 PV (roof) and heat pump	K2 PV (ground) and heat pump	L1 PV (roof) and power-to-gas	L2 PV (ground) and power-to-gas
Climate change, GWP 100a	2,76E-05	3,72E-06	4,89E-06	2,88E-05	2,89E-05	5,27E-06	5,42E-06	8,32E-06	8,68E-06
Freshwater and terrestrial acidification	7,11E-06	2,21E-06	1,03E-05	9,23E-06	8,99E-06	4,93E-06	4,63E-06	1,63E-05	1,56E-05
Freshwater ecotoxicity	1,19E-04	1,40E-04	3,79E-04	2,33E-04	1,24E-04	2,87E-04	1,47E-04	7,05E-04	3,94E-04
Freshwater eutrophication	8,83E-06	9,03E-06	2,51E-05	1,66E-05	1,35E-05	1,89E-05	1,51E-05	4,72E-05	3,85E-05
Marine eutrophication	2,98E-06	8,17E-07	3,02E-06	3,75E-06	3,72E-06	1,80E-06	1,77E-06	5,21E-06	5,13E-06
Terrestrial eutrophication	3,08E-06	7,56E-07	3,20E-06	3,74E-06	3,79E-06	1,61E-06	1,67E-06	5,11E-06	5,23E-06
Carcinogenic effects	1,47E-04	1,30E-04	4,81E-04	1,35E-04	1,43E-04	1,14E-04	1,25E-04	4,46E-04	4,69E-04
Ionizing radiation	3,00E-06	5,39E-07	6,79E-06	4,02E-06	4,00E-06	1,85E-06	1,83E-06	9,70E-06	9,66E-06
Non-carcinogenic effects	3,02E-05	4,34E-05	1,06E-04	5,73E-05	4,20E-05	7,82E-05	5,85E-05	1,84E-04	1,40E-04
Ozone layer depletion	1,02E-06	1,24E-06	5,28E-07	1,08E-06	1,08E-06	1,31E-06	1,31E-06	6,88E-07	6,93E-07
Photochemical ozone creation	7,83E-06	1,42E-06	5,55E-06	8,97E-06	8,98E-06	2,88E-06	2,89E-06	8,81E-06	8,84E-06
Respiratory effects, inorganics	5,98E-06	3,12E-06	1,32E-05	8,74E-06	8,78E-06	6,65E-06	6,71E-06	2,10E-05	2,12E-05
Resources, land use	2,57E-06	1,03E-06	2,71E-06	2,04E-06	2,82E-05	3,59E-07	3,40E-05	1,22E-06	7,62E-05
Resources, mineral, fossils and renewables	3,24E-05	3,20E-05	1,27E-04	7,04E-05	7,93E-05	8,08E-05	9,24E-05	2,35E-04	2,61E-04

Impact category ILCD 1.0.8 2016 midpoint, electric and heat combinations.

Notes: ILCD as implemented in ecoinvent v.3.4.

PV = photovoltaic panels, data in ILCS is split between open ground PV and on-roof PV. Data presented to participants are mean of both.

Gas (heat)—heat production, natural gas, at boiler condensing modulating < 100 kW [Europe without Switzerland]/heat, central or small scale, natural gas.

Normalization according to: Sala S, Benini L, Mancini L, Pant R (2015) Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalization factors. Int J Life Cycle Assess 20: 1568–1585, https://doi.org/10.1007/s11367-015-0958-8

Appendix B: Available choices for discrete choice experiment with respective data

	Employment - installation	Employment - maintenance	Cost per kWh	Security of supply	Effects on human health	Effecs on climate	Land consumption	Resource consumption
A: wind & photovoltaic	54	24	-35	-19	-55	-84	-91	-25
B: wind power & lithium battery	-24	1	20	5	86	-39	-73	128
C: wind & geothermal power	-20	3	-24	16	11	-36	-72	-67
D: photovoltiac & lithium battery	-8	-15	19	-3	92	-21	155	216
E: photovoltaic & geothermal power	-15	-13	-25	5	14	-27	42	-24
F: gas & geothermal power	-79	-27	-21	40	11	274	-62	-81
G: wind & gas power	-47	-16	-24	-30	-58	87	-77	-67
H: wind power & heat-pump	78	42	-12	5	-62	-75	-91	-67
I: wind power & power-to-gas			72	10	33	-67	-75	31
J: photovoltaic & gas power	-36	-27	-26	-25	-55	95	37	-23
K: photovoltaic & heatpump	95	26	-14	-4	-58	-64	56	-11
L: photovoltaic & power-to-gas			70	1	41	-43	250	-11

Note: All numbers represent the deviation from the arithmetic mean of all pairs of the respective variable in percent.

Abbreviations
CA: Conjoint analysis; DCE: Discrete choice experiment; MCDA: Multi-criteria decision analysis.

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RSS: empirical design, data collection and analysis, writing original draft. Wolfgang Hauser: data analysis, writing original draft. OS: empirical design, data collection and analysis, writing original draft, visualization. FM: data collection and analysis, visualization, draft—review and editing. LB, JB, HH, TJ, SS, CS, IT, PU: project members, draft—review and editing. UL, TV, AW: funding acquisition, project members, draft—review and editing. TN: project administration, funding acquisition, project member, draft—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

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Competing interests
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