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MCDA for the sustainability assessment of energy technologies and systems: identifying challenges and opportunities

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Abstract

Background Sustainability assessment comprises many different forms of assessment—from Life Cycle Sustainability Assessment to freely chosen indicator assessments—often yielding contradictory results. Multi-criteria decision-analysis (MCDA) methods have been recognized as a powerful and frequently applied tool to support decision-making in the field of energy. This study analyzes the application of MCDA in the sustainability assessment of energy technologies and systems within the Helmholtz Association, a network of German research centers addressing important topics ranging from cancer research to polar science. Energy technologies are a key focus of research within several Helmholtz research centers. Based on 20 case studies performed by Helmholtz researchers, we identify trends, challenges, and opportunities in criteria selection, MCDA method application, and stakeholder engagement.

Results The selection of criteria and indicators often reflects the triple bottom line framework, with a strong emphasis on environmental and economic dimensions, while social criteria receive little attention due to methodological gaps. For indicator aggregation, there were three preferred methods: the Weighted Sum Method (WSM), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for compensatory studies due to its ease of application and simplicity, and the Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) due to its non-compensatory attributes, consistent with the principles of strong sustainability. However, inconsistencies in weight elicitation methods, with frequent misalignment between the chosen methods and underlying MCDA principles, were found in the analyzed studies. The integration of stakeholders remains underutilized, with most studies involving experts but lacking broader societal involvement. Participatory techniques such as workshops and surveys are mainly applied for criteria weighting, but their implementation across all MCDA stages remains limited. Analysis of group decision-making approaches indicates a predominance of input-level aggregation, with few studies exploring comparative or output-level techniques.

Conclusions This paper highlights the need for methodological advancements in social sustainability assessments and more robust stakeholder engagement strategies. In addition, further education on MCDA methods is needed to bridge the knowledge gaps of practitioners. By comparing Helmholtz MCDA practices with best practices from other research, this work aims to strengthen the sustainability assessment of energy technologies and systems.

Keywords Sustainability assessment, Multi-criteria decision analysis, Sustainability criteria, Indicator selection, Stakeholder integration, Energy technologies

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Background

Energy systems worldwide are undergoing a transformative shift as nations strive to meet the growing demand for sustainable and resilient energy technologies. In this context, assessing and selecting appropriate energy technologies presents a critical challenge, given the myriad factors and criteria that can influence decisions in this complex domain. Addressing this challenge requires a systematic and comprehensive approach that can capture the diverse and often conflicting objectives associated with energy technology assessment.

In addressing this globally challenging topic, the Helmholtz Association's Research Field Energy aims to "lead the way and make a significant contribution to the transition to a sustainable global energy system" [1]. To achieve this goal, several Helmholtz research centers are involved in investigating the ethical, social, political, economic, technological, and environmental aspects of this transition at the level of energy technologies and systems. A working group consisting of representatives from these research centers has been established to work on the application of Multi-Criteria Decision Analysis (MCDA) for the sustainability assessment of energy technologies and systems [2]. The integration of MCDA with sustainability assessments in the Helmholtz Association's research activities demonstrates a strategic commitment to developing a comprehensive understanding of the multifaceted factors that influence the deployment of energy technologies.

MCDA is a sub-discipline of operations research that encompasses a range of theories, methodologies, and techniques for addressing decision-making problems with a discrete set of alternatives [3, 4]. In the context of energy systems and technologies, the integration of MCDA provides decision-makers with a systematic and transparent methodology to navigate the intricate web of technical, economic, environmental, and societal considerations [5]. MCDA enables decision-makers to make informed choices that balance trade-offs, align with overarching sustainability goals, and systematically involve other stakeholders. The MCDA process involves several steps that are broadly accepted by the research community. However, practitioners often focus on obtaining results rather than carefully selecting the most appropriate MCDA method for the specific decision problem [89].

The application of MCDA for sustainability assessment has been the subject of investigation for a number of authors [6–8], who elaborate on the set of theories and methodologies from MCDA that are most suitable for sustainability assessments. For instance, Lindfors [8] published a review paper about the use of MCDA in sustainability assessments in general. Due to the broad scope of this paper, he was only able to map the MCDA

methods used for aggregation. The same applies to the criteria selection, where he briefly tackles the different dimensions of sustainability. Although only briefly mentioned, he highlights the importance of stakeholder participation in MCDA for sustainability assessments. Another review published by Wang et al. [9] analyzed the criteria that were used in studies for sustainability assessments of energy supply systems and the different methods available for criteria selection, as well as weighting and aggregation methods. From a current perspective, however, the review criteria are not transparent enough, with limited detail on the search terms and databases they used. In addition, the reviewed criteria are quite specific for energy supply systems and could be more generalized. While the authors provide a good overview of the weighting and aggregation methods available, they do not analyze the context in which these methods are applied. Kurka, Blackwood [10] focused on MCDA method selection in the context of bioenergy systems, which consists of both general and case-specific aspects. The developed framework guides the user in selecting an appropriate MCDA method. The importance of MCDA method selection has also been emphasized by other authors in different reviews [11, 12].

However, a systematic analysis to identify the extent to which the Helmholtz Association's research activities are aligned with the theories of MCDA for sustainability assessment, and their impact on the goals of the Helmholtz Association Research Field Energy, is still lacking.

This paper presents an in-depth examination of the MCDA activities conducted by members of the Helmholtz Association in the context of sustainability assessments for energy technologies and systems. Through a comprehensive analysis of recent review papers in the field of sustainability assessment using MCDA, supported by specific studies and guidelines, this paper aims to compare Helmholtz MCDA studies with the literature to illustrate related challenges and opportunities. By focusing on a small set of example studies for the application of MCDA in the context of sustainability assessment, drawn from the research groups of the authors, an in-depth and intensive discussion of the chosen approaches is possible.

Sustainability concepts

The latest and most relevant political framework for sustainable development are the 17 Sustainable Development Goals (SDGs) with corresponding targets and 230 sustainability indicators defined by the United Nations [13]. They are aimed at a wide range of issues, such as reducing poverty, hunger, diseases, and gender inequality as well as improving access to fresh water and sanitation in specific regions and countries. Each SDG has specific

targets to be achieved by 2030 and corresponding indicators to measure their achievement. In the context of technology assessment, the SDGs are used as guiding principles. Several articles discuss the possibility of linking the SDGs with Life Cycle Sustainability Assessment (LCSA) [14–16].

The triple bottom line (TBL) approach is a framework that is often used for advancing sustainability in various sectors as well as for technology assessment. Originating in the business domain, the TBL extends beyond traditional profit-centered models to encompass three interconnected dimensions: social, environmental, and economic. By integrating people, planet, and profit (PPP) considerations, the TBL offers a comprehensive perspective that goes beyond a singular focus on financial outcomes [17].

In contrast to understanding sustainability as three pillars with an overarching roof or three overlapping circles, a nested approach has been discussed over the last few decades [18]. In this approach, the environment forms the outer circle, with society and the economy nested within it. This concept aligns with the idea of planetary boundaries, which all human activities must remain

within to avoid disastrous consequences for humanity [19].

General MCDA framework

Decisions made with the help of MCDA are more transparent and justifiable, as they need to be documented and traceable. These advantages have made MCDA methods one of the predominant techniques supporting sustainability assessments in the context of energy systems and technologies. In their review, Turkson et al. [20] found that MCDA approaches are widely used for sustainability assessments of energy systems or technologies as well as the integrated consideration of different objectives or indicators. MCDA methods can be used as an additional tool within another overarching framework, for example, normalization in Life Cycle Assessment (LCA) [21], or act as the framework itself [22].

In this paper, we understand MCDA as a general framework that can be used for sustainability assessments of energy technologies and systems. Figure 1 depicts the MCDA framework starting with the structuring of the problem. This part involves defining the goal and problem of the study, identifying the relevant stakeholders,

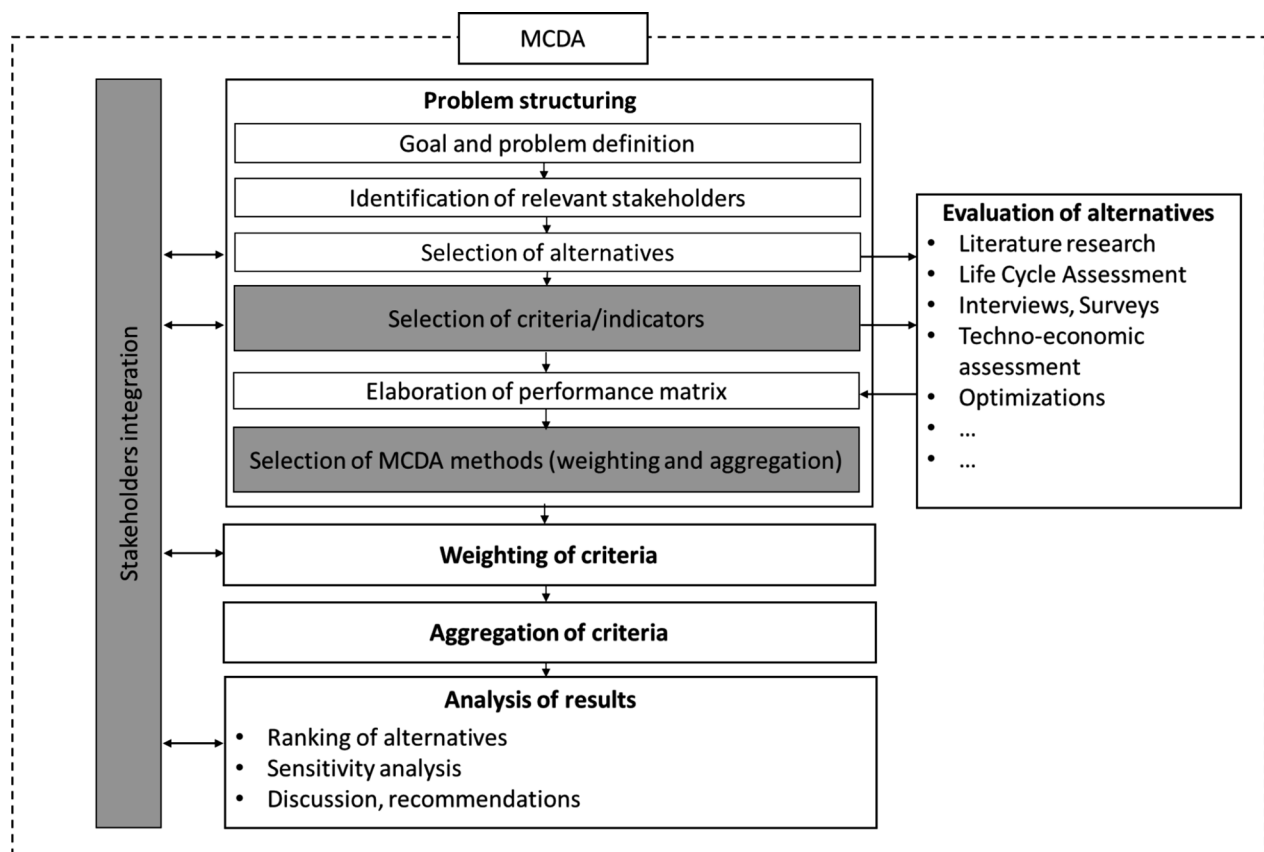


Fig. 1 General MCDA framework based on [23]; the focus of research in this article (gray)

selecting the alternatives to be assessed, identifying criteria and indicators, evaluating the performances of alternatives for the chosen criteria (elaboration of evaluation matrix), and selecting the MCDA methods. In addition to its various mathematical methods, MCDA for sustainability assessment should have a strong focus on the integration of stakeholders. These stakeholders might be decision-makers in industry, politicians, citizens, NGOs, etc. Stakeholders can participate in the decision-analysis process at various stages, for example, by selecting alternatives for the assessment, identifying criteria/indicators, and determining weights for sustainability criteria. In a comprehensive MCDA process, stakeholders should also be involved in analyzing and interpreting the results (see Fig. 1). For sustainability assessments, various types of analyses can be employed to evaluate the performances of alternatives for selected criteria. These might include data from literature research, results from LCAs, techno-economic assessments, optimization models, or other methods. These performance assessments, combined with the criteria weights, form the basis for criteria aggregation. Suitable MCDA methods must be chosen for the weighting and aggregation of criteria, depending on the respective use case and the underlying values. In this article, the focus is on the selection of criteria/indicators, the selection of MCDA methods, and the integration of suitable stakeholders.

Selection of sustainability criteria and indicators

The selection of criteria and indicators operationalizes the previously defined goal and problem of the MCDA study in relation to the alternatives under consideration. The following subsections describe the applied understanding of criteria and indicators, along with their potential applications and limitations.

Definition and purpose of criteria and indicators

In the context of MCDA studies, the terms “criteria” and “indicators” are often used interchangeably, and no clear differentiation could be obtained from the literature. From the authors’ perspective, criteria generally describe the aspects of the research object being analyzed, whereas indicators are means of measuring these criteria either in qualitative, semi-quantitative, or quantitative ways. Criteria and indicators are related to the specific goal and problem of the MCDA study and must be defined. Several indicators can contribute to one criterion. For instance, when analyzing the technical performance of batteries, response time (in ms) and energy density (in Wh/kg) are two potential indicators for quantifying this criterion. However, a single indicator might also be sufficient if the study leader and stakeholders have agreed to it, or if it adequately captures the essence of

this criterion. In such cases, the single indicator directly corresponds to the criterion. Moreover, indicators can also aggregate and weight previously obtained data from either experiments or simulation models, which are termed composite indicators or indices. Criteria and indicators enable the communication of complex matters to non-experts and decision-makers [24, 25]. However, the interpretation of quantitative indicators can suggest a misleading sense of (mathematical) precision due to their numerical representation [26]. Consequently, the transparency of the limits and goal/purpose should be mandatory for any study when defining, selecting, and interpreting indicators. However, due to inconsistent usage throughout the literature and studies, this paper was not always able to appropriately differentiate these terms in the publications, despite it potentially being relevant for distinguishing the different weights of criteria and indicators in later MCDA stages.

Approaches for the selection of criteria and indicators

In the course of this research, various approaches were identified for selecting and deriving criteria and indicators for sustainability assessments. These can be divided into three categories: (1) official principles/regulations/reports, (2) comparable research studies, and (3) opinions of stakeholders. In this context, they are also referred to as top-down approaches (1 and 2) and bottom-up approaches (3), which are described in the following paragraphs.

1. Official principles/regulations/reports: (Inter)nationally recognized and established approaches or regulations can serve as a helpful basis for deriving criteria and indicators, for example, concepts for sustainable development (see “Sustainability concepts” section). Depending on the object of investigation, national sector-specific principles may also be suitable for deriving criteria and indicators, for example, the objectives formulated in the German Energy Industry Act for a cost-effective, secure, and environmentally compatible energy supply in line with the energy policy target triangle [27].
2. Comparable research studies: Existing assessment studies with the same or similar objects of investigation can provide valuable information on the possible impacts of technologies or products and the relevant criteria and indicators. For example, before a new MCDA study is conducted, a literature review on the same topic can identify criteria and indicators that are already classified by a larger research community.
3. Opinions of stakeholders: Finally, stakeholders can be involved in the process of defining criteria and indicators in a bottom-up manner. The respective expe-

periences of the stakeholders (real-life knowledge) can often be used to better assess the potential impact of technologies (see “Stakeholder integration” section).

MCDA methods

The selection of appropriate MCDA methods for the aggregation and weighting of criteria is a crucial element of the problem-structuring phase.

Aggregation

Various techniques can be used to aggregate results, which essentially comprise compensating and outranking methods. One well-known compensating technique is the weighted sum method (WSM), also referred to as simple additive weighting [28]. With this approach, one criterion or indicator with a bad performance can be directly offset by a criterion/indicator with a good performance, for example, greenhouse gas (GHG) emissions versus costs. While easy to use, this method does not account for more complex decision-making contexts. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [29] is a more intricate MCDA approach that considers the compensation of impacts while also smoothing out some of the drawbacks of the WSM. Prior to using any of these aggregation methods, normalization is necessary. In addition, many compensating techniques require trade-off weights to ensure that they are applied correctly.

If compensation between different impact categories and sustainability dimensions is not permitted by the practitioner, outranking methods are recommended. The two most prominent methods are the Preference Ranking Organization METHod for Enrichment Evaluation (PRO-METHEE) [30] and Elimination Et Choix Traduisant la REalité (ELECTRE) [31]. These methods require more effort, such as defining thresholds for each criterion. While the results may be less transparent, they are also more robust and have already been further discussed by the practitioner and stakeholders while defining thresholds. These methods do not require normalization and are especially suitable for sustainability assessments, as they (1) allow for null/partial compensation of criteria, i.e., bad performance in one criterion cannot be compensated by good performance in another, (2) allow for the consideration of qualitative and quantitative data, and (3) consider weights as importance coefficients and not as trade-offs.

Weighting of indicators and criteria

Two types of weighting factors exist: (i) trade-off weights and (ii) importance coefficients. Trade-off

weights describe the relative importance of two or more criteria, whereas importance coefficients describe the absolute importance of a criterion.

Trade-off weights are case-specific and indicate when two options in a study can be considered of equal preference. As an example, option A with high costs and low GHG emissions can be considered as good as option B with very low costs and high GHG emissions, depending on the trade-off between costs and GHG emissions. For different cases, these trade-offs might vary. For electricity generation, for example, GHG emissions are much more important than costs in achieving climate neutrality. For electricity storage, however, with low overall GHG emissions, costs might become more important. These value-based trade-off weights are necessary for most compensating aggregation methods such as WSM.

Importance coefficients, in contrast, are absolute and non-case-specific. In LCA, for example, the Joint Research Center (JRC) of the European Commission—based on the judgement of experts—defined weighting factors as importance coefficients that can be applied to any LCA study following the environmental footprint method [32].

A simple pairwise comparison of indicator results is one way of defining trade-off weights. Each pair of results is set against each other to assess which is more relevant in the context of the defined problem.

Various methods can be utilized to identify important coefficients as well as trade-off weights with and without the integration of stakeholders.

A very popular and straightforward weighting approach for an initial estimation is to employ equal weights, if necessary in a hierarchical structure, for example, when following the TBL approach [33]. This can ensure results that are reliable and robust when coupled with a sensitivity analysis [34, 35]. The impact of the hierarchical structure of the study on the overall outcome of the MCDA has to be taken into account. Various studies have investigated alternative hierarchical structures, such as those aligned with the SDGs, and their effect on the results of the MCDA [36, 37].

In certain decision-making contexts, it is important to involve representative stakeholders to promote a participatory and collaborative decision-making process (see “Stakeholder integration” section). Various MCDA methods are available for assigning weights, including those based on trade-offs, such as the Simple Multi-Attribute Rating Technique (SMART) or the swing weighting technique [38]. For importance coefficients, the Deck-of-Cards Method (DCM) [39] provides a way of integrating stakeholders into the weighting process.

Stakeholder integration

Sustainability is a multidimensional concept that encompasses socio-economic, environmental, technical, and ethical perspectives [40]. Accordingly, societal stakeholders and their values and interests should be considered in decision-making analysis processes related to sustainability assessment [41]. MCDA has been recognized as a powerful approach for integrating these different perspectives into sustainability assessments [20].

This section aims to provide a basis for categorizing types of stakeholders, approaches for the integration of stakeholders, participatory techniques, and the level of participation in MCDA processes.

Types of stakeholders

Stakeholders can be defined as “people with an interest, financial or otherwise, in the consequences of any decision taken” [42]. Stakeholders involved in group decision-making processes or participatory MCDA can be categorized into the following groups: experts/academia, industry, government, and civil society. Experts can be referred to as people with a high level of knowledge and expertise on one or multiple topics [43]. In MCDA-assisted sustainability assessments, the joint participation of experts and/or academics with other types of stakeholders is desirable. Here, MCDA should provide a platform for the combination of different types of knowledge—both scientific and social—to support critical analysis by decision-makers [44]. As Munda [45] states, when dealing with topics which concern society, public participation is a necessary condition for understanding the problem, but not sufficient to make a decision. In general contexts, when only experts and/or academics are involved in an MCDA process, this is not considered a decision-making process, since it is based on knowledge aggregation and not on preferences [46].

Approaches for stakeholder integration

MCDA methods, as presented in the “Aggregation” section, are primarily designed for supporting individual decision-makers. When the decision-analysis process requires the incorporation of different actors or stakeholders, dealing with social interaction processes becomes part of the challenge [47]. Several approaches have been proposed to categorize different procedures for dealing with individual inputs in group MCDA. According to Belton, Pictet [47], common alternatives, a common aggregation method, and common criteria are needed for group MCDA. Within this framework, three main strategies were proposed for dealing with weights from different stakeholders: sharing, aggregating, and comparing. Sharing reduces differences through discussion. Aggregating reduces differences using a common

value (e.g., averages) that integrates the individual inputs without the need for discussion. Comparing does not aim to reduce conflict and instead allows each participant or stakeholder group to maintain their own individual results. Group decision and negotiation (GDN) considers two types of methods for preference aggregation [46]: (1) input-level aggregation—the aggregation of participants’ initial preferences (weights), which requires the same MCDA method and criteria set for each participant, and (2) output level aggregation—the aggregation of participants’ individual choices (rankings), which is possible with different MCDA methods and criteria sets for each participant, and even different levels of power per participant. Dean [48] developed a framework for categorizing strategies in participatory MCDA based on how individual preferences are treated and included at each stage of the MCDA process: exclusion, filtration, sharing, aggregation, and disaggregation by comparing. The first four strategies aim to generate a common value and are analyzed not only for weights—as was proposed by Belton, Pictet [47]—but also for criteria selection, alternative selection, and/or performance evaluation.

Participatory techniques

The combination of MCDA methods with participatory techniques has several advantages for both analysts and stakeholders alike. From the perspective of analysts, the context in which a decision process takes place can be understood and ultimately reflected in the selection of alternatives and criteria [48]. Stakeholders, meanwhile, develop learning processes and ownership of the decision at hand [49]. Some techniques include interviews, surveys/questionnaires, workshops, and focus groups. Different techniques can be selected within a participatory MCDA process to elicit different types of information. Their selection depends on the resources available (time, money, personnel) and the approach for eliciting stakeholder input [48]. Each technique has different goals and its application could lead to advantages and/or limitations, as shown by Marttunen et al. [50]. For example, large groups in workshops or focus groups could result in powerful stakeholders dominating the discussion, suppressing the opinions of others [45]. It might also be the case that some relevant stakeholders lack the resources (time, money) to participate in workshop formats, meaning that their input may not be reflected in the final results. Online surveys/questionnaires may prove an effective solution to the accessibility issue, although it could require a high degree of effort from the analyst to explain the content to each stakeholder. The creation of a booklet could be an option, but there would be still uncertainty as to whether the stakeholder understood and followed the instructions correctly [50]. Other

possibilities include the use of specialized software for supporting intensive group collaboration, such as in decision conferencing [51].

Level of participation

The level of participation refers to the extent to which stakeholders integrate their values into the MCDA process. Marttunen et al. [50] define the level of participation based on the stages of the MCDA process in which stakeholder input is considered and the interactivity of the preference elicitation process. The four-level scale ranges from low interactivity, when the MCDA is conducted by experts only, to very high interactivity, when different stakeholders are actively involved in different phases of the MCDA. McGookin et al. [52] assess the level of participation in MCDA in relation to the type of communication and its influence on energy system modeling and planning. Their three levels are: informing, consulting, and collaborating. Dean [48] defines a scale to evaluate the level of involvement, which is dependent on the stage of MCDA at which participant input is considered. It consists of 16 types of participatory MCDAs, ranked from limited participatory techniques (lowest level) to fully participatory exercises (highest level). In

sustainability assessment, a high level of participation is desirable, as this can potentially lead to more democratic and transparent decisions—if carried out properly [48].

Materials and methods

The analyses in this article include studies on MCDA-assisted sustainability assessments of energy systems and technologies from (i) a general literature review performed with a focus on criteria and indicator selection, MCDA methods, and stakeholder integration (see Table 1), and (ii) an analysis of Helmholtz studies on MCDA sustainability assessments in this field (see Table 2). Figure 2 depicts the workflows related to the selection of studies and the analysis schemes used in the results sections on criteria and indicator selection, MCDA methods, and stakeholder integration. The following two subsections describe the systematic literature review and the criteria of eligibility for Helmholtz studies to be analyzed in detail.

Literature review

Three specific literature reviews—on criteria and indicator selection, MCDA methods, and stakeholder involvement for MCDA sustainability assessments—were

Table 1 Results of the systematic literature review and search strings applied

Topic	Search string	# initial results	Excluded (reasons)	# from authors' repository	# Final
Criteria and indicators	(ALL = (indicator selection) AND ALL = (energy))	7	Indicator selection is not described Not related to energy research Not a review	1	9
	(ALL = (criteria selection) AND ALL = (energy));	8			
	(ALL = (criteria selection) AND ALL = (MCDA))	5			
	(ALL = (criteria selection) AND ALL = (MCDM))	4			
	(ALL = (selection) AND ALL = (impact categories) AND ALL = (sustain*))	32			
MCDA methods	(ALL = (indicator) AND ALL = (selection) AND ALL = (criteria) AND ALL = (energy))#	28	Duplicates Not a review 'multi' not referring to MCDA	4	15
	(TI = (sustainab*) AND TI = (MCDA OR multi* OR MCDM)) AND TI = (energy) AND TS = method*	14			
	(((((TS = (select*)) AND TI = (MCD*)) AND TS = (method)) AND TS = (sustainab*)) AND TS = (energy))	14			
	(((((TS = (select*)) AND TS = (MCDA)) AND TS = (method)) AND TS = (sustainab*)) AND TS = (energy))	12			
	((TI = (MCDA*) OR TI = (Multi* Criteria) OR TI = (Multicriteria*) OR TI = (MCA) OR TI = (multi-criteria*) OR TI = (MADM))) AND ((TI = (Particip*) OR TI = (stakeholder*) OR TI = (prefer*) OR TI = (group decision*) OR TI = (*actor))) AND (TS = (sustainab*) AND TS = (energy*))	43			
Stakeholder involvement			Review (1) Helmholtz works (1) Focus not on energy (10) No stakeholders involved (6) No MADIM (3)	3	25

Adjusted time span: 2016-10/2023

Table 2 Overview of Helmholtz MCDA studies analyzed

Source	Years	Objective and context	Alternatives	Sustainability issue
McKenna et al. [56]	2018	Develop energy concepts in small rural communities including stakeholder perspectives	Combinations of energy technologies	Economic sustainability, environmental sustainability, and local energy autonomy
Peters et al. [57]	2018	Importance of various aspects for a circular battery economy	N/a	Consideration of several criteria for battery recycling
Baumann et al. [58]	2020	To give an overview of the role of different sustainability-oriented indicators for the selection of a suitable battery energy storage system (BESS) depending on the application field	Different battery types in different applications	Comprehensive assessment including economic, environmental, social, and technology performance
Haase et al. [29]	2020	Comparative sustainability assessment of synthetic biofuel production from straw and wood and conventional gasoline production	Promising biomass-based technologies under development within the Helmholtz Association	Comprehensive assessment including economic, environmental, and social aspects
Wilken et al. [59]	2020	Development of an indicator system for the sustainability assessment exemplified by the case study on passenger cars	Different drivetrains for passenger cars	Comprehensive assessment including economic, environmental, and social aspects
Naegler et al. [60]	2021	Sustainability assessment of different national energy system transformation pathways including a discrete choice experiment	Ten different German energy system transformation pathways	Environmental, economic, social, and system-related/socio-technical aspects at system level
Wulf et al. [61]	2021	Introducing LCSA-specific thresholds for the application of PROMETHEE	Three different European countries with natural resources for hydrogen production	Comprehensive assessment including economic, environmental, and social aspects
Baumann et al. [62]	2022	Early stage cathode material screening for sodium-ion batteries	Cathode materials for sodium-ion batteries	Competitiveness, resource management, global warming
Gomez Trillos and Draheim [63]	2022	Determining the sustainability performance of a novel ship propulsion concept	Hydrogen FC battery, diesel–electric, diesel–battery–electric, and battery–electric alternatives	Environmental, economic, socio-economic, and technical aspects
Haase et al. [64]	2022	Application of a concise sustainability assessment framework	Promising technologies for future passenger mobility (BEV, FCEV, and ICEV) including the production and use of vehicles and fuels	Comprehensive assessment including economic, environmental, and social aspects
Ottenburger et al. [65]	2022	Incorporating citizen acceptance into regional energy system planning	Installation of wind power and solar plants in Karlsruhe	Social acceptance in sustainable energy planning
Röben et al. [66]	2022	To determine the sustainability performance of a novel hybrid BESS compared to other frequency containment reserve (FCR) technologies	Technologies for the FCR provision in Germany: pumped hydro power, hybrid BESS with PTH (reference with an electrode boiler), hybrid BESS with PTH using second-life battery cells, hybrid BESS with PTH ₂ (electrolyzer)	Holistic approach considering ecological, economic, social, and technology-related aspects
Wulf et al. [37]	2022	To understand the influence of the underlying sustainability concept, i.e., SDGs vs. triple bottom line, on hierarchical MCDA	Three different European countries with natural resources for hydrogen production	Comprehensive assessment including economic, environmental, and social aspects
Schwager et al. [67]	2023	Development and assessment of sustainable low-energy cruise ship cabins	Possible configurations of different technologies to be implemented	Environmental, economic, and social sustainability; implementation of C2C principles for the material selection
Rhoden et al. [68]	2023	Disclosing the hidden preferences of consumers when buying a passenger car	German passenger vehicles	Sustainability from a consumer perspective, including economic and environmental aspects
Vögele et al. [69]	2023	Identification of stakeholder preferences to support or oppose an energy transition pathway	Energy system transformation pathways to achieve Germany's net zero emissions target	Comprehensive assessment including economic, environmental, and social aspects (as well as risks and other indicators)

Table 2 (continued)

Source	Years	Objective and context	Alternatives	Sustainability issue
Wulf et al. [70]	2023	Weighting factor elicitation for sustainability assessments of emerging technologies	Hydrogen mobility with different supply chains compared to gasoline mobility	Comprehensive assessment including economic, environmental, and social aspects
Mesa Estrada et al. [71]	2024	To elaborate on the challenges of using MCDA for sustainability assessments of emerging technologies, focusing on MCDA methods and available software	Cathode active materials for sodium-ion batteries and lithium-ion batteries	Costs, material criticality, carbon footprint
Brand-Daniels et al. [72]	2025	Development and testing of macro- and socio-economic indicators for technology assessments	Technology options for electricity generation as well as the provision of heat and mobility	Socio- and macroeconomic aspects; ecological and micro-economic aspects
Mesa Estrada et al. [73]	2025	Gather stakeholder opinions on indicator selection and weighting	Short- and long-term energy storage technologies	Carbon neutrality, good health and well-being, environmental friendliness, affordability, positive public perception, reliable and stable supply chain, technical performance, and durability

BESS: battery energy storage system, BEV: battery-electric vehicle, C2C: cradle-to-cradle, FCEV: fuel cell Electric vehicle, FCR: frequency containment reserve, PROMETHEE: Preference Ranking Organization METHOD for Enrichment Evaluation, Pth: power-to-heat, Pth₂: power-to-hydrogen

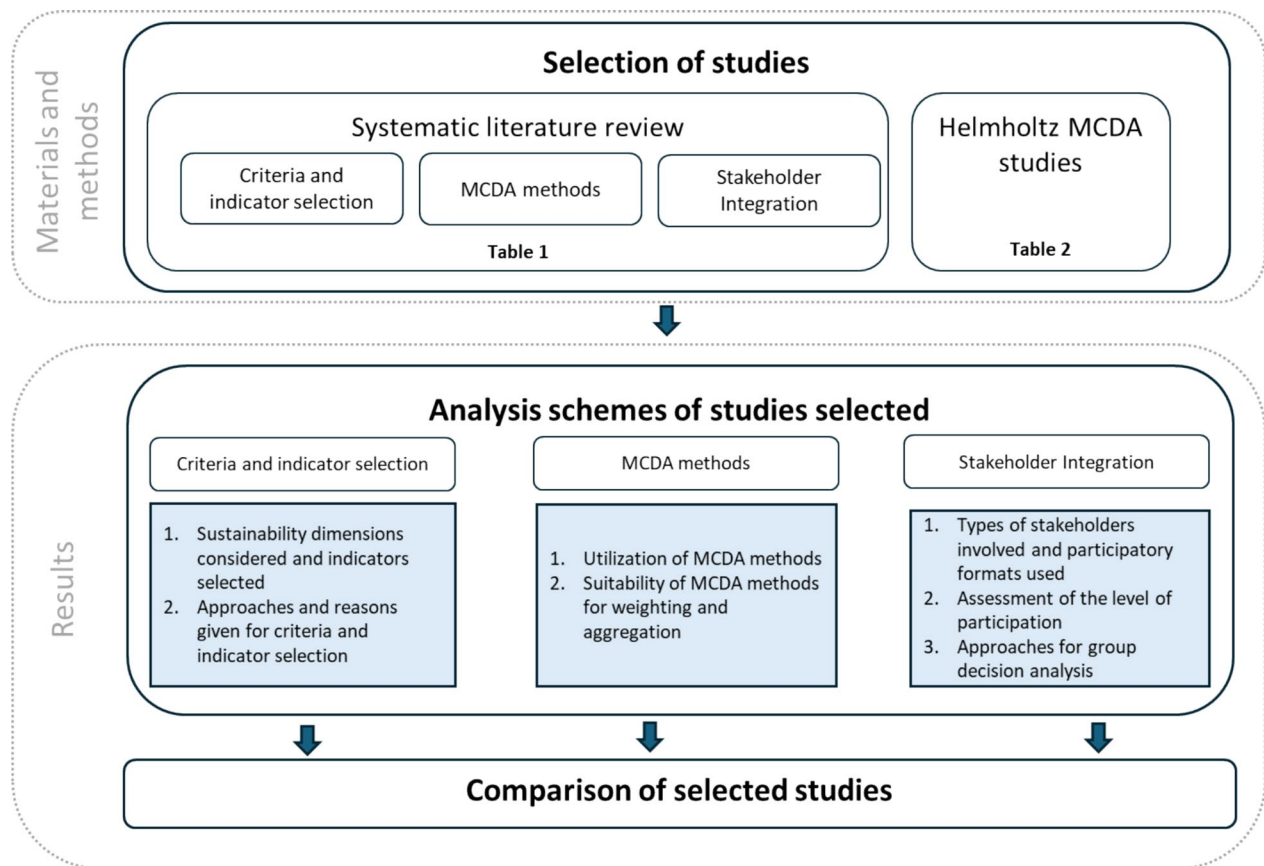


Fig. 2 Selection of studies and analysis schemes for criteria and indicator selection, MCDA methods, and stakeholder integration

conducted using the Web of Science database for the three topics addressed in this article. Unless stated otherwise, all three searches applied the following parameters:

- Scientific journal publications
- Start year of the search: 2009
- Search strings comprising two components: (1) key words for each focus area (criteria and indicator selection, stakeholder integration, and MCDA, and (2) the application field in sustainability and energy research
- Review publications

In addition to the articles found through these searches, other relevant papers from authors' repositories were included in the review.

The search strings for three areas—criteria and indicator selection, MCDA methods, and stakeholder integration—included several terms that were combined with the Boolean operators “AND” and “OR”. The terms “sustainability” and “energy” produced too high a number of hits due to their versatile use in literature. To reduce the potential number of hits to a reasonable amount, the two

terms were linked with an “AND” operator to each focus area. As the term “sustainability” is often used in different word forms (e.g., nouns and adjectives), the asterisk (*) wildcard operator was used to include the word stem and any variation after the asterisk operator (see Table 1). Similarly, the second component of the search string addressed the focus area of MCDA methods, stakeholder integration, and indicator selection with corresponding terms that are often used in the MCDA community.

Criteria and indicator selection

For the focus area of criteria and indicator selection, different search strings were used (Table 1). To limit the number of hits and to use the most up-to-date literature sources, a narrower time span—from 2016 to October 2023—was considered in certain cases. In total, 80 articles were identified as potentially relevant literature (partly redundant hits). The next step was to pre-screen and sort the articles according to their relevance to the systematic analysis. In general, the identified articles needed to address both the indicator selection and energy-related aspects. This reduced the overall number of articles from 80 to 9, as only these articles explicitly

mentioned the process of indicator selection. This included one article from the authors' repository.

MCDA methods

For the topic of MCDA methods, the aforementioned parameters were incorporated into search strings applied to either the title or to the combination of title, abstract, and keywords. After removing duplicates, 18 papers remained. However, not all papers were reviews, as some articles from the journal *Renewable and Sustainable Energy Reviews* were falsely classified as reviews from the database. Furthermore, the search string including "multi*" also returned results that were unrelated to multi-criteria. Such results were removed manually. Ultimately, eleven review papers were identified. In addition, four papers from the authors' repository were selected, as they tackle important issues for method selection but did not mention energy in the title or abstract explicitly due to their broader scope (Table 1).

Stakeholder involvement

The search string for the literature search on stakeholder involvement in MCDA sustainability assessment is given in Table 1. It is aimed at identifying titles of articles containing a term referring to MCDA together with a term referring to stakeholder integration. In addition, we searched for the terms "energy" and "sustainability" in the title, abstract, or keywords to narrow down the search results to the desired thematic focus. As this search string resulted in 43 results, including only one review paper [53], we decided to analyze original articles for the stakeholder involvement part and to use the results of the respective review paper for comparison. After screening all 43 articles, we excluded papers which did not focus on energy, did not actively involve stakeholders, or did not apply any multi-attribute decision-making (MADM) method. This process resulted in 22 original articles. In addition, three articles were included from the authors' repository, which were considered relevant for further analysis (see Table 1).

Selected Helmholtz studies on MCDA-assisted sustainability assessment

As evidenced by the literature review, the use of MCDA for sustainability assessment is not a new topic. Moreover, Helmholtz researchers used MCDA methods to enhance their understanding of sustainability in the energy field [54]. However, since late 2015, the Helmholtz Association has been strengthening the networking of researchers in the sustainability assessment of energy systems and technologies [55]. A report on MCDA activities for sustainability assessment, published by the Helmholtz Working Group on MCDA for Sustainability Assessment

in 2022, served as a stepping stone for the selection of Helmholtz studies [2]. Studies were excluded if no published, or soon-to-be published, article or report was available (e.g., only presentations). Studies could either be written in English or German.

Applying all these criteria, 20 studies (Table 2) were identified and will be analyzed in detail in the subsequent chapter.

Results

The analysis of Helmholtz studies identified in the "Selected Helmholtz studies on MCDA-assisted sustainability assessment" section is presented in this chapter with regard to criteria and indicator selection, choice of MCDA methods, and stakeholder integration. The three topics are discussed in relation to the current literature, as defined in the "Literature review" section. However, further analyses are performed individually for each topic.

Criteria and indicator selection

The identified review articles and Helmholtz studies were systematically analyzed according to the scheme described in the following subsection. Since the terms "criteria" and "indicators" are used synonymously in both the review articles and the Helmholtz studies, the results cannot distinguish between the two. Accordingly, both criteria and indicators are used interchangeably in the results and discussion section.

Analysis scheme for criteria and indicator selection

The selection of indicators should be based on criteria agreed on by the experts and stakeholders of each respective use case. The involvement of experts and stakeholders/decision-makers helps to build trust and acceptance [74, 75], making the indicator selection a crucial step for the success of any MCDA [23]. As no commonly agreed list of selection criteria for indicators was available, the criteria list of Hirschberg et al. [76] was used as an analysis scheme to evaluate the identified review articles and Helmholtz studies with respect to the underlying reasons for selecting criteria and indicators. The selection of MCDA criteria and indicators should be based on "selection criteria" agreed on by the experts and stakeholders of each respective use case. According to Hirschberg et al. [76], criteria and indicators must meet scientific (e.g., measurable, clear in value, unambiguous in content etc.), functional (relevant, leading, comparable, etc.), and pragmatic (e.g., manageable, understandable, etc.) requirements (see Supplementary Table A2). In total, 24 reasons were considered for the criteria and indicator selection.

The literature and Helmholtz studies were analyzed by counting the occurrences of each reason, where available.

MAXQDA 2020 [77] and Excel were used for the analyses, roughly adopting the qualitative content analysis methodology proposed by Kuckartz [78]. Qualitative content analysis is a methodological approach used to identify, categorize, structure, and analyze the content of different text formats (ibid.). It was chosen here to provide a comprehensive yet aggregated overview of the selected indicators. The three sustainability dimensions from the TBL approach were used as main categories, subsuming the indicators. As an indicator used to measure the same phenomenon can have more than one name—and in some cases might be assigned to a different sustainability dimension—both designation and naming were harmonized in accordance with the predominantly used assignment.

Sustainability dimensions considered and indicators selected in Helmholtz studies

In this section, results are presented for the Helmholtz studies, while results for the review articles are given in Supplementary Table A3. The analysis indicates that most of the Helmholtz studies used criteria and

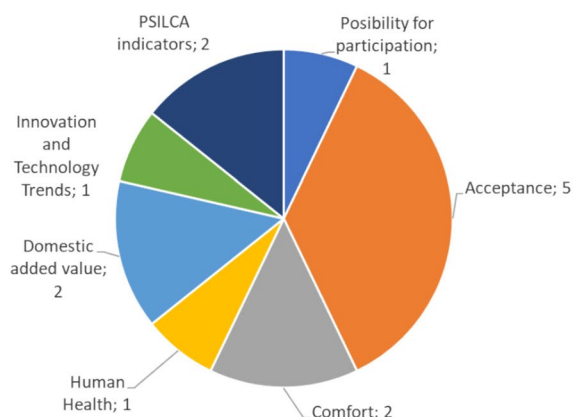
indicators from all three TBL sustainability dimensions—economy, environment, and society—as well as system- or technology-specific criteria and indicators. Table 3 depicts the total number of Helmholtz studies ($N = 20$) and the proportion of studies that considered different (sustainability) dimensions. While all studies considered environmental and economic indicators, social indicators were only considered in 70% of the studies. System- or technology-specific criteria and indicators (e.g., technology readiness level or performance indicators) were used in 55% of the studies, while other types such as dependencies or risks appeared in 20%. Since some criteria and indicators are not always unambiguously assignable to only one (sustainability) dimension (e.g., *human health* might be assigned to either an environmental or social dimension), attempts were made to follow the interpretations and classifications of the study authors. As described in the “Literature review” section, a coding system was established using the TBL sustainability dimensions as main categories (cf. Kuckartz 2014). The results of the analysis are shown in Table 3.

In the Helmholtz studies analyzed, the criteria and indicators were most often selected in the context of the triple bottom line (TBL) approach. However, since the TBL approach was not followed in five of the analyzed studies, the criteria and indicators used in these cases were only assigned to one of the dimensions. Subsequently, the criteria and indicators used in the Helmholtz studies were analyzed in more detail for each dimension. The results for the social and economic dimension are shown in Fig. 2a, b, while the results for the environmental dimension are shown in Fig. 3. In Fig. 2a, the social criteria and indicators considered in the Helmholtz studies are presented. These include 34 indicators from the

Table 3 Sustainability dimensions considered in the analyzed Helmholtz studies

Dimension	Number of studies (N = 20)	Total share (%)
Environmental	20	100
Economic	20	100
Social	14	70
System- or technology-specific	11	55
Others	4	20

a) Social dimension



b) Economic dimension

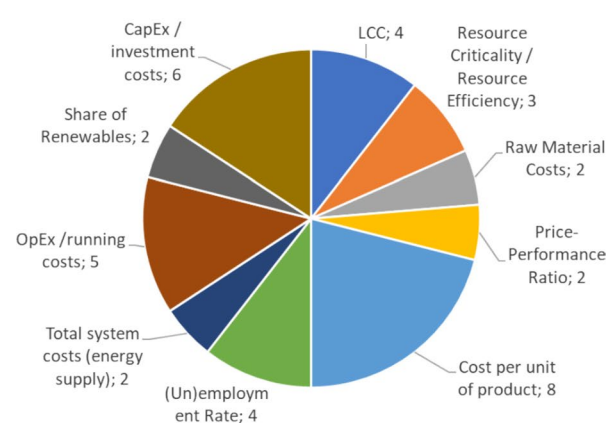


Fig. 3 a Social and b economic criteria and indicators used in the Helmholtz studies

Product Social Impact Life Cycle Assessment (PSILCA) database as well as six additional indicators. The majority of the Helmholtz studies focused on the acceptance of stakeholders ($n=6$) as a social criterion, while innovation and technology trends ($n=3$), comfort ($n=2$), and domestic added value ($n=2$) were less frequently mentioned. The “possibility for participation” indicator was only considered once [69]. A selection of different indicators from the PSILCA database [79] was also used twice [37, 61] (see Supplementary Table A1). For clarity, the 34 indicators are summarized into a single indicator in Fig. 2. The LCA endpoint impact category “human health” [80] was once assigned to the social dimension, although it is often linked to the environmental sustainability dimension.

The number of economic indicators is slightly higher than that of the social dimension (10), but these indicators were used more frequently among the Helmholtz studies (Fig. 2b). Nine out of ten economic indicators can be attributed to the micro-economic perspective, which are further differentiated into energy system- and technology-related studies. The technology-related studies mainly focused on cost per unit of product, which was applied in eight Helmholtz studies and can also be related to the Life Cycling Costing (LCC) perspective. Similarly, four out of twenty studies explicitly focused on life cycle costs, whereas several studies specifically stressed components of LCC: capital expenditure (CapEx, i.e., investment) and operational expenditure (OpEx, i.e., operational costs) in six and five studies, respectively. Furthermore, the material costs and their criticality were analyzed in two and three studies, respectively. At the energy system level, two studies focused on total system costs—which refers to the optimized technology setting of a specific energy scenario [60]. The macroeconomic perspective was considered in four studies focused on the (un)employment rate, which can also be assigned to the social dimension. Moreover, the composite indicator “price-performance ratio” was analyzed in two studies, which shifts the focus from the industrial to the consumer perspective for identifying their behavior. It should be noted that individual indicators combined in composite indicators can also be used separately, namely, price/performance ratio.

Although most of the Helmholtz studies addressed at least two sustainability dimensions at the indicator level, the detailed analyses indicated a strong tendency towards environmental indicators also having the most diverse indicator set compared to the other dimensions. This might be linked to the fact that the well-established Life Cycle Impact Assessment (LCIA) methods were mostly used for the environmental dimension, which includes a collection of various indicators that can be

considered in each assessment. Figure 3 illustrates the diversity of the indicators used for environmental assessments, which mainly focus on impact categories, such as climate change (15 considerations), resource depletion (12 considerations), and human toxicity (10 considerations). Moreover, other indicators that are also associated with conventional LCIA methods cover terrestrial and freshwater acidification, particulate matter formation potential, ozone layer depletion potential, and (eco)toxicity, which were each considered in seven to nine studies. Surprisingly, land use ($n=5$) and water dissipation ($n=2$) were investigated less frequently. These indicators will become increasingly relevant in the future [81, 82]. Only a minority of the studies considered ecosystem quality ($n=2$) and environmental friendliness ($n=3$), which may be related to the specific purpose of the studies. Environmental friendliness was considered in two studies [57, 68] to reflect the general importance of environmental aspects for one or more stakeholder groups in their decision-making process. In the third study [73], the “environmentally friendly technologies” objective is considered by the “ecosystem quality” criterion, which—in this case—consists of the following indicators: marine eutrophication, ozone depletion, terrestrial eutrophication, acidification, freshwater ecotoxicity, and freshwater eutrophication.

Figure 3 shows the total number of studies that considered the indicators in the sustainability assessments conducted. To ensure the chart remains concise, only criteria and indicators that were considered in at least two studies were included. Since some criteria and indicators were categorized differently—for example, due to the application of different LCIA methods within a previously performed LCA—but reflected the same or similar impacts, they were subsumed as follows for the analysis:

- Acidification: terrestrial and freshwater acidification
- Climate change: GHG and CO₂ emissions, global warming potential (GWP)
- Ecotoxicity: freshwater and marine ecotoxicity
- Eutrophication: freshwater, maritime, and terrestrial eutrophication
- Human toxicity: non-carcinogenic effects and carcinogenic effects
- Land use: natural land transformation
- Particulate matter formation: respiratory effects
- Photochemical oxidation: ozone creation potential

It can be concluded that the economic and environmental sustainability dimensions were most frequently included in the Helmholtz studies. This is predominantly down to the better availability of data and the more established methods for quantifying the indicators, for

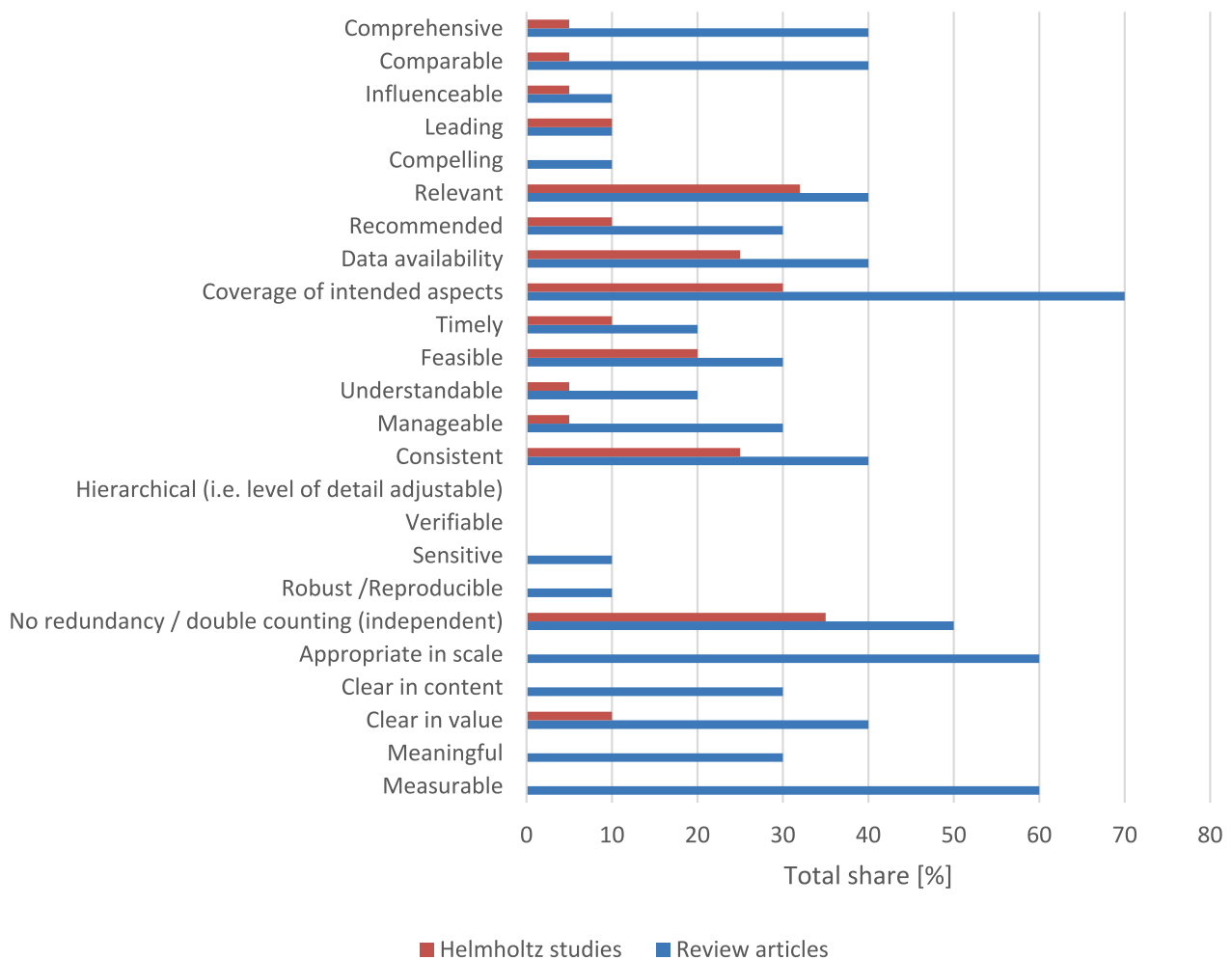


Fig. 4 Share of reasons given for criteria and indicator selection in multi-criteria decision analyses for sustainability assessments in review articles ($n=9$) and Helmholtz studies ($n=20$)

example, LCA. Social aspects were considered in fewer studies overall; the diversity of the criteria and indicators were also found to be more limited than in the other sustainability dimensions.

Reasons given for selecting indicators in the literature and Helmholtz studies

The following results present the reasoning behind the selection of certain criteria and indicators in the Helmholtz studies and are compared with the state-of-the-art review articles. The analysis of review articles revealed that 9 out of 28 studies explicitly mentioned the reasons behind their choice of criteria and indicators for MCDA-assisted sustainability assessments (Fig. 5). Interestingly, the majority of studies did not describe the criteria and indicator selection process itself. In contrast, information about the criteria and indicator selection process were available ($n=20$) for all of the Helmholtz studies.

Figure 4 summarizes the criteria mentioned in the review articles and the Helmholtz studies. Neither the review articles nor the Helmholtz studies considered all 24 reasons proposed by Hirschberg et al. [76] (see Supplementary Tables A2 and A4). Instead, they mostly used a selection of these reasons. The analysis also shows that in the review articles, a higher number of reasons were used compared to the Helmholtz studies. This was despite a lower number of review articles being included in the analysis. The most commonly cited reasons for the review articles were “coverage of intended aspects” (70%) as well as “measurable” and “appropriate in scale” (both 60%). Interestingly, the latter two criteria were not used in any Helmholtz study. Furthermore, the reasons “relevant”, “data availability”, “feasible”, “consistent”, and “no redundancy” were mentioned in 25–50% of the Helmholtz studies and review articles, with the latter generally having higher shares than in the Helmholtz studies.

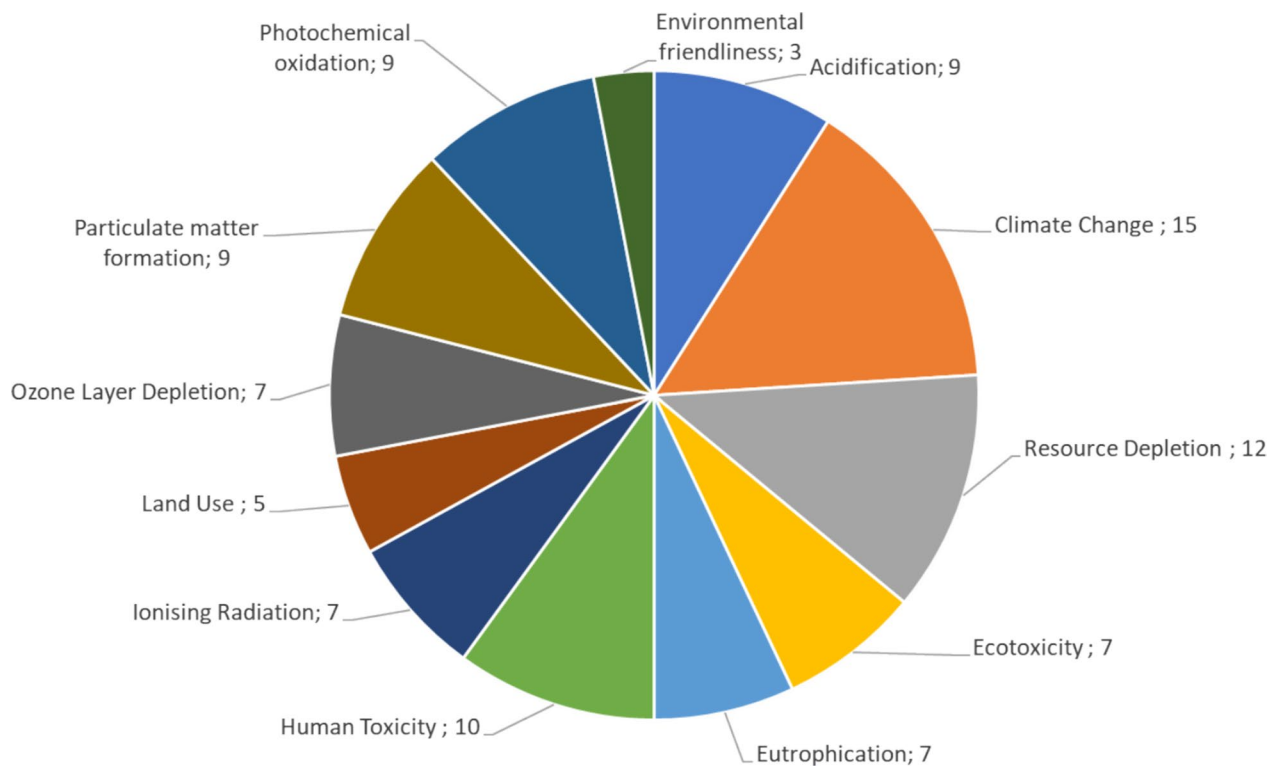


Fig. 5 Environmental criteria and indicators used in the Helmholtz studies (mentioned in at least two different studies)

Other reasons cited in the review articles were “comprehensive”, “comparable”, “recommended”, “timely”, “understandable”, “manageable”, and “clear in value”, with shares ranging from 5 to 40%. The other remaining reasons were only mentioned by the review articles. The “verifiability” and “hierarchical aspects” of indicators were not mentioned in any of the studies.

MCDA methods

The subsequent sections will present the findings of the literature review concerning MCDA methods and will describe the methods used in the identified Helmholtz studies. In the second section, the studies are evaluated in accordance with the literature with respect to the proper utilization of MCDA methods.

Utilization of MCDA methods

The literature review is first discussed in terms of the MCDA aggregation and weighting methods applied, followed by the utilization of methods in the Helmholtz studies.

Literature review

Although all eleven selected review papers (see supplementary Table A5) adopted a similar focus on MCDA

for sustainability assessments in the field of energy, their scope—i.e., the sustainable energy alternatives analyzed—differs significantly. A number of review papers focused on specific technologies, such as wind energy [83] and concentrated solar power [84]. Others had a more extensive scope, addressing sustainable energy in general [9, 85, 86]. The scope of the studies also ranged from technology assessment, as exemplified by Baumann et al. [23], to energy system modeling and energy planning, as illustrated by Cajot et al. [87]. Similarly, the analysis of MCDA methods varied across these articles. Wang et al. [9] explicitly distinguished between methods for criteria selection, weighting methods, methods for defining weights, and MCDA methods (i.e., aggregation methods). In contrast, most of the other studies did not distinguish between the different types of methods. Wang et al. [9] also highlighted that some methods are capable of being used for defining weights as well as aggregation. TOPSIS, for instance, includes features for defining weights, but is mostly only used for aggregation. A more prominent example is AHP, which is mainly used as a method for defining weighting factors with stakeholders but is also labeled as an aggregation method—where it is often implicitly combined with WSM.

In Fig. 6, the findings of the review publications regarding the use of different MCDA aggregation methods

in their reviewed papers are compared with the review of the Helmholtz studies. Several review publications show a relative value above 100%. This is because studies either used several MCDA methods for a sensitivity analysis, or no clear separation was made between methods for weight elicitation and for aggregation. The most commonly used method across the review publications is AHP. An exception is the paper by Martin-Gamboa et al. [88], in which the authors subsume this method under MAVT, as well as our analysis of the Helmholtz studies, where AHP was never used for aggregation—a strict prerequisite for this analysis. However, one study [58] used AHP to elicit weighting factors. PROMETHEE, the most prominent method among Helmholtz studies, was also frequently identified by the review studies, although to a lesser extent. When also taking ELECTRE into account, it becomes evident that outranking methods are seldom used for the sustainability assessment of energy technologies. This is notable, as the full compensation of criteria might become problematic in sustainability assessments when tipping points or boundaries are reached. Some review studies also show that many more methods are available than previously discussed in this article, even surpassing the 205 methods listed in the Multi-Criteria Decision Analysis—Methods Selection Software (MCDA–MSS) [89].

MCDA methods not only include methods for aggregating the criteria and indicators, but also weighting them. Nevertheless, the identified review papers address this subject in a variety of different ways. Martin-Gamboa et al. [88] do not mention this topic at all. Several other publications [83–85, 90] do not specifically consider weighting, but discuss AHP as an MCDA aggregation method. However, they do not take into account the fact that this method is mostly used to elicit weighting factors, and that a separate method is needed for aggregation. Five of the review papers [12, 23, 86, 87, 91] mention and discuss, to varying extents, the use of AHP for deriving weighting factors. However, none of these papers mention that weighting factors are derived from AHP in the form of importance coefficients, which are not suitable for all aggregation methods. Only Kügeman and Polatidis [92] briefly touch on the concept of trade-off weights. A more detailed analysis is performed by Estévez et al. [53] regarding the involvement of stakeholders for the elicitation of weighting factors, but they do not look at the specific methods used for the integration.

Only three papers deliver a detailed discussion about methods for eliciting weighting factors. Wang et al. [9], and Ibáñez-Forés et al. [93] distinguish between objective methods (based on measurement data and criteria information) and subjective methods (based on stakeholder

opinions) if equal weighting is not applied. Both reviews observe that objective methods are used seldomly, identifying three and one studies, respectively, that used such methods. An equal weighting approach was found in a significantly higher number of studies, appearing in ten and 15 studies, respectively. For subjective weighting methods, such as AHP, the reviews identified a very similar number of studies (28 and 29, respectively), making this the most popular approach for eliciting weighting factors. In particular, Wang et al. [9] discuss which methods are available for subjective weighting and which are actually used in case studies. The review by Lindfors [8] takes a different approach to eliciting weighting factors. The author has a focus on subjective methods and distinguishes between the involvement of experts (e.g., technology developers) and stakeholders (e.g., potential users, politicians, or local communities). More than two thirds of the analyzed studies involve either experts and/or stakeholders in their assessments. Only 6% use an equal weighting approach. This review is the only one in this selection to mention studies that develop weighting scenarios, for example, using synthetic stakeholder profiles to explore more extreme weighting results.

Helmholtz studies

Of the 20 Helmholtz studies using MCDA for sustainability assessments, 19 performed aggregation. Peters et al. [57] only selected criteria and derived weighting factors for the circular economy of batteries. They did not apply criteria and weighting factors to a case study. The other 19 studies applied five different methods: WSM, TOPSIS, PROMETHEE II, ELECTRE III, and multi-attribute value theory (MAVT) (Fig. 7, Table 4). By far the most popular method was PROMETHEE II, as almost 50% of analyzed studies used this method. For seven out of nine studies [37, 59, 61, 66, 67, 70, 71], the main reason for selecting PROMETHEE was that it is an outranking method, allowing compensation between criteria to be restricted. For Vögele et al. [69], the successful use of the method over decades played an important role in its selection, while Rhoden et al. [68] did not give a reason for their choice. In the literature, PROMETHEE is also cited as being easier to understand for the practitioner than other outranking methods, making it more approachable [30]. Ease of use and frequent applications are likely the main reasons why ELECTRE III was not chosen in these studies, which would have been another viable method to use. Furthermore, several tools are available to support the use of PROMETHEE, for example, the Helmholtz MCDA tool [94], Visual PROMETHEE [95], and PROMETHEE-Cloud [96]. Mesa Estrada et al. [73] opted for ELECTRE III, because it permits the integration of veto thresholds. This feature allows the user to integrate official

Table 4 Application of multi-criteria decision-analysis methods selection software and the implemented guidelines for Helmholtz studies

Source	Aggregation method	Method for eliciting weights	# 1	# 2	# 3	# 4	# 5	# 6	Guideline alignment
McKenna et al. [56]	MAVT	SWING	Trade-off	✓	cardinal	✓	–	✓	No
Baumann et al. [58]	TOPSIS	AHP	Imp. coefficient	✗	cardinal	✗	–	✓	No
Haase et al. [29]	TOPSIS	Pairwise comparison with synthetic stakeholder profiles	Imp. coefficient	✗	cardinal	–	–	✓	No
Wilken et al. [59]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	–	–	✓	No
Naegler et al. [60]	WSM	Discrete choice experiment	Trade-off	✓	cardinal	–	–	✓	No
Wulf et al. [61]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	–	–	✓	Yes
Baumann et al. [62]	WSM	Equal weighting	Imp. coefficient	✗	cardinal	–	–	✓	No
Gomez Trillos and Draheim [63]	TOPSIS	Equal weighting	Imp. coefficient	✗	cardinal	–	–	✓	No
Haase et al. [64]	TOPSIS	Equal weighting	Imp. coefficient	✗	cardinal	–	–	✓	No
Ottenburger et al. [65]	WSM	Stakeholder survey with synthetic stakeholder profiles	Imp. coefficient	✗	cardinal	✗	–	✓	No
Röben et al. [66]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	✓	–	✓	?
Wulf et al. [37]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	–	–	✓	No
Schwager et al. [67]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	✓	–	✓	?
Rhoden et al. [68]	PROMETHEE II	Market analysis	Imp. coefficient	✓	cardinal	✓	–	✓	No
Vögele et al. [69]	PROMETHEE II	Stakeholder survey with synthetic stakeholder profiles	Imp. coefficient	✓	cardinal	✓	–	✓	?
Wulf et al. [70]	PROMETHEE II	SMART	Imp. coefficient	✓	cardinal	–	–	✓	No
Mesa Estrada et al. [71]	PROMETHEE II	Equal weighting	Imp. coefficient	✓	cardinal	–	–	✓	No
Brand-Daniels et al. [72]	WSM	Stakeholder survey during workshop	Imp. coefficient	✗	cardinal	✗	–	✓	No
Mesa Estrada et al. [73]	ELECTRE III	Deck of cards	Imp. coefficient	✓	ordinal	✓	–	✓	No

AHP: Analytical Hierarchy Process, ELECTRE: Elimination Et Choix Traduisant la Réalité, MAVT: Multi-Attribute Value Theory, PROMETHEE: Preference Ranking Organization METHOD for Enrichment Evaluation, WSM: weighted sum method

constraints or other limits, such as planetary boundaries, into the analysis.

In the realm of compensatory methods, WSM and TOPSIS were used equally. The studies using WSM [60, 62, 65, 72] highlighted the simplicity of this method or gave no further explanation for choosing this method [65]. Another four studies [29, 58, 63, 64] used TOPSIS for aggregation. It was also chosen, because it is more advanced than WSM while also remaining easy for practitioners and stakeholders to understand. Moreover, the papers by Haase et al. [29, 64] mention that TOPSIS is a compensatory method, implying that the authors follow the concept of weak sustainability [6], where natural capital is interchangeable with man-made capital. In contrast, outranking methods can be used as an approach to follow the concept of strong sustainability, where natural capital cannot be substituted by man-made capital. The last study by McKenna et al. [56] applied MAVT due to the transparency of the whole process. Furthermore, they highlighted the suitability of including both quantitative and qualitative criteria (Fig. 6).

All 20 identified Helmholtz studies applied some kind of weighting. For the weighting procedure, either the study authors developed a specific weighting scheme, or external stakeholders were integrated into the weighting process. For details of how stakeholders were integrated

into the MCDA studies, see the “Stakeholder integration” section. Only seven studies used weighting methods which include stakeholders. Nine of the 13 studies that did not integrate stakeholders for criteria weighting used an equal weighting approach (Fig. 7, Table 4). This is a basic approach used in MCDA that is often followed by a sensitivity or scenario analysis of the weighting factor sets to test their robustness [62, 64]. There are several reasons why only an equal weighting approach is used in these MCDA studies. First and foremost, these studies do not deal with actual real-life decision problem. Instead, they are academic pursuits that look to discuss methodological issues, for example, what a sustainability assessment with MCDA might look like [64], how thresholds in outranking methods can be used in LCSA studies, or how different hierarchies of criteria can influence results [37]. Other studies using equal weighting have more of a screening-oriented focus on the process under investigation [59]. Due to the high level of effort that is often required for the proper integration of stakeholders to elicit weighting factors, three studies opted to develop synthetic stakeholder profiles to derive weighting factors. Vögele et al. [69] combined their own assumptions and literature results to define weighting factor sets for nine different stakeholder groups. In contrast, Haase et al. [29] leaned into cultural theory and defined weighting factor

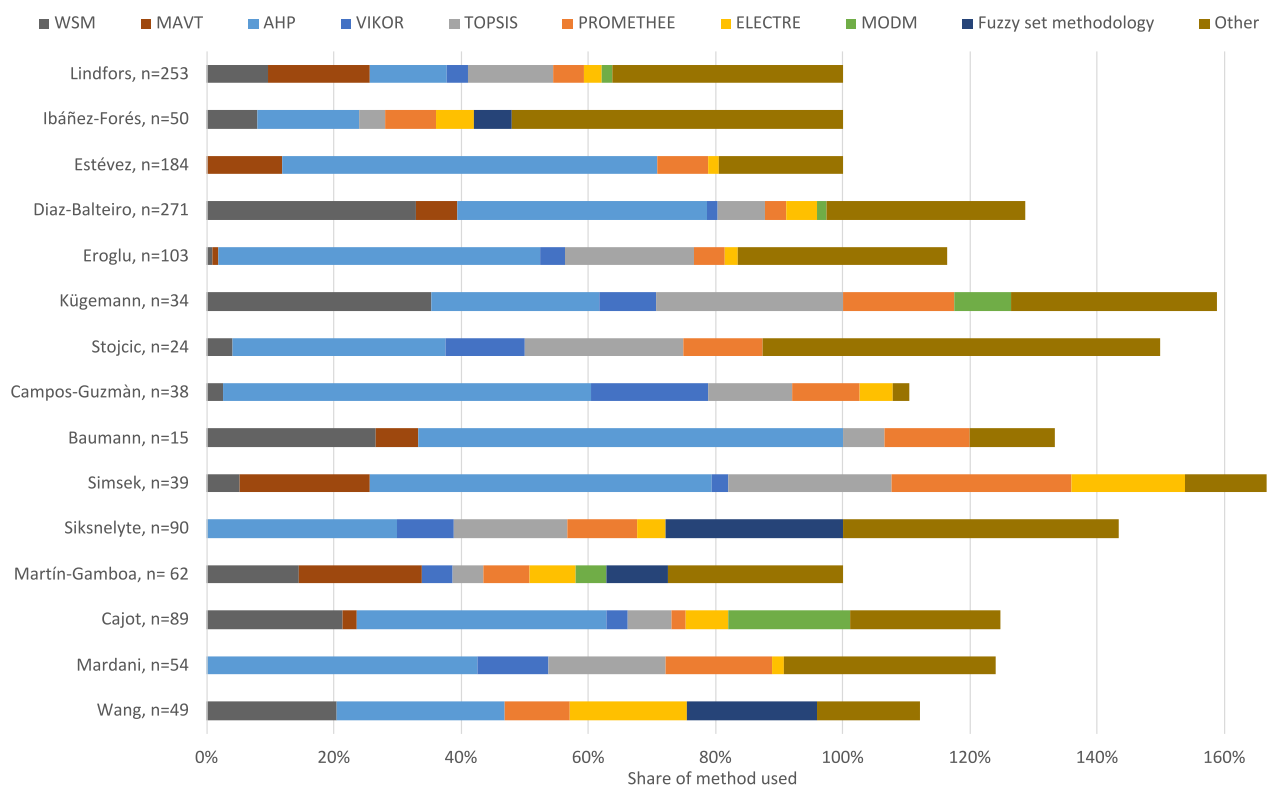


Fig. 6 Meta review for MCDA methods related to sustainability assessments of energy systems and technologies

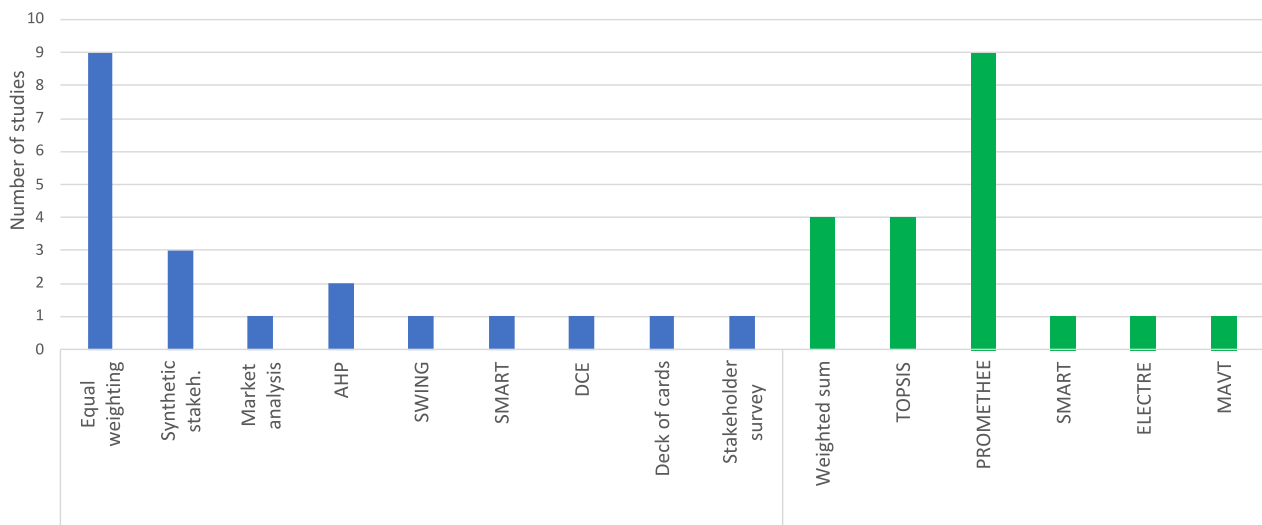


Fig. 7 Applied MCDA methods for weighting ($n=20$) and aggregation ($n=19$) in Helmholtz studies

sets for stakeholders based on the three profiles: hierarchist, individualist, and egalitarian. Ottenburger et al. [65] developed an agent-based model for their synthetic stakeholder profiles. Another approach was developed by Rhoden et al. [68], who used purchase decisions to define weighting factors. Studies including stakeholders in their weighting step opted for a variety of methods. Peters et al. [57] and Baumann et al. [58] performed an AHP, which is a common MCDA method for defining importance coefficients. The other methods applied—the swing weighting technique, SMART, DCE, and DCM—are specific participatory methods that can be used in MCDA studies. Their selection is largely based on the context of the study and the resources available. Mesa Estrada et al. [73] used the DCM for small group discussions after a general survey was conducted.

Suitability of MCDA methods in Helmholtz studies

This section first introduces the analysis scheme for assessing the suitability of MCDA methods and then discusses the findings in a second subsection.

Analysis scheme for suitable MCDA methods

Cinelli et al. [89] developed a taxonomy for selecting MCDA aggregation methods that encompasses 205 different methods. The authors also tested the taxonomy against published MCDA case studies [3] and derived six guidelines highlighting the most common mistakes in selecting an MCDA method:

1. Criteria weights are tailored to each MCDA method: Weights are defined either as trade-off weights between criteria, which imply the amount you are

willing to trade-off performance on one criterion against another, or as importance coefficients, defining the intrinsic importance of a criterion (see also “Weighting of indicators and criteria” section).

2. The desired decision recommendation should be carefully selected: With MCDA, a problem statement is needed that should specify the type of outcome that is desired, such as ranking, sorting, choice, or the clustering of options. This also includes whether the outcomes are depicted as binary relations (an ordinal ranking such as in ELECTRE III) or as a scoring function (a cardinal recommendation such as in PROMETHEE II).
3. Numerical does not always mean quantitative: Qualitative criteria are often transformed into numerical values for ease of communication and integration into MCDA (e.g., good = 1, medium = 0, poor = -1). This approach is often used for criteria describing comfort or acceptability, but these values have a subjective meaning and the difference between good and medium might not be the same as the difference between medium and poor. This conflicts with MCDA methods designed for quantitative criteria (e.g., WSM).
4. Numerical does not necessarily indicate a ratio scale: Indicators might have a ratio scale or an interval scale. Scales with an absolute zero, such as temperature in Kelvin, are ratio scales, whereas temperature in degrees Celsius reflects an interval scale. The zero is defined arbitrarily in an interval scale. This is problematic for methods such as the Analytical Hierarchy Process (AHP), as they are only designed for ratio scales.

5. Not all the MCDA methods implement the same steps: Some methods, such as TOPSIS, require normalization in the MCDA process. For others, such as outranking methods, this is redundant.
6. The interdependencies between the criteria can refine the preference model: Redundancies in criteria should be avoided. Criteria that show the same result across all analyzed options should, therefore, be deleted.

The Helmholtz MCDA studies were analyzed in detail against these six guidelines.

Findings

Out of the 19 Helmholtz studies performing a complete case study, eight studies used either an incorrect MCDA aggregation method based on their chosen list of criteria and their definition of weighting factors, or they made mistakes leading to biased results (see Table 4).

Most of the Helmholtz studies consider their criteria weights as importance coefficients (Table 4). According to guideline 1, however, most of the compensating aggregation methods, such as WSM or TOPSIS, require trade-off weights. Prado et al. [97] brought this issue to attention in the LCA community in 2019, since ISO 14044 only considers importance coefficients as weighting factors. MCDA literature, for example, Steele et al. [98], highlights that in compensation methods, weighting factors are closely related to the scoring scales of criteria. Of the nine Helmholtz studies applying compensatory methods, only two [56, 60] used trade-off weights correctly. The other seven studies [29, 58, 62–65, 72] use importance coefficients instead. Some of these studies just use equal weighting [62–64] followed by a subsequent discussion of sensitivities, while others [58, 65, 72] use stakeholder surveys to obtain importance coefficients, but do not discuss trade-offs for their case study. The remaining study [29] applied cultural profiles to define synthetic stakeholder profiles to perform a pairwise comparison, resulting in importance coefficients. To use importance coefficients as criteria weights, outranking MCDA methods are the correct choice. Otherwise, further efforts are needed to determine trade-off weights.

Guideline 2 highlights the difference between results on a cardinal scale and on an ordinal scale. Of the 19 Helmholtz studies analyzed, only Mesa Estrada et al. [73] use a method producing ordinal results. The other 18 studies provide cardinal results. However, several studies, such as Wulf et al. [37], do not use the additional information given by the more detailed result structure.

Nine studies used semi-quantitative criteria with compensating aggregation methods (WSM and TOPSIS), as cautioned in guideline 3. For example, Baumann et al.

[58] assessed social acceptance on a scale from 1 to 5. However, it is not possible to say that an acceptance value of 4 is double the acceptance of the value of 2, as is possible with the Life Cycle Costing (LCC) results. Combining these different types of criteria in compensatory aggregation methods leads to inaccurate results. For the five studies using outranking methods [66–69, 73], this issue did not arise. The same applies to the study using MAVT [56]. With these methods, the semi-quantitative criteria are not directly offset against quantitative criteria.

Guideline 4 did not apply to any of the Helmholtz studies, as none of the studies used AHP for aggregation.

Furthermore, all Helmholtz studies performed the correct number of steps for their MCDA processes. None of the studies, for example, used a redundant normalization step for outranking methods.

Wulf et al. [61] clearly disregarded guideline 6. In their economic part of the assessment, they included four indicators that produced the same results across all analyzed options, making them redundant. Baumann et al. [58] were more conscious about this topic, as they removed one economic indicator from the assessment due to redundancy. In general, most studies did not have an issue with this guideline. However, it was not possible to assess this topic for three studies [66, 67, 69], as the publications provided did not display their criteria results transparently.

Stakeholder integration

This section gives an overview of the type and level of stakeholder involvement in (1) the Helmholtz MCDA studies for sustainability assessments, and (2) the studies from the literature search. Here, the term “stakeholder involvement” refers to the direct involvement of stakeholders or experts in the respective studies. Only 11 out of the 20 Helmholtz studies meet this criterion (see Supplementary Table A7). The remaining nine studies using only indirect stakeholder involvement—for example, via literature sources on stakeholder opinions—are excluded from this analysis. From the literature search, 25 articles were included (see Table 1). As Kowalski et al. [49] carried out two different participatory MCDA processes, our analysis considers them as two separate case studies—Kowalski (1) and Kowalski (2)—resulting in a total of 26 case studies from the literature search (see Supplementary Table A8). In this section, criteria/indicator selection and criteria/indicator weighting are referred to as criteria selection and criteria weighting, respectively.

Analysis scheme for stakeholder integration

Within the analysis of studies on stakeholder integration, the following aspects were assessed:

- a. **Type of stakeholders and experts included and participatory formats used.** The following categories are used to summarize the types of stakeholders: experts including academia (E), industry (manufacturers, energy companies, network operators, etc.) (I), government (local authorities, policy makers, etc.) (G), organized civil society, i.e., interest groups including statutory associations (e.g., lobby groups) and non-statutory associations (e.g., trade unions, NGOs, religious communities) (OC), broad civil society, i.e., individuals affected by or interested in a specific initiative (C).¹

In addition, the studies are screened to identify the participatory techniques used at every stage of the MCDA process: interviews, workshops/discussions, surveys, discrete choice experiments (DCE), and focus groups.

- b. **Level of participation.** The level of participation is assessed by identifying the number of stages of the MCDA process (alternative selection, criteria selection, weighting, and analysis of results) in which the preferences of individual stakeholders and experts are integrated. Together with the types of stakeholders involved, the following four categories are used to assess the level of participation (based on Martunen et al. [50] and Dean [48]): low (only experts are involved in the process, OR stakeholders participate in only one stage); moderate (stakeholders participate in two stages); high (stakeholders participate in three stages); very high (stakeholders participate in all stages). The categories “low” and “very high” can be referred to as “analyst-led MCDA” and “fully participatory MCDA”, respectively.
- c. **Approach for group decision analysis.** To categorize the approaches for group decision analyses, the following distinction—based on de Almeida et al. [46] and Dean [48]—is used: exclusion, filtration, aggregation input level, aggregation output level, comparison (disaggregation). A brief description of the categories can be found in Table A6 in the Supplement.

Types of stakeholders included and participatory formats used

Figure 8 shows the stakeholder categories that were included in the MCDA process of Helmholtz studies ($n=11$) and studies from the literature search ($n=26$). For the Helmholtz studies, the predominant group

consists of studies that only include experts (E) ($n=5$ or 45%). For studies from the literature search, the number of studies that only include experts (E) is as high as the number of studies that include experts (E), industry (I), and government (G) ($n=6$ or 23%).

In the Helmholtz studies, the majority of studies ($n=10$ or 91%) included experts (E), followed by industry (I) ($n=4$ or 36%), governmental stakeholders (G) ($n=4$ or 36%), and organized civil society (OC) ($n=3$ or 27%). Stakeholders from broad civil society (C) are only included in two studies (18%). Five studies (45%) involved experts together with other stakeholders, while one study involved broad civil society (C) but no experts.

For studies from the literature search, the majority ($n=24$ or 92%) involved experts, followed by government ($n=17$ or 66%) and industry ($n=17$ or 65%). Broad civil society (C) and organized civil society (OC) were each included in nine studies (35%). With the exception of two studies, all other studies from the literature search (92%) included experts with or without other stakeholders.

Figure 9 shows the percentages of different participatory formats used for different stages of the MCDA process in the Helmholtz studies and the studies from the literature search. In both cases, participatory techniques vary among the stages of MCDA, except for the discussion of results, where only workshops/discussions are used. This stage is also the least frequent point at which stakeholders are considered in the studies (Helmholtz studies and studies from the literature search).

Tables A7 and A8 in the Supplement present the types of stakeholders considered, the MCDA stages in which they participate, and the respective participatory formats used for Helmholtz MCDA studies and studies from the literature search, respectively.

As shown in Fig. 9A, the majority of Helmholtz studies involve stakeholders for the weighting of criteria as well as criteria selection (each $n=7$ or 64%). Studies involving stakeholders for problem structuring (criteria selection, selection of alternatives) either include stakeholders for the selection of alternatives and criteria ($n=4$ or 36%), the selection of alternatives only ($n=2$ or 18%), or the selection of criteria only ($n=3$ or 27%). The integration of stakeholders to discuss results was carried out in five Helmholtz studies (45%). In Helmholtz studies, workshops are the most frequent technique used across the different stages. Interviews are the second favorite option for problem structuring (selection of alternatives and criteria), but are not considered in criteria weighting or the discussion of results.

In the studies from the literature search (Fig. 9B), the distribution among the different stages tends to be more uneven, depicting a very strong trend for including stakeholders in weighting ($n=26$ or 100%), followed by

¹ The division of civil society into organized and broad civil society is based on BMBF [99].

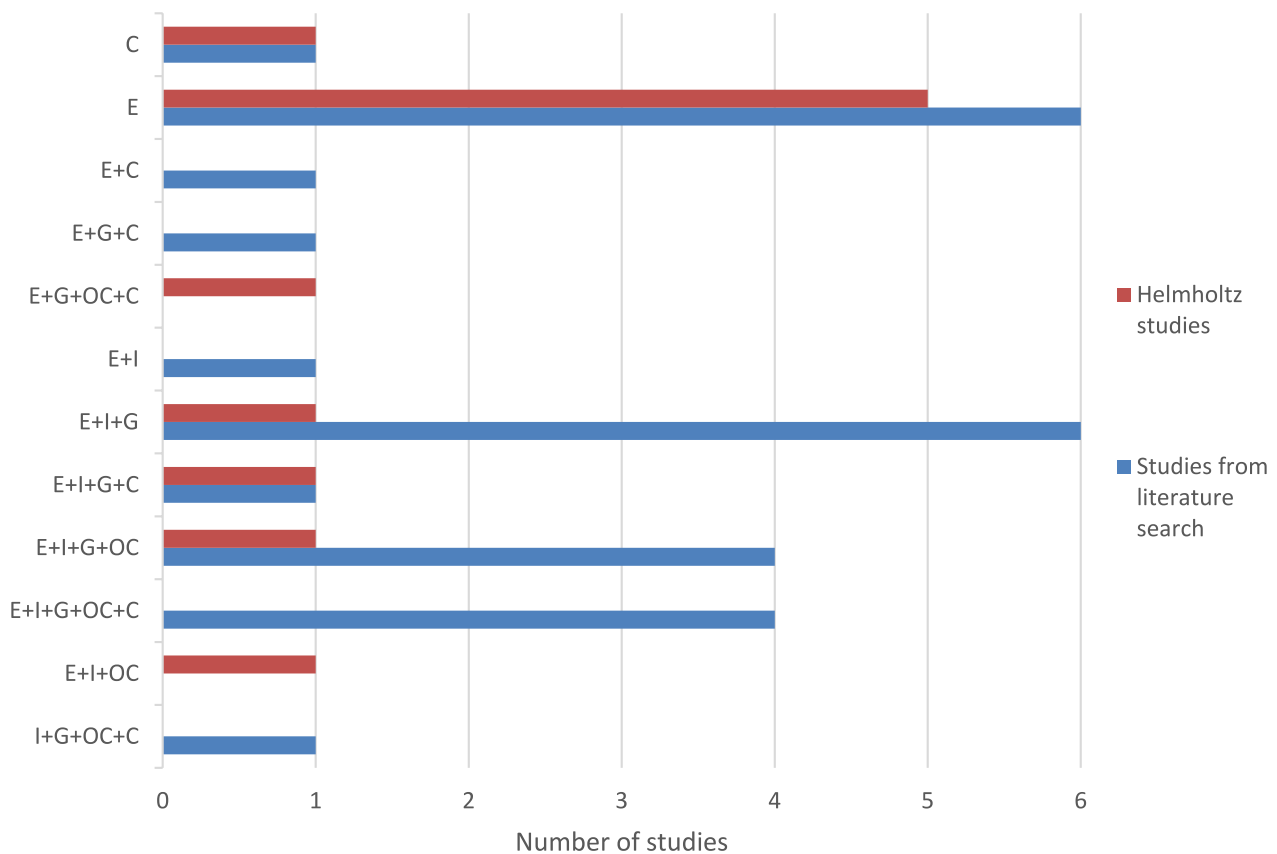


Fig. 8 Stakeholder categories (E—experts, I—industry, G—government, C—broad civil society, and OC—organized civil society) involved in Helmholtz studies ($n = 11$) and studies from the literature search ($n = 26$)

criteria selection ($n = 11$ or 42%), the selection of alternatives ($n = 8$ or 31%), and the discussion of results ($n = 4$ or 15%). Although workshops are present at all stages, techniques such as interviews and surveys are predominant for weighting and criteria selection. Compared to Helmholtz studies, studies from the literature search use surveys to a much higher extent, especially for criteria weighting and criteria selection.

Level of participation

The level of participation consists of two elements: the types of stakeholders involved and the stages at which they participate (see “Analysis scheme for stakeholder integration” section). Figure 10 shows the level of participation assessed for Helmholtz studies and studies from the literature search according to the categories defined in this study, i.e., low, moderate, high, very high (see “Analysis scheme for stakeholder integration” section). In both cases, more than half of the studies considered had a low level of participation.

In Helmholtz studies, the low level of participation ($n = 6$ or 55%) is mainly driven by the high percentage of studies including only experts ($n = 5$ or 45%). There

is also one study that includes citizens at only one stage of the MCDA process [60]. In studies from the literature search, the low level of participation ($n = 14$ or 54%) is divided almost equally between studies which only include experts ($n = 6$ or 23%) and studies which include stakeholders at only one stage of the MCDA process ($n = 8$ or 31%).

In both the Helmholtz studies and those from the literature search, only one study (9% of Helmholtz studies, 4% for studies from literature search) had a very high level of participation: McKenna et al. [56] and Lode et al. [100], respectively. McKenna et al. [56] combine SWING weighting with MAVT to integrate inputs from experts, government, civil society, and organized civil society. Lode et al. [100] implement the multi-actor multi-criteria analysis (MAMCA) framework using AHP, involving citizens, organized civil society, government, and industry.

Approach for group decision analysis

The approaches for group decision analysis are categorized as follows: exclusion, aggregation input level, aggregation output level, and comparison (see Table A6 in the Supplement). The analyzed studies show significant

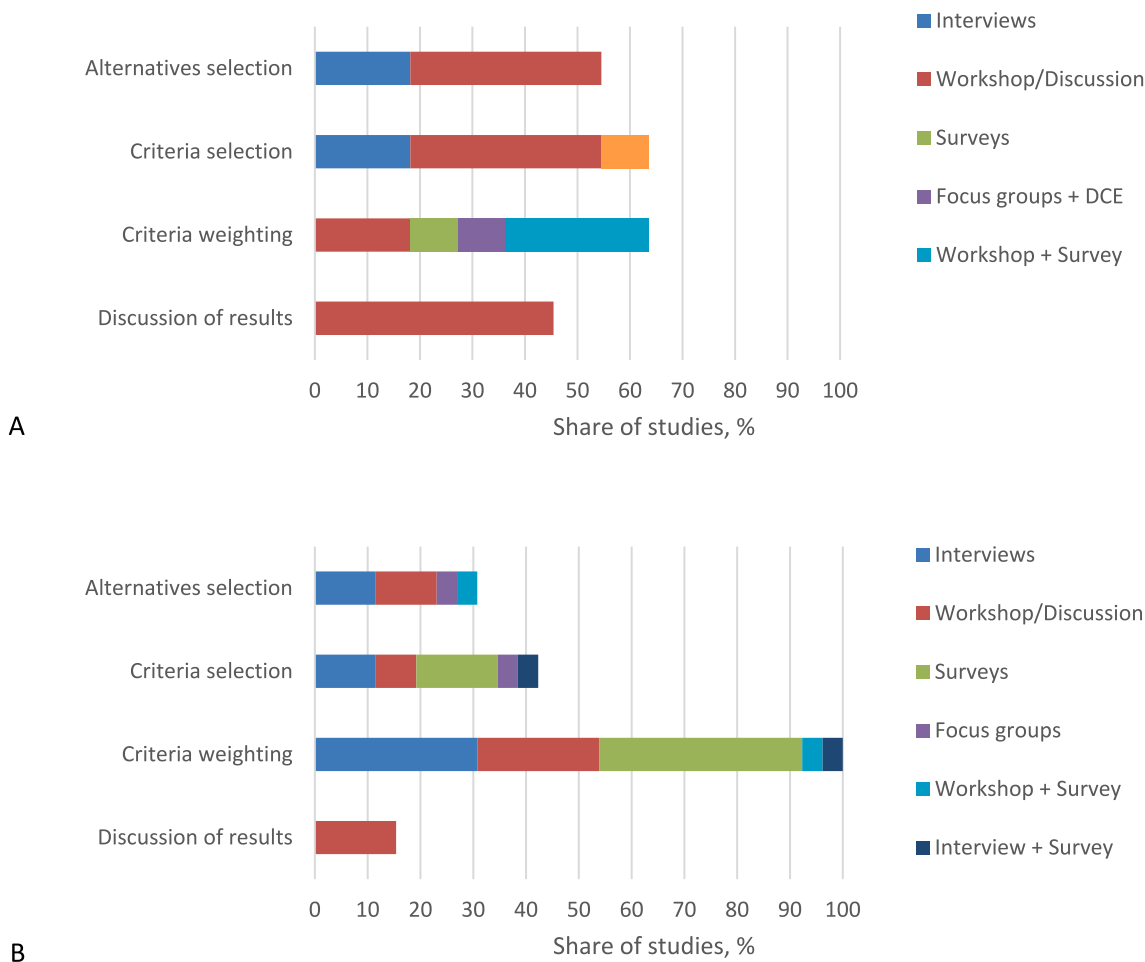


Fig. 9 Frequency of participatory formats used for different stages of the MCDA process in the analyzed Helmholtz studies ($n=11$) (A) and the studies from the literature search ($n=26$) (B)

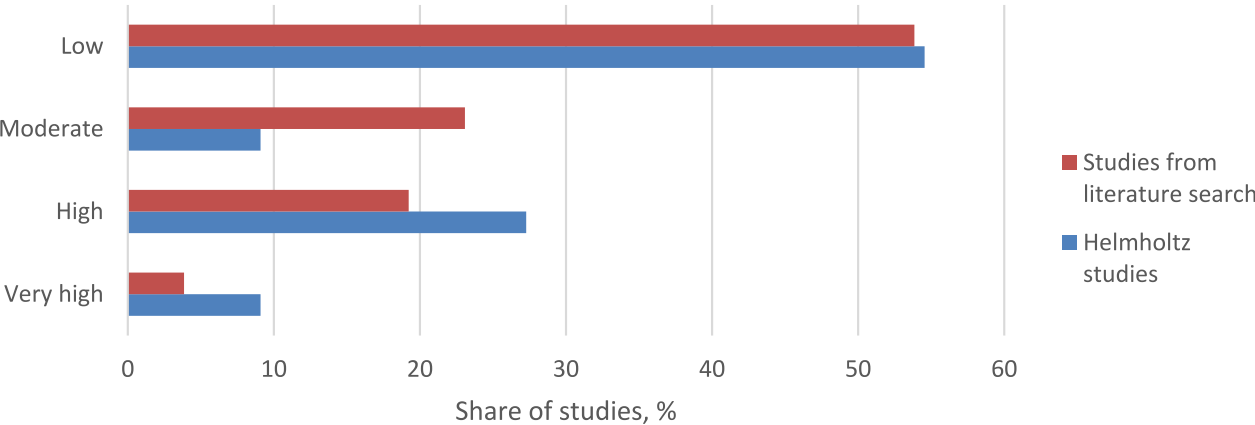


Fig. 10 Assessed level of participation for Helmholtz studies ($n=11$) and studies from the literature search ($n=26$)

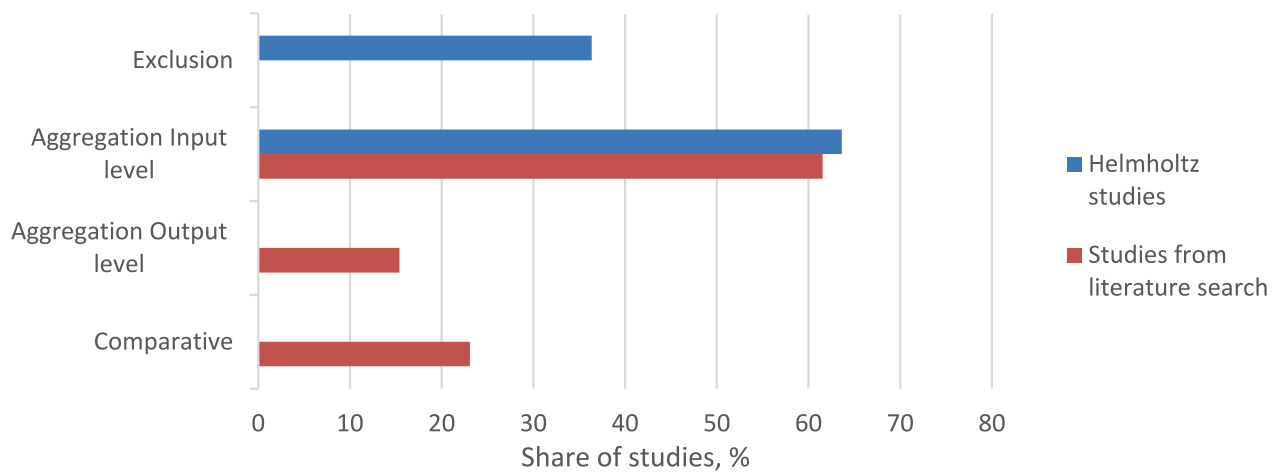


Fig. 11 Approaches for group decision analysis in Helmholtz studies ($n = 11$) compared to studies from the literature review ($n = 26$)

differences among these categories (see Fig. 11). In the case of the Helmholtz studies, only two categories appear: exclusion ($n = 4$ or 37%) and aggregation input level ($n = 7$ or 64%). The exclusion studies involved experts only and used theoretical weight profiles and sensitivity analysis to obtain and analyze rankings [29, 62, 66, 67] (see Table A7 in the Supplement). The input-level aggregation is carried out using individual weights from SWING, SMART, AHP, direct weighting combined with DCM, and DCE. One of the studies included consensus calculations within AHP [57].

In contrast, the studies from the literature search are primarily distributed between aggregation input level, aggregation output level, and comparative approaches. The majority of cases utilize the aggregation input-level approach ($n = 16$ or 62%). AHP and fuzzy approaches are the most commonly used for weight elicitation. Among the studies from the literature search, the aggregation output level approach is the least frequently used ($n = 4$ or 15%). Two of these studies involve the MAMCA framework, aggregating final rankings using WSM and assigning equal weights to stakeholders [101, 102]. Marques et al. [103] provide an example of a voting procedure for the aggregation of final rankings at the output level. The comparative approaches ($n = 6$ or 23%) include two studies using the MAMCA framework supported with WSM [43] and AHP [100].

Discussion

According to the structure of the results chapter, the discussion is structured into sections on criteria and indicator selection, choice of MCDA method, and stakeholder involvement.

Criteria and indicator selection

With regard to the three sustainability dimensions, it became apparent that in the Helmholtz studies, the environmental dimension is discussed more often in sustainability assessments of energy systems or technologies, followed by the economic dimension. The diversity and number of social criteria and indicators is still smaller than those of the other two dimensions. This might be, because social assessment methodologies are still less established than those for the environmental and economic dimensions. Methodological development is, therefore, required for the social dimension. The actual selection of criteria and indicators is not often explicitly documented in either Helmholtz studies or review articles, as illustrated in Fig. 5. The reasons for this can be manifold, with the actual intention behind the selection of criteria and indicators differing among the Helmholtz studies and review articles, as these are always related to different goals. It should also be noted that although the total number of review articles is smaller than those of the Helmholtz studies, the review articles include more articles and thus represent a larger variety of reasons for selecting criteria and indicators. However, the results indicate a more pragmatic selection strategy in the Helmholtz studies, as the focus was on the coverage of aspects regarded as being important for the actual decision process (relevance, coverage, and data availability). In addition, from a scientific perspective, both the review articles and the Helmholtz studies often focused on avoiding redundancies, which was one of the more frequently mentioned reasons for the selection. Other reasons for the indicator selection might have played a role but could have been perceived as being too self-evident to be mentioned, for example, meaningfulness or measurability. In particular, the identification of indicators

from the literature or through stakeholder consultation can lead to the omission of mentioning the explicit reasons for their selection.

Based on the results, where the majority of review articles did not describe the criteria and indicator selection process, it is generally recommended that the indicator selection process be guided and communicated more explicitly. Other criteria should also be considered to improve MCDA reliability, which in turn would improve the acceptance of MCDA studies in the energy research field.

Furthermore, the need for a precise definition of criteria and indicators must be stressed, as a clear distinction would not only have facilitated the analysis but would also increase the transparency of MCDA studies. The selection of criteria and indicators is crucial in any MCDA; it is important to clearly communicate their definition and selection, along with their aggregation and weighting. The synonymous use of criteria and indicators can cause confusion and complicate the interpretation of both methodology and results. As long as single indicators are equal to the actual criterion used for the MCDA, these values are directly reported. However, as soon as several indicators contribute to one criterion, it becomes challenging to comprehend and communicate the main assumptions regarding their selection, weighting, and aggregation into composite indicator/criteria.

MCDA methods

The choice of aggregation methods is an important decision for MCDA-assisted sustainability assessments. It reflects an explicit understanding of sustainability and must be considered carefully. The analysis of the chosen aggregation methods in Helmholtz studies showed that this is a challenging task, with several pitfalls to be avoided. Most critical is the difference between trade-off weights and importance coefficients, and the need to subsequently use appropriate aggregation methods. While it is acknowledged that the definition of trade-off weights is much more difficult to determine than importance coefficients [104], a correct understanding of the meaning of weighting factors is essential when designing compensatory aggregation methods in a real decision-making process. This is, of course, well-acknowledged within the MCDA research field [105], but when it comes to application (e.g., for sustainability assessment), practitioners in the Helmholtz Association and other research organizations [3, 53] are not sufficiently informed to make conscious decisions regarding the choice of aggregation method and the elicitation of weighting factors. A paper by Cinelli et al. [89] and the MCDA–MSS webtool [106] are a great support for the method selection.

However, the information can be hard to comprehend for people new to the topic. In addition, one Helmholtz study showed that an outranking method such as PROMETHEE can also be applied in a way that compensation between the criteria is possible [69]. They defined the linear preference function in such a way that the preference was never reached, with two options always in partial preference to each other.

Another important point is the choice of aggregation method when using qualitative or semi-quantitative indicators, such as comfort or acceptance. Many Helmholtz studies that allow compensation fail to use a correct method, for example, MAVT. These indicators are important for allowing sustainability assessments to describe the assessed system from different perspectives and enabling the integration of different stakeholders. A better understanding of MCDA aggregation methods for practitioners is, therefore, necessary to ensure that the MCDA produces reliable results.

One issue that was not tackled in the Helmholtz studies, nor was it addressed in more detail in the literature review, is rank reversal, which can occur when the addition of another alternative reverses the resulting ranks of established alternatives [107]. This phenomenon can arise when using WSM and, to a lesser extent, TOPSIS, PROMETHEE, or ELECTRE. More elaborate methods, such as the Characteristic Objects Method [107], might prevent it from occurring.

The analysis of the Helmholtz studies and the literature review further showed that Helmholtz researchers are not yet fully exploiting the potential of MCDA methods. They could make better use of the methods they already utilize. For example, they could use the cardinal result structure, which is obtained by applying PROMETHEE II. In publications to date, only the ranks of the different options have been discussed. However, this method also provides the distances between the assessed options. In addition, the general literature review demonstrated that many more different MCDA methods can be used for the sustainability assessment of energy technologies and systems. The MCDA–MSS tool might be one way of exploring different MCDA aggregation methods. Even the currently applied methods might offer more features to support assessments. Only one study uses ELECTRE. Wang et al. [9], Diaz-Balteiro et al. [90] demonstrated the usefulness of this method for sustainability assessment.

With regard to the elicitation of weighting factors, Helmholtz studies more frequently rely on equal weighting factors compared to the findings from the literature review. There might be good reasons for this—for example, the study is focused on a very specific methodological aspect—but for proper decision-making processes, equal weights are insufficient.

Stakeholder integration

Designing an integrated energy system of the future is a complex process that not only involves innovative technologies but also affects multiple societal actors (stakeholders), such as interest groups, political decision-makers, and the general public [1]. The results for the “Stakeholder integration” section confirm the dominance of expert-based MCDA processes in both Helmholtz studies and external literature, as observed by previous reviews [53]. Significant efforts have been made by Helmholtz researchers to broaden the participation of stakeholders beyond the academic/expert domain, involving interest groups and political decision-makers. However, when compared to external studies from the literature review, the types of stakeholders engaged are rather limited. For example, the integration of stakeholders from industry (I), government (G), and broad civil society (C) is relatively rare in the Helmholtz studies. The integration of broad civil society (the general public) poses several challenges, which helps to explain its low frequency in the studies analyzed. These challenges include: (i) informing and empowering citizens to feel like important actors in the decision-making process [108], (ii) handling large samples and very diverse audiences, and (iii) using strategies to group the participants, for example, based on socio-demographic characteristics, to analyze preferences [109]. Although not included in this study, it is important to note that a stakeholder group can be internally homogeneous or heterogeneous in terms of values and priorities [48, 110]. In the case of internally heterogeneous groups, the opinion of a single participant might not represent the entire group, making it necessary to increase the number of participants [108]. However, the participatory techniques currently used only allow for the involvement of a limited number of participants while still maintaining a practical and meaningful process [48].

Identifying the most suitable participatory technique is key to the successful application of the process. This study highlights the abilities of the Helmholtz group to integrate different types of participatory techniques. The trends are very similar to those observed in the reviewed literature. For example, in both cases, focus groups are used for involving broad civil society (C), although at different stages of the process. Similarly, authors showed a preference for workshops to discuss results. This technique is frequently used for the selection of alternatives, criteria selection, and weighting. Workshops are a good example of formats that allow for practical and meaningful processes. However, they remain a format, where only an exclusive group of participants can take part. While they are often successful at involving interest groups and political decision-makers, they fail to integrate the general public. The combination of participatory techniques

to tackle different stages of the MCDA process appears to be common practice. In future Helmholtz MCDA studies, it might be worth considering different participatory techniques to approach different stakeholders at different MCDA stages. For example, workshops could target interest groups and experts, while surveys might be used to involve the general public. Although surveys are a potential format for integrating broad civil society (C) due to their accessibility, the challenge is to present them to stakeholders in a clear and empowering manner. Within the Helmholtz Association, the use of transdisciplinary approaches, such as the real-world lab, is a desirable target [1]. In this context, surveys could be tailored to the socio-demographics of participants depending on the context in which it is implemented.

The transformation of decision-making attitudes requires interactions among the different stakeholders. Approaches for stakeholder integration should, therefore, support: first, the recognition of individual values and preferences; and second, the identification of common values through interactions. The Helmholtz studies that use the exclusion approach in weighting—although providing a scientific base for understanding the system—fail to identify stakeholder values or preferences. Among the remaining approaches, Helmholtz studies only apply the aggregation input-level approach. This makes sense, since the aim of the group is to support transformation, for which negotiation and the identification of common values are key. Studies from the literature search go beyond the exclusion approach and focus on actively incorporating stakeholder values in the assessment. Beyond the aggregation input level, several studies also focus on the aggregation output level and comparison approaches, which allow them to identify different weighting sets and highlight the individual values of the different types of stakeholders [102]. These approaches might also be of interest for Helmholtz to explore. An approach that enables the creation of weighting sets and also promotes “negotiation” between stakeholders is necessary to support the desired transformation.

The level of participation is important not only for identifying the values of the stakeholders but also for empowering them and increasing awareness of their role in the energy system transformation. Although challenging, Helmholtz must aim to achieve the highest level of interaction between scientific and social knowledge. The analysis of Helmholtz studies shows that the level of participation is similar to that observed in the studies from the literature search. The tendency towards low levels of participation in both cases could be a decision of the authors based on the relevance of integrating stakeholders at specific stages [60] and/or resource limitations [29].

Sensitivity

A topic only briefly touched upon so far is sensitivity analysis. A thorough examination of this topic would require a separate article. Nevertheless, it is worth providing a brief overview in this article.

Depending on the school of thought of the respective study authors, there are different approaches to addressing sensitivity. In MCDA, a distinction is made between external and internal uncertainty [111]. Internal uncertainty refers to the structure of the model and its judgment-based inputs (e.g., weighting factors). External uncertainties refer to aspects that are not controlled by the modeling practitioner (e.g., oil price fluctuations). Sustainability assessment practitioners often follow the customs of their field of research. For example, in LCA, Rosenbaum et al. [112] define uncertainty as “... the degree to which we may be off from the truth”. In a strict sense, this does not include variability, i.e., the possible difference between two or more things, for example, the height of male persons in Germany. In LCA, sensitivity can address uncertainty as well as variability, where “the variation of an input parameter or a choice (e.g., time horizon in the functional unit) leads to variation of the model result.” [112]. This can either be addressed by a local sensitivity analysis, when just a single parameter is changed, or a global sensitivity analysis, when several parameters are changed simultaneously. Uncertainty can also arise for the model itself, scenarios, or relevance of selected indicators.

These considerations can lead to very different approaches when it comes to sensitivity analysis, for example, Monte Carlo simulations for input parameters or fuzzy sets for weighting factors. This might also mean excluding certain criteria or applying only one criterion for the analysis. As mentioned in the discussion of the applied MCDA methods for Helmholtz studies, simpler methods are preferred, such as equal weighting. The most commonly applied analysis was, therefore, a percentage change of weighting factors [29, 58, 59, 62, 64, 65, 69–71]. Other studies [37, 63, 66, 67] developed alternative scenarios with more extreme conditions to test the sensitivity of the results to the weighting process. McKenna et al. [56], who have a strong background in MCDA, looked at intervals for the elicited weighting factors to test their sensitivity. Another approach for testing the derived weighting factors was pursued by Naegler et al. [60], who backed up their qualitative DCE with a quantitative focus group. All these analyses refer to the sensitivity of the preference mode. Only three studies [29, 58, 64] also looked at the sensitivity of the input model, calculating sustainability criteria and indicators either by the simple percentual variation of input parameters [29,

64] or using a Monte Carlo simulation [58]. Based on this review, it is clear that MCDA practitioners within Helmholtz cover the basics when it comes to sensitivity analysis. However, other research groups focusing on MCDA are further ahead, using a multidimensional sensitivity analysis, for example [113].

Limitations

This paper is focused on analyzing studies of the Helmholtz Association on the sustainability assessment of energy technologies that integrate MCDA. Restricting the analyzed studies to a certain group of authors in Germany limits the variety of studies analyzed. Only a small number of the most popular MCDA methods were applied, while more advanced methods, for example, in the field of fuzzy sets or sensitivity analysis, were not adopted and are, therefore, not discussed in detail here. However, by not having to analyze more than 100 publications, this enabled an in-depth examination of the Helmholtz studies—for example, identifying which stakeholders were integrated into the MCDA process and why. Furthermore, ongoing research on LCSA studies that use MCDA clearly shows that LCSA practitioners tend to focus on a small number of MCDA methods and repeat similar mistakes discussed in this paper [114].

Applying MCDA for sustainability assessment throws up a number of discussion points. To ensure a manageable scope in this paper, we focused on criteria selection, the choice of methods for weighting and aggregation, and stakeholder integration. We made this selection both to cover a wide range of aspects occurring in sustainability assessments with MCDA, because these are the most important aspects. Based on the discussions in this paper, we were also able to analyze further aspects, for example, the normalization method for certain MCDA structures, the role of decision-makers in scientific papers in the field of sustainability assessments with MCDA, and the depiction of MCDA results.

This paper did not delve into the energy technologies and systems investigated by the Helmholtz studies. The term “energy” was only used to limit the number of publications so as to perform an in-depth analysis. This paper is clearly focused on the application of MCDA for sustainability assessments and its implications. Other review papers address specific technologies, such as Simsek et al. [84] on concentrated solar power, Eroglu et al. [83] on wind energy, and Martin-Gamboa et al. on energy systems [88]. Furthermore, there are countless other review articles dedicated to energy technologies focusing on technical, economic, or environmental aspects which do not include MCDA.

Conclusion

MCDA for sustainability assessment provides important insights for the energy system transformation goals pursued by the Helmholtz Association. Twenty Helmholtz studies published in the last 7 years were analyzed against the capabilities of MCDA for sustainability assessment as well as existing case study literature to identify best practices, challenges, and opportunities for improvement. The assessment focused on three key aspects of MCDA sustainability assessment in the context of the energy system transformation: selection of criteria and indicators, choice of MCDA methods, and stakeholder integration.

For criteria selection, future work needs to address the relevance of criteria, the handling of qualitative data, issues of practicability, and the influence of underlying sustainability concepts. It would be desirable to thematically enhance, broaden, link, and adapt criteria and indicators according to the particular societal context in a transparent and changeable way. In addition, the following points should always be addressed:

- The applied sustainability concept should be mentioned, as it can influence indicator selection and MCDA method selection.
- A distinction should be made between indicators and criteria.
- An explanation should be given as to why indicators and criteria were chosen.

The analysis of MCDA methods in Helmholtz studies reveals both recommendable practices and significant areas for methodological refinement. While the selection of methods reflects practical considerations, such as usability and tool support, compliance with methodological guidelines is often insufficient. Addressing these gaps will require enhanced methodological training, improved stakeholder involvement in weight elicitation, and greater transparency in criteria selection and results presentation. By leveraging the extensive range of available MCDA methods, future studies can achieve more robust and context-sensitive sustainability assessments. With respect to methods for weighting factor elicitation, the analyzed literature review articles do not explore the full potential of methods available in this field. Further research is, therefore, needed to incorporate methods for subjective weighting methods that are simpler than AHP, such as the best–worst method and objective methods [115].

Active stakeholder integration is rarely used within Helmholtz MCDS activities due to a lack of time, resources, and expertise. In cases where stakeholders are involved, different approaches are used, making it difficult to draw a general conclusion or make a comparison.

Further effort is needed to systematically integrate stakeholder values into the MCDA process. This integration should aim to identify individual values while allowing them to interact with different values in a meaningful way. A combination of existing theories and the principles of inclusivity and accessibility must be considered when designing participatory processes. In this way, different formats are used for different stakeholders, considering, for example, their location, level of information, education, and age.

All three analyzed aspects of the MCDA process for sustainability assessments can benefit from considering guidance from other research fields, for example, operational research, sustainability science, and social sciences. Drawing on this guidance can help in broadening the scope of criteria and indicators, choosing an appropriate aggregation method, and integrating stakeholders. This stresses the importance of interdisciplinary work in the context of sustainability assessment not only for the quantification of indicators but for the whole process.

Abbreviations

AHP	Analytical hierarchy process
BESS	Battery energy storage system
BEV	Battery–electric vehicle
C2C	Cradle-to-cradle
CapEx	Capital expenditure
DCE	Discrete choice experiments
DCM	Deck-of-cards method
ELECTRE	Elimination Et Choix Traduisant la Réalité
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCR	Frequency containment reserve
GDN	Group decision and negotiation
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment
LCIA	Life cycle impact assessment
MADM	Multi-attribute decision-making
MAMCA	Multi-actor multi-criteria analysis
MAVT	Multi-attribute value theory
MCDA	Multi-criteria decision analysis
MCDA–MSS	Multi-criteria decision analysis–methods selection software
OpEx	Operational expenditure
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluation
PSILCA	Product social impact life cycle assessment
PtH	Power-to-heat
PtH ₂	Power-to-hydrogen
SDG	Sustainable development goal
SMART	Simple multi-attribute rating technique
TBL	Triple bottom line
TOPSIS	Technique for order of preference by similarity to ideal solution
WSM	Weighted sum method

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13705-025-00546-8>.

Additional file 1.

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Author contributions

CW: conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. LME: methodology, investigation, writing—original draft, and writing—review and editing. MH: methodology, investigation, writing—original draft, writing—review and editing. MT: methodology, investigation, data curation, and writing—original draft. HW: methodology, investigation, data curation, writing—original draft, and writing—review and editing. UBD: supervision and investigation

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Consent for publication

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