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MCDA for sustainability assessment

– insights to Helmholtz Association activities

Working Paper

Helmholtz Working Group MCDA for Sustainability Assessment

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Abbreviations

AHP	Analytic hierarchy process
ANP	Analytic network process
BESS	Battery storage systems
BEV	Battery electric vehicles
CA	Conjoint analysis
DC	Decentralized grid
DCE	Discrete choice experiments
DST	Decision support tool
ELECTRE	Elimination Et Choix Traduisant la realité (elimination and Choice Expressing the Reality)
EPV	Environmental performance value
ETS	Energy time shift
F-AHP	Fuzzy - analytic hierarchy process
FCEV	Fuel cell electric vehicles
F-PROMETHEE	Fuzzy - Preference Ranking Organization Method for Enrichment Evaluation
GHG	Greenhouse gas
HILCSA	Holistic and integrated life cycle sustainability assessment
ICEV	Internal combustion engine vehicles
ICoS	Integrative Concept of Sustainable development
LCA	Life cycle assessment
LCC	Life cycle costing
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LIB	Li-Ion batteries
LVL	Laminated veneer lumber
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADM	Multi-attribute decision making
MAUT	Multiple attribute utility theory
MAVT	Multiple attribute value theory
MCDA	Multi-criteria decision analysis
MCM	Multi-criteria Mapping
MILP	Mixed-integer linear programming
MODM	Multi-objective decision making
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments
OWA	Ordered weighted averaging
PAPRIKA	Potentially All Pairwise Rankings of all Possible Alternatives
PbA	Lead-acid
PC	Pairwise comparison
PMCA	Participatory multi-criteria analysis
PR	Primary regulation
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PV	Performance value
RES	Renewable energy sources

SAW	Simple additive weighting
SDGs	Sustainable development goals
S-LCA	Social - life cycle assessment
SMART	Simple multi-attribute rating technique
SMCE	Social multi-criteria evaluation
TCO	Total Cost of Ownership
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology readiness level
VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje (Multi-criteria optimization and compromise solution)
VRFB	Vanadium redox flow
WES	Wind energy support
WSM	Weighted Sum Method

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1. Introduction

Decision-making with regard to sustainability assessment of technologies and systems is complex due to sometimes conflicting goals (e.g. low costs for end users, minimum environmental impact, maximum social acceptance) and requires an integrated consideration of economic, environmental and social criteria. Beside this, decision making has also to account aspects that emerge from the embedment of these systems within a socio-technical system. Sustainable energy systems are one of the major and pressing challenges of society, science and industry. In this regard, the Helmholtz research program Energy System Design[1] (ESD) aims to support the transformation of energy systems through the development of methods to design, validate and assess societally-feasible transformation pathways (Topic 1 "Energy System Transformation").
From several approaches and methodologies available to conduct sustainability assessment, multi-criteria decision analysis (MCDA) methods have been recognized as a powerful and – in the field of energy – frequently applied supporting tool given its flexibility and the possibility to organise available information supported by the integration of relevant stakeholders [1]. Decisions made through MCDA are transparent and justifiable if they are documented and traceable. By applying MCDA methods for sustainability assessment of (energy) technologies, an integrated, i.e. simultaneous consideration of economic, environmental social and also further criteria and indicators, if considered necessary, is possible. With the MCDA approaches, the preferences of different stakeholders can be included and made visible in the assessment process. In order to make the degree of robustness and uncertainties of the results visible, the multi-criteria evaluation can be coupled with sensitivity analyses. This allows, for example, to reveal and evaluate the influence of different weightings of criteria and of the number of technology options on the results.
Several studies have been dedicated to find the best approach to assess different technologies using MCDA methods in different contexts. These efforts resulted in a great deal of strategies and approaches; however, in the context of sustainability assessment there is need for improvement/further elaboration in several respects: the identification and application of sustainability criteria and indicators that better address the socio-technical characteristics of technologies and systems, accordingly enhanced or modified indicator analysis and MCDA methods (selection and implementation), and suitable approaches for stakeholders' integration.
This Working Paper aims to compile and reflect previous and on-going work within the Helmholtz Association related to MCDA, in particular, to present use cases and key methodological aspects. It has a focus on (but is not limited to) energy technologies and systems and is mainly based on the presentations held at the online workshop "Multi criteria decision analysis for sustainability assessment of energy technologies and systems". The workshop was organized within the Helmholtz program ESD Topic 1 activities and took place on November 22nd, 2021. It can therefore be seen as the starting point i.e. basis of the Helmholtz Working Group on MCDA for sustainability assessment (subsequently referred to as Helmholtz Working Group MCDA).

[1] https://www.helmholtz.de/en/research/research-fields/energy/energy-system-design/

2. MCDA for sustainability assessment

Authors: Laura Mesa Estrada, Martina Haase, Christina Wulf, Manuel Baumann

This chapter presents relevant concepts associated to the implementation of MCDA- assisted sustainability assessment.

2.1 Sustainability assessment

The definition of the sustainability concept that shapes the assessment approach is a basic requirement to conduct sustainability assessment [2]. The most common definition of sustainable development is the one presented in the Brundtland Report *"Our common future"* released in 1987 which states: *"Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs".* Since then, several definitions resulted from the effort of different authors and institutions to better describe what sustainability means in a given context, e.g.:

- The triple bottom line model, i.e. economic, ecological, and social sustainability [3],
- the Sustainable Development Goals (SDGs) [4] or
- the Integrative Concept of Sustainable development (ICoS) [5].

Sustainable development of economic sectors as complex socio-technical systems embedded in the environment, cannot take place on a technical level alone, but requires transformations at the economic as well as the social level. For this reason, it is necessary that technology assessment is oriented towards comprehensive principles and values of sustainability.
Kopfmüller, J. and Rösch, C. [2] suggest that in order to contribute in the social-learning and decision-making processes, sustainability assessment must be conducted in an integrative manner aiming at the following conditions:

- Interdisciplinary analysis of relevant aspects within sustainability dimensions, requiring systemic consideration and application of quantitative, qualitative, model-based and non-model-based methods.
- Active participation of stakeholders in the whole process.
- Consideration of relevant spatial and temporal scales.
- Analysis of interactions between criteria or indicators, e.g. in order to at least disclose conflicts between criteria.

2.2 MCDA-assisted sustainability assessment

MCDA methods can be divided into Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). In the context of decision-making for sustainability, MADM is preferred since it allows to choose from a finite number of well-defined alternatives and criteria; whereas in MODM the optimization problem is subject to a set of constraints (maximization and minimization of objectives) that can result in a large number of feasible alternatives that are difficult to handle by decision-makers [6]. MCDA methods have a flexible (and often complex) structure that makes it difficult to find a standard procedure for their application [7]; however, in a general context, MCDA applications include commonly the following components/steps:

- problem definition,
- alternatives selection,
- criteria selection,
- scoring alternatives and criteria weighting, and
- preference aggregation.

Decisions made through MCDA are transparent and justifiable because they are documented and traceable. These advantages have made MCDA methods one of the predominant techniques to support sustainability assessment in the context of energy systems and technologies [1, 8]. Despite the benefits of MCDA on decision-making processes, its application on technology assessment is still limited by the demand on deep knowledge on different scientific disciplines in the field of economy, ecology, social, as well as the large amount of efforts and time to execute relevant steps, e.g. identification of relevant stakeholders and execution of participatory formats [7].

The following paragraphs describe three fundamental components of MCDA-assisted sustainability assessment: sustainability criteria, MCDA methods and stakeholder's integration.

Sustainability criteria

The selection and definition of criteria and indicators should be guided by the sustainability concept applied, the substantiating sustainability principles, and the type of decision problem [6, 9-11]. Despite its importance, several authors report that the selection of criteria for MCDA-assisted sustainability assessment of (energy) technologies suffers from lack of scientific foundation, in particular with respect to addressing socio-technical characteristics suitably, and lack of consensus between the stakeholders, e.g. [12], [13].

MCDA methods

Selecting an adequate MCDA method to support sustainability assessments is an important concern common to all areas of application. In general, for not sustainability-related applications, MCDA method selection depends on the decision problem and the type and degree of information available, e.g. criteria structure, scale, uncertainties, etc [14, 15]. In sustainability assessment applications, additionally to the already mentioned criteria selection, MCDA methods should ideally fulfil the following pre-requisites: capability to handle qualitative and quantitative information, treat weights as importance coefficients, handle uncertainty, sensitivity analysis, robustness verification, good graphical representation, ease of use (simplicity), learning dimension and be aware of compensation issues [16-18]. Kumar, A., Sah, B. [19] present in their review the following classification of methods commonly used in energy decision-making studies (Figure 1). Table A1.1 in Annex 1 presents a table with advantages and disadvantages of some of these MADM methods.

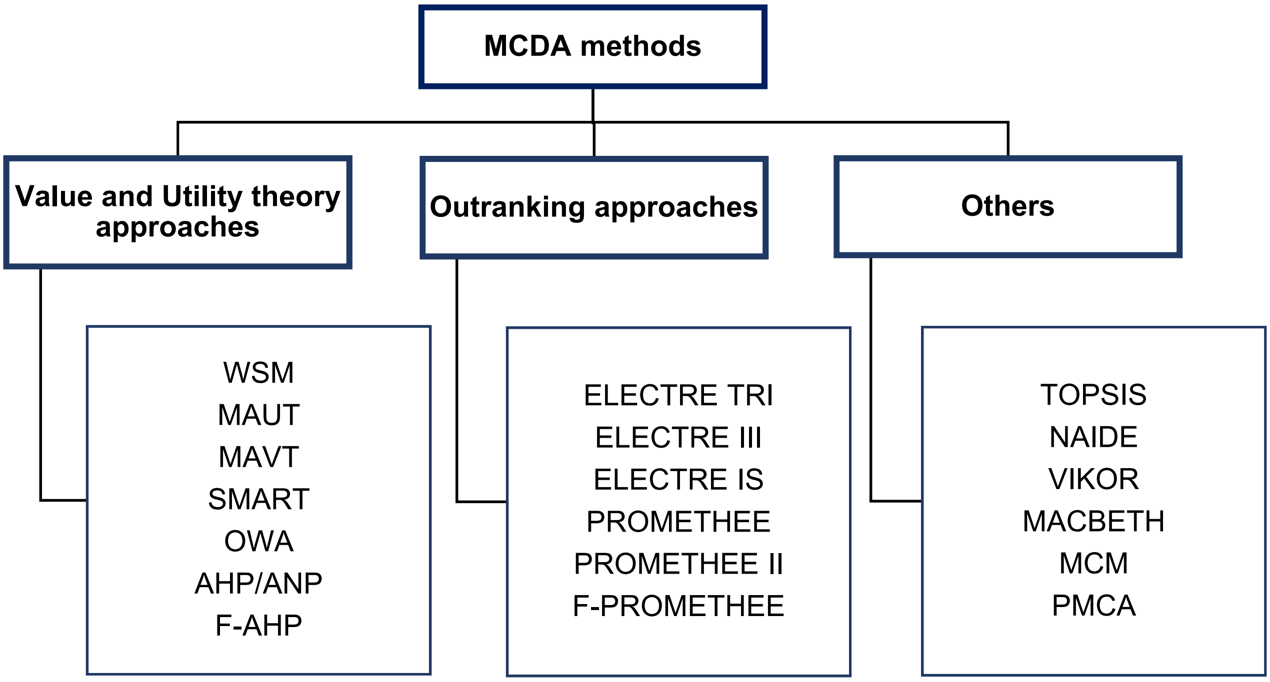


Figure 1. MCDA methods classification based on [19, 20].

Stakeholders' integration

Several participation formats exist that can be used within MCDA methods to integrate stakeholders' preferences, e.g. surveys, questionnaires, workshops. Depending on the scope of the project and the purpose to integrate stakeholders into decision-making processes, different forms and levels of participation are defined.

Table 1 compares the levels of stakeholders' participation according to Citizen Science research and decision-making processes using MCDA:

Table 1. Levels of stakeholders' participation, based on [21], [22]

Level of participation	Participation pyramid Citizen Science [21]	Participation of stakeholders in MCDA [22]
Low	Passive observation-communication of research results	MCDA process done by experts
Moderate	Active participation	**Limited participation** of stakeholders to certain phases and weight elicitation is realized **without personal support** using e.g., a questionnaire
High	Co-production	Stakeholders are involved in some phases of the process, **personal interaction** in weight elicitation and analysis of the results, group discussions of the results.
Very high	Co-design	Stakeholders are **actively involved** in different phases of MCDA, and there are **face-to-face** personal or small group computer-aided interviews and a seminar after the interviews.

Ideally, the level of participation of stakeholders in sustainability assessment would be *very high* [22, 23]. However, given the complexity of this task and the lack of consolidation of the procedures (or common understanding) among practitioners, the use of participatory formats in MCDA- assisted (sustainability) assessments is limited, e.g. with respect to weighting of criteria only [24, 25] or weighting of criteria and criteria selection [26, 27].

3. MCDA activities of Helmholtz Institutes

In this section, selected activities, methodological aspects and/or use cases (methods, specific work, etc.) of DLR (VE), FZJ (IEK-STE), KIT (ITES and ITAS), and UFZ (Department Bioenergy) are shown. The presented work is structured alongside the three topics "Sustainability Criteria/Indicators", "MCDA Methods" and "Stakeholder Integration" (if possible) and highlights respective challenges. Alongside this chapter, a Working Table (see Supplementary Material) was completed in which authors provide more details about the work presented in this chapter or add additional case studies.

3.1 DLR-VE

Authors: Matthias Oswald, Urte Brand-Daniels, Jens Buchgeister, Tobias Naegler

DLR-VE is using the MCDA approach and MCDA methods to combine the different sustainability dimensions within one assessment to identify, assess and analyse the economic, environmental and social impacts of (future) energy technologies, considering their entire life cycle and feedback effects. In this context, the DLR-VE usually use the term of "multi-dimensional assessment" in order to emphasize that not only criteria in one dimension but criteria in several dimensions will be considered. This is close to what we refer to as the MCDA approach in this publication. In this chapter some of the current DLR-VE research, approaches and challenges are described by means of a specific case study.

Case study 1: Multidimensional assessment of passenger cars: Comparison of electric vehicles with internal combustion engine vehicles (DLR1)

Original authors and contributors: Matthias Oswald, Urte Brand-Daniels

In this study Internal Combustion Engine Vehicles (ICEV) were compared to Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV) by assessing various environmental, economic, technical and social criteria [28]. The aim of this study was to assess the sustainability of the vehicles as well as to apply a MCDA method to integrate the different indicators and aggregate them to an overall assessment. In total, 9 different alternatives were assessed, because different energy mixes for charging the BEV as well as different hydrogen production pathways were considered.

Criteria Selection

The first step comprised the development of a set of assessment criteria. The study aimed at a comprehensive, but also practical selection of criteria. The selection was done by the authors based on a literature review. As basis, the UNEP/SETAC guidelines for a life cycle sustainability assessment were used, which resulted in over 300 possible indicators for 120 criteria. In the next step, a bottom-up approach was used, identifying the relevant criteria for a comparative assessment of the selected alternatives. Based on [29] and [30] , the following requirements were used to select the criteria set: relevancy, holistic set, data quality, comparability and usability. In the end, seven environmental indicators were selected, based on the life cycle impact assessment method ReCiPe, as well as three economic and three technical/social indicators. In the case of the environmental dimension, Bauer, C., Hofer, J. [31] was used as data source. In order to calculate the economic indicators, the method of Total Cost of Ownership (TCO) was applied. In the case of the social dimension, three rather technical indicators with relevance from a user perspective, were included (Fuelling/Charging time, Fuelling/Charging points in Germany, Driving Range).

MCDA Method

In order to integrate and aggregate the results of the indicators, several MCDA methods were considered and compared: AHP, ELECTRE III, MAUT, TOPSIS and PROMETHEE. Finally, PROMETHEE I & II were selected, because PROMETHEE does not allow trade-offs between criteria and dimensions, as required by the strong sustainability concept. Additionally, since there was no direct integration of stakeholders, participatory methods like AHP were identified as not suitable. Lastly, PROMETHEE allows to integrate several weighting scenarios, which was used to show the influence of different weighting factor. Therefore, the software of VisualPROMETHEE was used to carry out the assessment.

Stakeholder Integration

In this study, no stakeholders were directly integrated in the assessment, but it was tried to cover different user types by different weighting distributions of the indicators (e.g. users with high environmental awareness). Thus, different weighting scenarios with varying weighting distributions as well as nine preference scenarios were defined. The preference scenarios included varying preference and indifference thresholds for the preference function, a part of the PROMETHEE method.

As preference function, a linear preference function with an indifference area was chosen with different percentage-based thresholds. In one preference scenario the uncertainty classification for impact categories of the ILCD was used to specify the thresholds, while the other scenarios were used as a sensitivity analysis to show the influence of the preference function [32].

As mentioned above, the weighting scenarios were based on different sustainability goals, e.g. intergenerational or intragenerational justice, or on the economic and technical performance from a car user's perspective. The weighting factor ranged between very important (factor 2), important (factor 1) and not important (factor 0), depending on the respective goal of the scenario. The six weighting scenarios and 9 preference scenarios were combined for a total of 54 scenarios.

Results

Even though 54 different scenarios were used, the results show a rather robust ranking of most of the alternatives, as seen in Figure 2. However, it can be argued that a wider range of weighting factors could be used. Nevertheless, the analysis of the scenarios shows, that BEV vehicles using renewable energy are ranked as the best alternatives, while FCEV are mostly ranked last. It also shows the importance of using renewable energy for BEV charging as well as for the hydrogen production.

	Alternatives								
Rank	BEV_wind	BEV_PV	ICEV_diesel	ICEV_gas	FCEV_wind	FCEV_PV	BEV_EU-mix	FCEV_NG-SMR	FCEV_EU-mix
1	71.11%	0.00%	28.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	13.33%	62.22%	8.89%	15.56%	0.00%	0.00%	0.00%	0.00%	0.00%
3	15.56%	6.67%	57.78%	15.56%	4.44%	0.00%	0.00%	0.00%	0.00%
4	0.00%	31.11%	0.00%	51.11%	13.33%	4.44%	0.00%	0.00%	0.00%
5	0.00%	0.00%	4.44%	13.33%	57.78%	0.00%	24.44%	0.00%	0.00%
6	0.00%	0.00%	0.00%	4.44%	24.44%	48.89%	13.33%	8.89%	0.00%
7	0.00%	0.00%	0.00%	0.00%	0.00%	31.11%	26.67%	42.22%	0.00%
8	0.00%	0.00%	0.00%	0.00%	0.00%	15.56%	35.56%	48.89%	0.00%
9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%

Figure 2. Rank distribution of all alternatives based on the combination of all six weighting scenarios and all nine preference scenarios [28].

Case study 2: Multidimensional sustainability assessment of different national energy system transformation pathways (DLR2)

Original authors and contributors: Jens Buchgeister (ITAS), Tobias Naegler (DLR), Heidi Hottenroth (INEC), Ricarda Schmidt-Scheele (ZIRIUS), Wolfgang Hauser (ZIRIUS), Oliver Scheel (ZIRIUS)

In this case study an approach for an integrated and interdisciplinary sustainability assessment of national energy system transformation pathways is presented. It integrates energy system modelling with a multidimensional impact assessment that focuses on life cycle-based environmental and macroeconomic impacts. The approach couples energy system models with life cycle inventory databases in order to assess life-cycle based environmental impacts and concatenates energy system models with macroeconomic models in order to assess macroeconomic effects of different transformation pathways. Then, stakeholders' preferences with respect to defined sustainability indicators are inquired, which are finally integrated into a comparative scenario evaluation through a MCDA, all in one consistent model-based sustainability assessment framework. This holistic approach is applied to the sustainability assessment of ten different transformation strategies for Germany. Applying MCDA reveals that both ambitious (80%) and highly ambitious (95%) carbon reduction scenarios can achieve top sustainability ranks, depending on concrete design of the underlying energy transformation pathway.
The research questions focus on the variety of these energy transformation pathways:

- How can strategies to transform an energy system towards low CO2 emissions, as formulated in variety of different studies, be compared in terms of their environmental and socio-economic impacts? How can these different strategies obtained with different modelling approaches and different boundary conditions be compared in a fair, unbiased manner?

On the other hand, the research addresses the challenge of integrating various sustainability dimensions, setting the scene for a more genuine sustainability assessment:

- How do variations in technical solutions in these different CO2 reduction strategies influence environmental and (socio-)economic impacts?
- How can stakeholder preferences be integrated into MCDA methods? What influence do stakeholder preferences have on the ranking of scenarios? How can robust results be achieved?

Criteria Selection

For the selection of the relevant and significant sustainability indicators an intensive literature research analysis was conducted. The analysis was systematised on the basis of the following procedure. First, literature was consulted that reflects the international and national discussion in Germany of sustainability or sustainable development in a political and scientific context in order to develop guidelines and frameworks for a sustainability assessment [5, 33-43]. Then the search was concentrated on literature which handles with energy technologies or a sector of the energy system [44-50]. In a further step, literature on the assessment of environmental impacts of products, processes and services was evaluated, as the debate on environmental protection in an industrial society was the precursor to the concept of sustainable development [51-54].

As a result of the literature analysis including the international and national sustainability debate, more than 300 sustainability indicators were available for selection. Therefore, the number of indicators had to be narrowed down on the basis of selection criteria in order to evaluate the different transformation strategies of the energy system of the examined ten energy scenarios ex-post. Based on the selection criteria listed on the left-hand side in Figure 3, a reduction to 23 sustainability indicators was made.

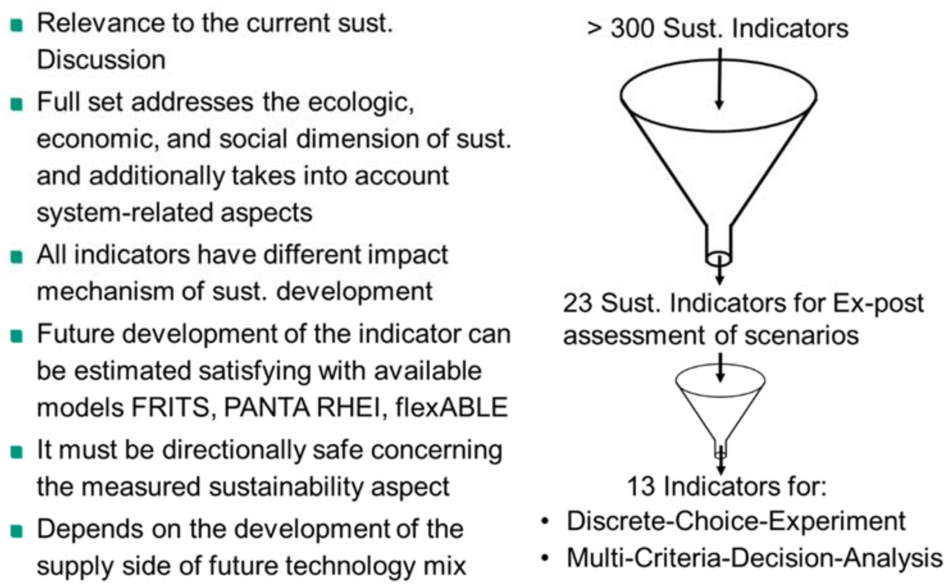


Figure 3. Complete procedure of the selection of sustainability indicators [55].

The full set of the 23 selected indicators is documented in Figure 4.

Category	Sub-Category	Indicator	Unit	Calculated with	Used MCDA	Used DCE	Method/Reference
Ecological	Climate Change	Climate Change	kg CO2 eq.	FRITS	CUM	X	ILCD 2018
	Ecoystem Quality	Freshwater & terr. Acidific.	mol H+ eq.	FRITS			ILCD 2018
		Freshwater ecotoxicity	CTUe	FRITS			ILCD 2018
		Freshwater eutrophication	kg P eq.	FRITS			ILCD 2018
		Marine eutrophication	kg N eq.	FRITS			ILCD 2018
		Terrestrial eutrophication	mol N eq.	FRITS			ILCD 2018
	Resources	Dissipated water	m^3 Water eq.	FRITS			ILCD 2018
		Land use	points	FRITS	CUM	AGG	ILCD 2018
		Fossil energy carriers (CED)	MJ	FRITS	CUM	AGG	ILCD 2018
		Minerals and metals	kg Sb eq.	FRITS	CUM	AGG	ILCD 2018 (updated)
	Human Health	Carcinogenic effects	CTUh	FRITS	CUM	AGG	ILCD 2018
		Non-Carcinogenic effects	CTUh	FRITS	CUM	AGG	ILCD 2018
		Ionising radiation	kg U235 eq.	FRITS	CUM	AGG	ILCD 2018
		Ozone layer depletion	kg CFC-11 eq.	FRITS	CUM	AGG	ILCD 2018
		Photochem. ozone creation	kg NMVOC eq.	FRITS	CUM	AGG	ILCD 2018
		Respiratory effects, inorg.	disease incidence	FRITS	CUM	AGG	ILCD 2018
Socio-Economic		System costs	Bn €	MESAP	CUM	X	
		Gross domestic product	Bn €	PANTA RHEI			
		Structural change	-	PANTA RHEI			
		Regional inequality	-	PANTA RHEI			
	Employment	People in employment	-	PANTA RHEI		X	
		Unemployment rate	%	PANTA RHEI	X		
System-related		Security of electricity supply	-	flexABLE and Tech. Charac.	X	(X)	MCDA: Stirling Index DCE: Expert judgement

Figure 4. Overview of the full set of indicators, as well as the sub-sets used in the discrete choice experiment (DCE) and the MCDA. "AGG" indicates that DCE uses an aggregated indicator for "human health" and "resources". "CUM" indicates that cumulated values (2021–2050) used in the MCDA. References: ILCD 2.0.2018 [53], van Oers: [56], Stirling Index: [35], [55].

It comprises 16 environmental indicators (in the sub-categories climate change, human health, ecosystem quality and resources) that have been compiled for the European environmental footprint version 2 [53]. However, the indicator for mineral and metals resources has been updated, according to [56]. In addition, six socio-economic indicators and one socio-technical "systemic" indicator were selected [35].

Although this full set of indicators is used for the comprehensive impact assessment of transformation strategies for the energy system, it is too comprehensive to be practical for discussions with stakeholders, which took place through focus groups and discrete choice experiments (DCE). Therefore, a sub-set of indicators was selected for the discrete choice experiment which additionally met the following criteria:

- The number of indicators is manageable for discussions with non-experts;
- The indicator relevance is also understandable for non-experts;
- The indicators are relevant for the citizens' daily lives;
- The sub-set of indicators still addresses ecologic, (socio-)economic, and technical dimensions.

The sub-set of indicators used for the discrete choice experiment (DCE) is depicted in column "used DCE" in Figure 4. It comprises the indicator "climate change", the socio-economic indicators "system cost" (as a proxy for consumer prices) and "people in employment", as well as the socio-technical indicator "resilience/security of supply". Finally, the indicators "human health" and "resources" are used in the DCE. Note that more detailed information on human health and resource issues are available from the impact assessment (see column "Indicator" for both sub-categories). However, for practical reasons, in the DCE, only preferences for the aggregated indicators are determined. In contrast to the DCE sub-set, the MCDA sub-set uses six differentiated indicators within the sub-category "human health" and two differentiated indicators within the subcategory "resources", as provided under the environmental footprint life cycle impact assessment method 2.0. Disaggregation of the aggregated preferences for "human health" and "resources" from the DCE was performed using the weighting set provided under this scheme.

MCDA method

At the conclusion of the multi-level scenario evaluation, an attempt is made to rank the scenarios based on the previous impact assessment, along with stakeholder preferences (see sub-chapter *Stakeholder integration* p.21). The MCDA was applied to consider the interests of multiple actors, to include the combination of objectivity (MCDA method) and subjectivity (stakeholder preferences), and user friendliness, which altogether improves the understanding of the assessed alternatives.

In this case study, the weighted sum method (WSM) was used for the assessment. Several studies with a focus on a life cycle-based sustainability assessment of energy systems and technologies use weighted sum methods for MCDA [57-59] because of its simplicity. In WSM, the first step is the normalization of the indicator scores. Here, it was performed by min-max normalization, considering that the lowest possible values for environmental impacts, but the highest possible values for GDP and employment are aimed for. This means the best value in an indicator gets the score of 1, and the worst value gets the score of 0. The values in between are interpolated linearly. The score A_i for alternative i was calculated by multiplying the normalized alternative score for each criterion (a_{ij}) with the criteria weight (w_j). The criteria weight is determined in the stakeholder integration step (*Stakeholder integration* p.21). Subsequently, the multiplied score for each criterion was summarized for all n criteria. The alternative which had the highest total score was the best alternative. The alternative scores a_{ij} result from the impact assessment (results for indicator i and scenario j). The basis for the weights were the ß-coefficients, as a result of the DCE (see sub-chapter *Stakeholder integration* p.21). In order to apply the WSM, resulting weights from discrete choice experiment for the aggregated indicators (“resources” and “human health” (see Figure 4), had to be disaggregated and allocated to the single indicators. Disaggregation of ß-coefficients was performed using the weighting set provided by the EU environmental footprint [60]. To determine the final weighting factors, according to the approach taken by Sala, S., Cerutti, A. K. [60], the ß-coefficients are multiplied with a robustness factor to consider that the methods used to survey (environmental) impacts vary in validity. The robustness of the indicators “unemployment rate”, “resilience” and “system costs” were assessed by expert judgement within the project team.

For environmental indicators and system costs, cumulative values from 2021–2050 were applied, since most of the environmental burdens and costs do not occur in the target year, but over the whole transformation period. Socio-economic and socio-technical indicators were taken from 2050, as their state in the target year is decisive for the assessment. The full workflow of the WSM MCDA-method is presented in the following Figure 5.

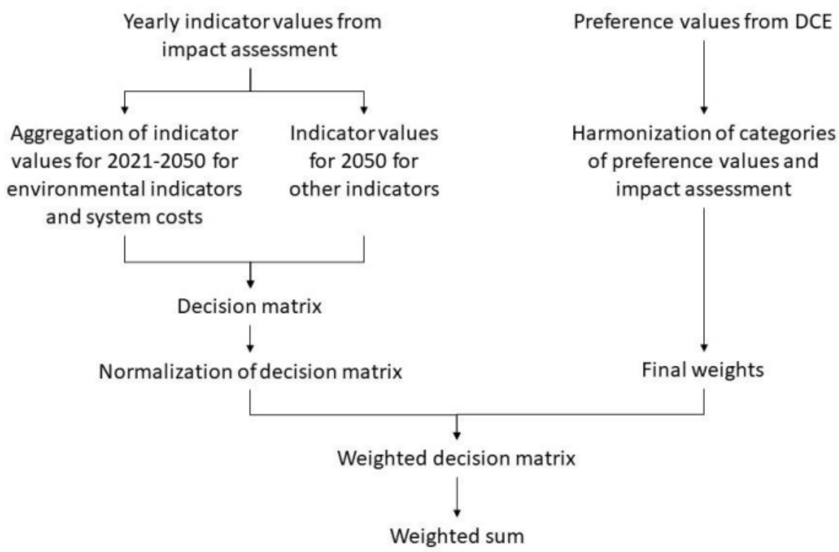


Figure 5. Workflow for the integration of indicator values from impact assessment and preference values from DCE in the MCDA (WSM model) [55].

Stakeholder Integration

In order to gain insights into citizens' preferences regarding future energy systems, a mixed method approach was applied. Qualitative focus groups and a quantitative discrete choice experiment were conducted. While the quantitative analysis grants compatibility and serves as input to the MCDA, the qualitative data enhance the insight in the reasoning of citizens where necessary. The former focused on three core concepts of social sustainability:

- Quality of life—as a totalizing variable to include the degree of fulfilment of multiple diverging lifestyles and their goals found among different societal groups;
- Justice of distribution—as a variable to address the distribution of cost and benefits connected to any scenario to be debated within society;
- Justice between generations—as a variable to give special attention since the worldwide implementation of the "Fridays for Future" movement.

To gather data on these aspects, in-depth focus groups among six groups (in total 63 people) were conducted in two different German cities (Stuttgart and Osnabrück). Here, the participants were not only asked to assess multiple energy technologies along their impact on the three social aspects of sustainability, but also to explain their evaluations and define the three concepts with their own words. This puts emphasis on the strength of qualitative social science - the exploration of complex concepts and their underlying dimensions of meaning to several different individuals. To foster a diverse perspective gained in this measurement, the groups varied in age (young adults, general public and seniors) and were selected in equal gender proportions. The discussion was recorded and later transcribed and analysed with Max QDA software by three different social scientists to ensure inter-coder reliability.
Quantitative data was gathered via DCE [61], where respondents were asked to choose between eight different energy scenarios. DCE have a long tradition in marketing research, where they are used to discover the importance of different traits of a product for consumers' buying decisions [62]. They are seen as a more valid measurement than directly asking for the importance of different characteristics for one's decision [63], and have been applied in energy related research to analyse, e.g., investments in energy technologies [64], nuclear waste storage [65] or wind power developers' perspectives on the effect of support policies [66].

The scenarios in the decision set of this DCE were chosen to represent a variety of energy futures with reduced CO2-emissions, originating from different technologies. The scenarios therefore differed with regard to system costs, employment effects, security of supply, health effects, climate effects, land use and resource depletion. To facilitate the decision between scenarios, they were characterized by their relative effects on these variables compared to the other scenarios in the set (see Figure 6).

Employment	System Costs	Security of Supply	Human Health	Climate Effects	Land Use	Ressource Depletion
−7%	−35%	−19%	−55%	−84%	−91%	−25%

Figure 6. Way of representation of energy scenarios in the discrete choice experiment [55].

For example, the value of −7% for "employment" in Table 2 meant that the scenario discussed here performed 7% worse than the arithmetic means of all scenario values. To facilitate processing of the scenario's performance, these values had been color-coded: more sustainable values by comparison with the alternative scenario with green, less sustainable values with red, equally sustainable values with yellow. In total, 1488 pairwise comparisons were made by 130 interviewees in Stuttgart and Osnabrück. The interviews were conducted online and in workshops in spring 2019 using Qualtrics software.

To account for unobserved heterogeneity, a respective multinomial logit model was applied [67] when analysing data. The utility U of a chosen alternative j for individual n on choice t is given by:

$$U_{njt} = \beta_n \cdot x_{njt} + \varepsilon_{njt}$$

"where β_n is a vector of individual-specific coefficients, x_{njt} is a vector of observed attributes relating to individuals and alternative j on choice occasion t, and ε_{njt} is a random term that is assumed to be an independently and identically distributed extreme value" [68].

To enable direct comparison of the β-coefficients, the indicators have been normalized. The weights passed on to the MCDA equate to the mean of the estimated unconditional β-coefficients corresponding to the normalized indicators x_{njt}.

3.2 FZJ IEK-STE

Authors: Christina Wulf, Florian Siekmann, Christopher Ball

At FZJ IEK-STE we understand MCDA as an inter- and transdisciplinary approach to combine different disciplines, e.g. social science, engineering and economy. In this manner, we identified two guiding principles: 1st The Sustainable Development Goals as guidelines for indicator selection and 2nd PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) as non-compensating outranking method to prevent indicator compensation. Based these principles the following sections present MCDA activities in our institute.

Indicator selection

Original authors and contributors: Florian Siekmann, Sandra Venghaus

Following the definition of a specific goal within a decision-making process, it is essential to develop a set of indicators on which the analysis using an MCDA approach can proceed and the degree of achievement can be measured. A common goal the international community agreed upon and is often underlying activities in research and policy is the pursuit of sustainability. Therefore, the Sustainable Development Goals can serve as guidance and starting point for the selection of indicators. Frequently, this leads to the necessity to account for distinct features and socio-economic characteristics of complex societal systems related indicator frameworks need to address.

In order to identify a suitable set of indicators and develop a comprehensive framework, various considerations must be considered. This includes the need for an exhaustive depiction of the decision problem and a balanced representation of sustainability dimensions. In this connection, approaches based on MCDA illustrated their applicability and usefulness in striving for sustainable development in various geographical and cultural settings [69]. Outranking methods, in particular, have notable advantages here, as they are partially non-compensatory so that weights can be considered as a measurement of importance instead of trade-offs [70]. Further, they allow combining quantitative and qualitative indicators and data sources within one evaluation model. Thus, indicators can serve as an intersection for processing empirical and modelled data gathered throughout research projects and thereby synthesize insights from different disciplines within inter- and transdisciplinary research settings.

The flexibility of MCDA methods further allows involving stakeholders in the process of developing an indicator framework. Inclusive and participatory approaches can support a detailed understanding of the circumstances and enable the utilization of indicators in accounting for the perspectives of affected members within communities. Thereby, it is possible to shed light on a decision problem from different angles. While MCDA approaches and indicator sets can often be applied in a similar manner in various decision-making contexts, specific adjustments with respect to the selected indicators or chosen method may be necessary to account for peculiarities. Applying MCDA approaches in the context of regional or local transformation processes, for instance, entails the need for addressing respective specifies as well as accounting for an appropriate level of granularity and aggregation concerning the selected indicators.

Another aspect of the flexibility of MCDA methods is the possibility of application in a group decision-making context that brings along further considerations for the selection of indicators. Depending on the respective setting and involved stakeholder groups, an increased necessity for communicability can arise, especially in cases where a decision can potentially affect policy decisions. Since several MCDA methods require stakeholders to assign weights to the selected indicators throughout the decision process, a solid understanding of the meaning of an indicator along with its relevance for the desired outcome is essential and might not be equally pronounced among the involved groups. Hence, traceability of how and why indicators are included or excluded in the assessment should be considered. Beyond that, different options to visualize results and the effects of indicators within decision support systems can be beneficial to ensure a common understanding of the multiple facets of a decision problem.

Determination of weighting factors without stakeholder survey

Determining the weighting factors is, arguably, the part of MCDA which is the most uncertain. Usually, the weightings that stakeholders attach to criteria are determined empirically, through, for example, surveys, discrete choice experiments and focus groups [55, 71]. However, there are occasions where it is not possible or optimal to empirically investigate preferences, due to methodological concerns about the problems of stated preferences [72, 73], or the prohibitive cost of surveys and workshops, or, perhaps, the dynamic nature of weightings over time.

Reverse MCDA

Original authors and contributors: Christopher Ball, Stephan Vögele, Wilhelm Kuckshinrichs

"Reverse MCDA" uses (i) the performance matrix for different alternatives and (ii) the actual revealed stakeholder preferences to uncover the weightings. In a recent paper [74], sales figures from 2020 for different types of vehicle (battery electric, internal combustion engine and hybrid) are used, corresponding to the revealed preferences of consumers, combined with the performance matrix, detailing the characteristics of these vehicles, to estimate the weightings. Revealed preferences show what consumers actually choose and this avoids the unreliability of stated preferences, where actual purchasing decisions may diverge from the preferences given in surveys.

Under this reverse MCDA approach, weightings are not treated as fixed, but dynamic, therefore, it is possible, for example, to investigate how high the weighting for a particular criterion (or constellation of criteria) would have to be to shift consumers' preferences from one alternative to another. This can also be done with an alternative's performances on particular criteria. For example, in the example of different mobility technologies, it is possible, using this reverse MCDA approach, to investigate how high consumers' weighting for environmental protection would have to be to shift their preferences from ICEs to hybrids or from hybrids to battery electric vehicles. Likewise, it would be possible to change the cost competitiveness of electric vehicles compared to conventional vehicles whilst increasing consumers' weighting for environmental protection and to investigate the extent to which this performance-weighting constellation can shift preferences from one mobility technology to another. In treating the stakeholder weightings (and certain criteria) as dynamic, the reverse MCDA approach can offer policy makers insights into the parameters or weightings that they need to influence if they want to shift stakeholder preferences and, for example, promote the diffusion of an alternative technology.
This approach also allows the inclusion of interaction among the stakeholders - i.e. to assess how the position of one stakeholder regarding a particular alternative influences the preferences of the other stakeholders. For instance, [74] consider the effect of government and vehicle manufacturer support for electric vehicles on preferences of consumers - i.e. the support of the government leads to subsidies for electric vehicles which, in turn, changes their characteristics (better performance on price). From the perspective of vehicle manufacturers, if consumers support electric vehicles, this leads to increased demand and drives learning effects which feeds into cost reductions. To generate results, FastPyMCDA[2] is used and this leads to pictures which visually represent the effect of weightings under a constellation of characteristics. These pictures can be easily interpreted by, e.g. policy makers, and this enhances the usability of this MCDA approach.

[2] https://github.com/mgrajewski/FastPyMCDA

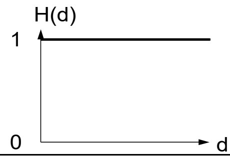
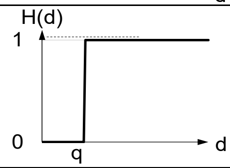
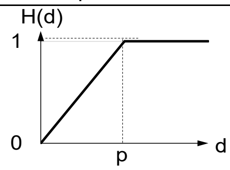
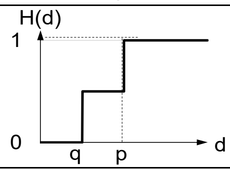
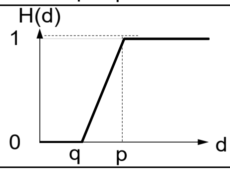
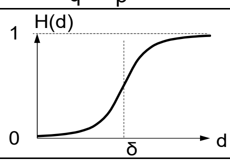
The availability of suitable data, from which revealed preferences can be identified, as described for the case of mobility technologies, is crucial for the reverse MCDA approach to work.

Thresholds in PROMETHEE for uncertainty integration

Original authors and contributors: Christina Wulf, Petra Zapp, Wilhelm Kuckshinrichs

For PROMETHEE and other outranking methods it becomes of utmost importance to clarify when results become preferable. Thus, thresholds are commonly used to prevent decisions based on results that are actually indifferent between the analysed options. In [75] we presented a new approach to identify and quantify such thresholds based on uncertainty of Life Cycle Impact Assessment (LCIA) methods. PROMETHEE introduces six preference functions for these thresholds, Table 2 [76]. They translate the difference between the indicator results obtained by two alternatives into a preference degree ranging from zero to one. Strict preference (one), indifference (zero) and the zone of weak preferences (between zero and one) are denoted. In this way, the user can implement their opinion what preference actually means. Based on the analysed indicator different functions have their purpose regarding the level of uncertainty and the nature of the values, i.e. qualitative, discrete or continuous. The values of the here practiced LCSA are continuous, resulting in the suitable linear preference function No. 5 [77]. Common thresholds include several aspects of uncertainty based on, e.g. inventory and impact assessment. Instead of defining absolute thresholds q and p for each indicator individually, it is convenient to use the concept of relative thresholds. However, using these default values has a certain degree of arbitrariness [78] and LCSA practitioners know that for some impact categories uncertainties are higher than for others. In the case study on finding a preferred location for sustainable industrial hydrogen production, comparing three locations in European countries the new thresholds based on LCIA uncertainty were applied. The new thresholds had a large impact on S-LCA indicators. Only eight out of 26 indicators showed strict preference in the case study. However, also for the LCA results only 47% (worst case) of the indicators showed strict preference. The comparison of the newly developed specified

Table 2. Six types of preference functions for criteria, based on [76].

1.	Usual criterion	
2.	Quasi-criterion	
3.	Criterion with linear preference	
4.	Level criterion	
5.	Criterion with linear preference and indifference area	
6.	Gaussian criterion	

q: indifference threshold ; *p*: strict preference threshold; *δ*: tipping point thresholds based on LCIA uncertainty with default thresholds provided important insights of how to interpret the LCSA results regarding industrial hydrogen production.

3.3 UFZ

Authors: Walther Zeug, Alberto Bezama

The relevant activities at UFZ for this purpose are being carried out at the SABE research group[3] (System Analysis of the BioEconomy) at the Department of Bioenergy which is overall engaged in developing frameworks for a sustainable bioeconomy [79]. The SABE group follows the vision to support the transition towards a bio-based economy by understanding and evaluating the bioeconomy system under a life cycle perspective. As a goal, we development and apply of a toolbox of life cycle methods to assess the potential impacts of technological concepts at different geographical scales (Figure 7).

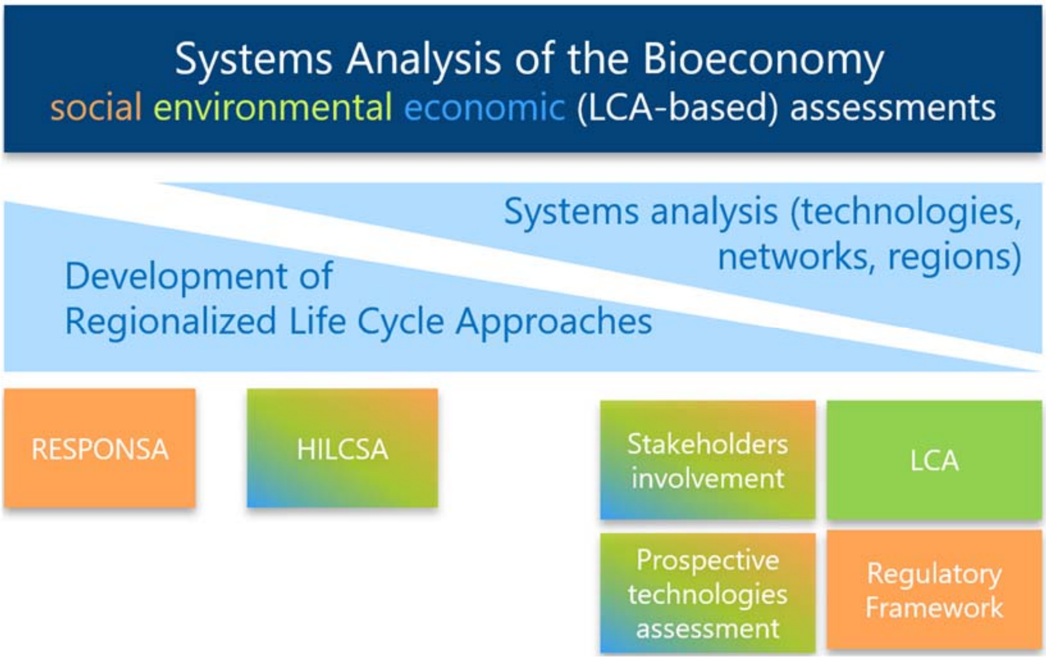


Figure 7. Methods and models developed and applied by the SABE research group.

Systematic stakeholder & MCDA involvement started in 2012 with RESPONSA and SUMINISTRO as a social LCA method addressing stakeholders within the Spitzencluster BioEconomy in central Germany [80-84]. In the meanwhile, methods and models are being expanded and further developed, applying them more broadly in different case studies, aligned with the POF4 activities (in particular, D5.18, D5.21). The methods and models aim to answer research questions in three fields of action (colours according to Figure 7):

[3] https://www.ufz.de/index.php?en=37105

Societal:

- How is bioeconomy being influenced by regulatory framework? What are policy conflicts of BE?
- Which stakeholders play a role in bioeconomy development and how?
- What are the potential social and socio-economic risks and chances of bioeconomy development?

Environmental:

- What are the global and regional environmental effects of the bioeconomy development?
- What is the contribution of bio-based concepts/technologies/products on the reduction of GHG emissions in relevant sectors to the bioeconomy?

Integrated assessments:

- What are environmental, social and economic risks and challenges of bioeconomy development?
- What are the synergies, trade-offs and contradictions in technologies and political economy of bioeconomy?

In the following, we show the application of MCDA methods for a recent application within the SYMOBIO project (Systemic Modelling and Monitoring of the Bioeconomy) [85-87] and its integration into the innovative holistic and integrated life cycle sustainability assessment (HILCSA) [88-90].

Stakeholder participation in SYMOBIO

In the context of the SYMOBIO project - as the development of scientific basics for a systemic and multicriteria monitoring and modelling of the German bioeconomy in an international context, in line with the SDGs - our objective was to capture, map, and analyze the societal interests and perceptions of the most relevant stakeholder groups of BE in Germany. The assessment was done empirically by means of the SDGs, to provide indications on key aspects and potential indicators, and to gain insights into underlying perceptions helping to clarify the constellation of visions and narratives [86]. This Stakeholder analysis explored configurations of issues of the bioeconomy from multiple (or at least different) perspectives and delivered critical reflections on social preferences. For this activity we employed the Social Multi-criteria Evaluation (SMCE) method, conducting the following steps:

(i) Identify and classify relevant stakeholders

(ii) Define the problem

(iii) Create alternatives and define evaluation criteria
(iv) Assign values to criteria in a multi-criteria impact matrix (v) Select a multi-criteria evaluation method
(vi) Assess social actors' preferences, values, and weights
(vii) Apply the model through a mathematical aggregation procedure
(viii) Conduct social analysis and discuss the results to check the robustness of the analysis.

The highlights/summaries of these steps are described as follows:

(i) Three stakeholder-workshops were held independently, according to the identified stakeholder-groups (shg): Society (Soc), where 15 institutions participated, representing NGOs, journalists, and social foundations; Business (Bus), with the participation of 21 representatives of the industrial sector and other commercial stakeholders; as well as Science (Sci), which gathered 28 representatives of national and non-profit research institutes.

(ii – iii) The stakeholder-groups had to classify the SDG sub goals according to their relevance to bioeconomy monitoring. To initiate discussions within a stakeholder group, to gain a differentiated picture, and to reduce complexity of the SDGs, the stakeholder groups were divided into several smaller working groups (consisting of 4 persons on average). The SDG sub goals were arranged into the relevance classes "must be," "may be" and "should not be" part of bioeconomy monitoring (ordinal variable). Afterwards, all working groups were able to assess and comment on the categorization of the other groups via sticky notes (for example, for attributing more or less relevance, and to provide questions and new ideas). In all cases, a documentation of the discussions and feedbacks within the stakeholder-groups took place.

(iv – vi) To each class we then assigned values to evaluate and aggregate the social actors' relevances for the SDGs to relevance scores (non-compensatory weights). A feedback-round was initiated and adopted as quantified adjusting values which could increase (more relevance) or decrease (less relevance) the score
(vii) Finally, through a straight forward aggregation procedure the results as scores of relevance of each stakeholder group were given for each SDG and SDG sub goal (Figure 8).

Figure 8. Relevances of the SDGs for different stakeholder groups for the monitoring of the German Bioeconomy [86].

As overall results, we showed that the stakeholder groups “Sci” and “Soc” are led by more universal interests, whereas the stakeholder group “Bus” has particular interests. In general, the dimensions of sustainability are far beyond local ecological concerns, whereas the awareness of global shifts and big societal challenges (hunger, poverty, and inequality) is rising and is considered as very relevant.

Ecological, economic and social risks and chances are interrelated and equally important. Besides, there is a strong influence of changing discourses and narratives affecting policy process and public opinion

The SDGs aren’t guided by a founded theory, and in this case serve more to identify important normative aspects and to make analyses comparable. A systematic stakeholder participation by this method was implemented in SYMOBIO from the beginning. This method of deliberative and discussed preferences of members of society is supposed to reflect the convergence of collective preference (social choice theory). Assuming this, the results from the stakeholder groups and the general aggregation are able to reflect the appropriate relevance of an SDG. However, this method is of purely qualitative character and assessment, even if ordinal variables were rescaled as numerical scores for better processing and presentation. Consequentially, no meaningful statistical analysis possible.

Application in holistic and integrated life cycle sustainability assessment (HILCSA)

For one of the innovative models and methods of the SABE group, these results on relevances of the SDGs are applied. First, reflecting on transdisciplinary and critical research we revised common sustainability concepts like the often times criticized three pillar approach and developed an integrated sustainability framework (Figure 9) [88, 89].

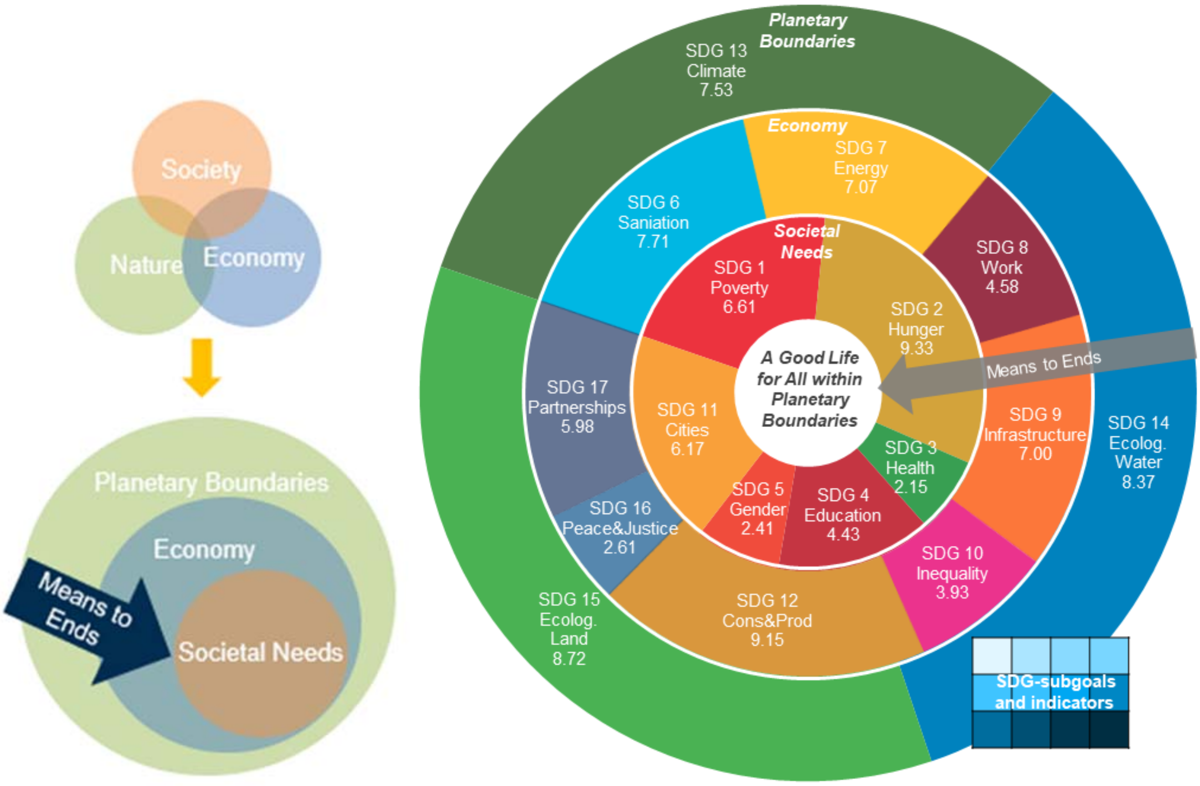


Figure 9. Integrated and holistic sustainability framework of HILCSA [91] .

The SDGs and their relevances given by the stakeholders are assigned to planetary boundaries, economy and societal needs. We define social sustainability as the long-term and global fulfilment of societal needs and well-being as an end, ecological sustainability as long-term stability of our environment as a basis of reproduction within planetary boundaries, and economic sustainability as technologies and economic structures as efficient, effective and just provisioning systems enabling the fulfilment of societal needs within planetary boundaries.

Recently, HILCSA was applied to a first case study on laminated veneer lumber (LVL) production in central Germany [92] guided by the following research question: What are the social, ecological and risks and chances of substituting fossil (steel beam) with renewable building materials (wood beam)? At this point it is not intended to go into detail of the actual HILCSA methodology, but present the results applying the MCDA stakeholder participation. For 74 indicators we calculated substitution factors of impact, which represent the relative ratio of negative social, ecological and economic impacts of LVL compared to steel beams. All indicators are aggregated and weighted according to the relevances of the SDGs the indicator is assigned to.

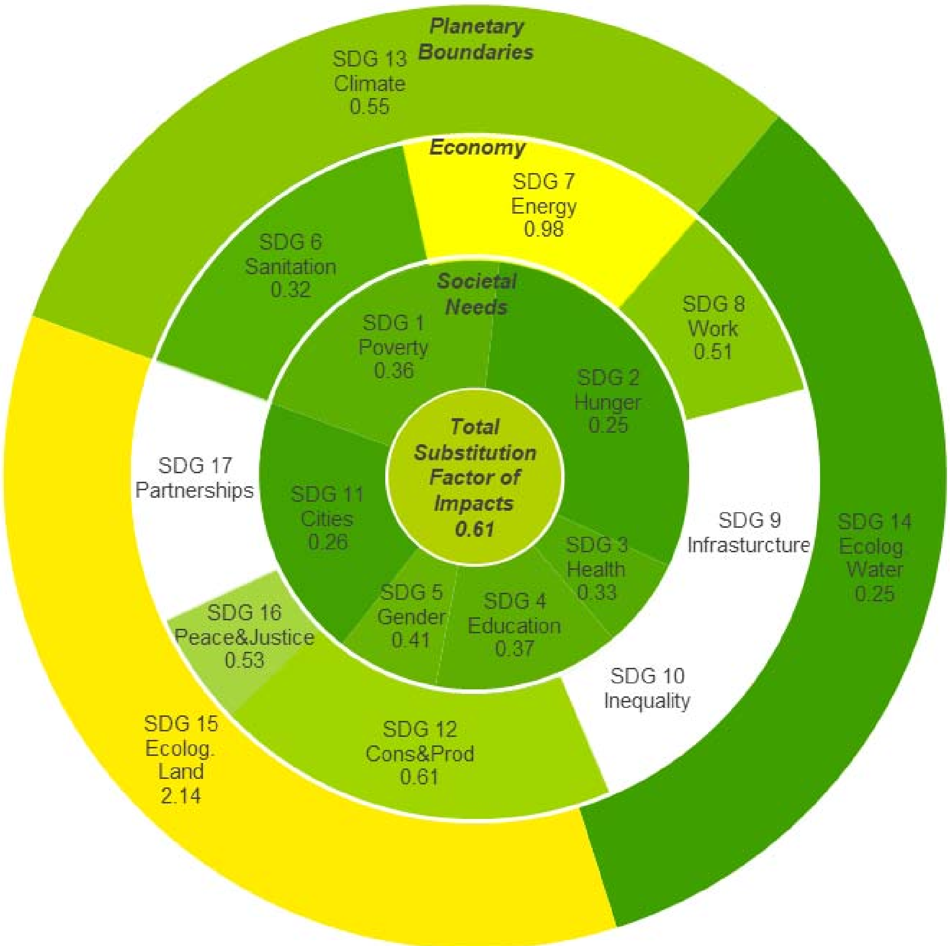


Figure 10. Substitution factors of impact of LVL compared to steel beams [92].

With a total substitution factor of impact of $ff = 0.62$, LVL beams are less unsustainable than steel beams in most terms and come with only 60% of negative impacts. Out of 74 indicators, 70 indicators have a $f < 1.0$ and 56 indicators a $f < 0.5$. The social ($f\_ social = 0.31$) and economic sustainability ($f\_ economic = 0.60$) of LVL perform significantly better than steel, because of better working conditions, less externalization of negative impacts, less fossil resource extraction as well as less energy consumption.

However, ecological sustainability entails significant trade-offs ($f\_ecological = 1.01$), since although there is less ecotoxicity and less GHG-emissions, but they are compensated by much more land use ($f\_ ID83 = 18.15$). In a nutshell, bioeconomy can be more sustainable, but encounters inherent contradictions if it is only intended to be substitution and if global inequalities and externalizations are maintained. Land use is the most significant planetary boundary for bioeconomy, as well as social, ecological and economic effects are intertwined in synergies and trade-offs. Consequentially, innovations and technology are necessary but by no means sufficient for a necessary socio-ecological transformation.

It can be shown that HILCSA allows an integrative (ecological, economic, social in one method) and holistic (transdisciplinary and critical) sustainability analysis and assessment based on aggregated indicators and qualitative discussion, retrospective and prospective. The results of our method are depending on the chosen reference and neither neglected should be the sensitivity due to the weighting factors on aggregated levels of SDG and in total. A small sensitivity analyses, however, shows that the overall aggregated results do not change qualitatively, e.g. when all weightings are set as equal ($\mathrm{R}=1$), then $\mathrm{f} = 0.57$, $f\_social = 0.33$, $f\_ecological = 1.02$ and $f\_economic = 0.59$. Nevertheless, in other regional contexts the weightings should be newly determined and the indicators set should be revised as well, e.g. when child labour, hunger or modern forms of slavery play a more significant role. Further participation formats with involved stakeholders would also be necessary to ensure co-creation, collaboration and cooperation.

3.4 KIT - ITES

Author: Tim Müller

The ITES works in the area of nuclear emergency management in consequence of the Chernobyl accident since shortly after 1986, providing a European funded decision support system and according tools to decision makers. MCDA methods were always of relevance in this system, but were amplified since 2011 with the development of a standalone generic MCDA tool, aiming at both scientific research of MCDA methods as well as providing an operational system to according stakeholders. Since then the tool MCDA-KIT has been presented in many stakeholder workshops to make MCDA methods and processes known to the emergency response community. In the following, the results of a recent workshop will be presented as a use case.

Case study 1: European Project CONFIDENCE (ITES1)

Original authors and contributors: Wolfgang Raskob, Nick Beresford, Tatiana Duranova, Irène Korsakissok, Alessandro Mathieu, Milagros Montero, Tim Müller, Catrinel Turcanu, and Clemens Woda

The project CONFIDENCE (**CO**ping with u**N**certainties **F**or **I**mproved modelling and **DE**cision making in **N**uclear emergen**C**i**E**s) aimed at the goal to better understand the source and effects of uncertainties within the nuclear emergency response chain and to provide means to handle these uncertainties accordingly [93]. Part of the project was the task to make the general

MCDA approach used for decision making better known to the international community of stakeholders and to improve the existing tool MCDA-KIT provided by ITES to cope with uncertainties for a more robust decision making.
Decision making in case of nuclear emergencies mainly requires selecting short- and long-term management strategies from a set of strategies in respect to several criteria, which are outlined by the given scenario. An advisory body composed of different stakeholder groups analyses the scenario and suggests the most reasonable strategy to the political decision makers. Based on their background, these groups may have different preferences and views on the scenario, leading to controversy suggestions within the advisory body.
The set up and results of the different workshops of CONFIDENCE are in detail described in [94]. In brief the scenario consists of a fictive release of radioactive material from the Bohunice nuclear power plant in Slovakia, spreading to a small town called Piešťany with 28000 inhabitants, which is well known for tourist activities and especially 6000 spa guests per year. The release would have a direct impact on health and quality of life of the population, but also commercially in respect to tourism and long-term reputation as spa town. The goal of the advisory body was to determine the best long term to recover from the accident.
The tool MCDA-KIT was used throughout the workshop for data assembly, as basis for discussion of values and preferences, presenting different MCDA methods, processing and visualizing of the actual results. Figure 11 shows a snapshot of the tool in the context of the workshop.

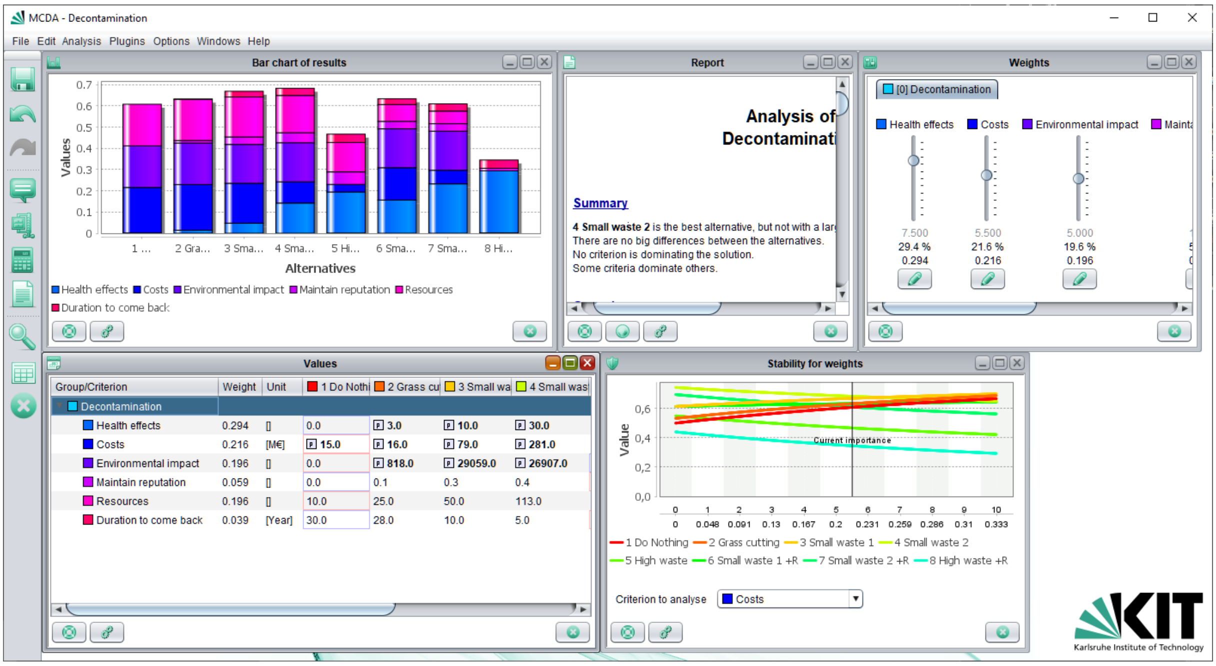


Figure 11. The MCDA tool as used in the workshops, showing some utilities for analysis. The upper left shows the ranking of alternatives, while the table below shows the criteria values. Further windows show human readable reporting, stability analysis and direct weighting of criteria. The tool is freely available at [95].

Determining alternatives

The general intervention guidelines suggested eight long term strategies respectively alternatives, three of which were extended versions of three others. The stakeholders were not supposed to add or remove strategies. For completeness the labels of the eight strategies were: “Do nothing”, “Grass cutting”, “Small waste 1”, “Small waste 2”, “High waste”, “Small waste 1 + Relocation”, “Small waste 2 + Relocation”, “High waste + Relocation”.

Determining criteria

Several intervention criteria were suggested beforehand, leaving it to the stakeholders whether to take them into account or not. The values for these criteria in respect to each strategy were calculated through simulations, given the according strategy would be implemented. Additionally, other criteria be added by the participants during the play, especially soft criteria concerning social aspects like acceptance in the public, leading to slightly different MCDAs in the different workshops. The main criteria considered in the end were:

- **Public health (health effects)** expressed in terms of number of averted cancers caused by the radiation spread in the accident, which is directly related to the dose averted
- **Costs (economical effect)** reflecting the sum of costs for accommodation during relocation, compensation of loss of productivity during relocation, clean-up strategy implementation, waste transport and storage, and cancer treatments
- **Personal and technical resources** divided in the number of workers needed for the implementation of strategy, personal resources expressed by “How difficult is it to allocate the workers” and technical resources needed for implementing a particular strategy
- **Wastes** considers the availability of storage locations which is affected by the amount of waste created
- **Population acceptance and willingness to cooperate** when implementing a specific strategy (self-help), attitude to the property and home, considerations to the society affected by relocation (stigmatization) and to certain degree indifference of people in times of peace and during the emergency preparedness process

The “duration to implement the countermeasures” was initially discarded but in in the conclusion of the workshop reconsidered and suggested to be included in the official guidelines.
For simplicity and understanding of the MCDA process the **WSM** was used for aggregation. In consequence the criteria values were normalized with the proportional method (normalized sum). Min-max was discussed for some criteria but discarded as some criteria contributions “vanished” in the results as their normalized values were zero.

Determining preferences

Again, for better understanding and due to limited time, the preferences were determined by direct weighting on a scale from 0 to 10 by open discussion, implicitly using the SMART method by balancing the criteria against each other, instead of other more sophisticated methods that were available like AHP. The tool was highly valued during this process as an overview on the criteria and alternatives as well as the interim ranking were always projected overhead. Also, the possibility and ease of dynamically changing of preference values and receiving immediate feedback was appreciated. As experienced in other workshops the opinions were rather different in the beginning, but the transparent discussion supported by the MCDA process lead to an acceptable agreement on the preferences in the end.

Working with uncertainties

Real world scenarios are always affected by uncertainties in many different ways and can have a significant impact in decision making. Therefore, uncertainties should be considered in general. There are two common ways to outline uncertainties: on one hand to provide a distribution function and the necessary parameters, on the other hand to provide a set of examples forming a histogram of potentially possible values. For the workshops the simulation tools used to calculate the values of the scenario were capable of providing the necessary information to set up according distribution functions, e.g. the criteria values of the overall costs were defined as normal distribution with mean and standard deviation. In contrast the preferences of the stakeholders are frequently given as histogram of individual preference. However, in the workshops deterministic preference values were used, which were commonly agreed upon.
The uncertainties were evaluated by ensembles, creating a set of deterministic MCDAs and aggregating the individual results in various ways [96]. Figure 12 shows one way of visualization as "ranking bubble matrix". As the uncertainties respectively, variances of the criteria values were very strong the overall results were also very widely spread. Nevertheless, the highest ranked alternatives could still be identified as probably the best approaches in the given scenario.

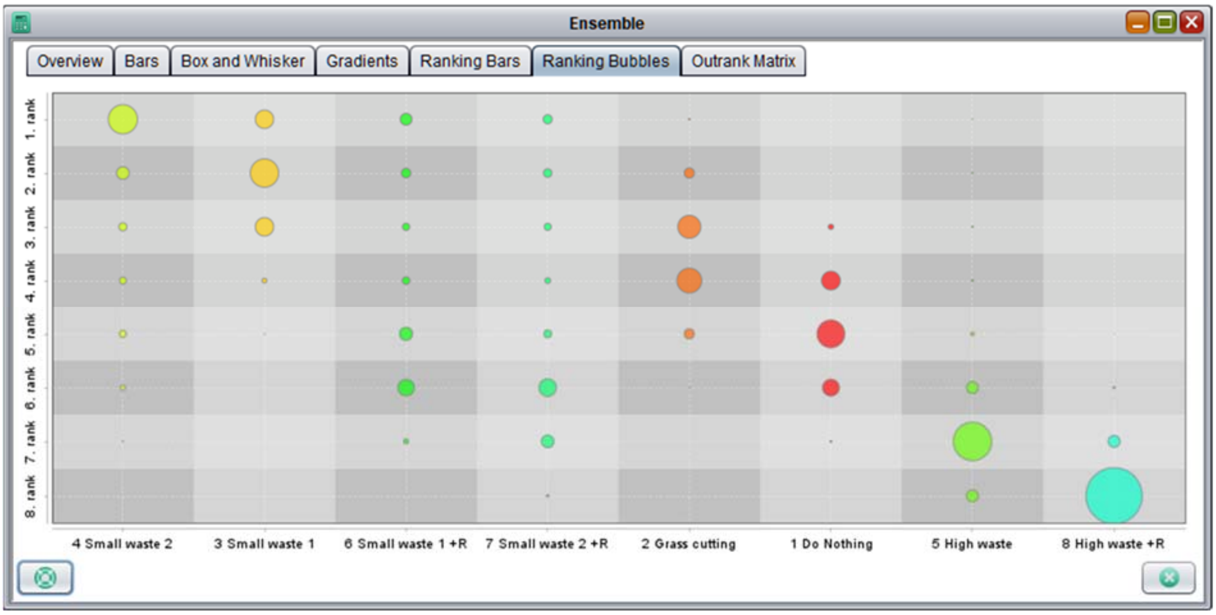


Figure 12. Visualization of the uncertainty evaluation in the tool MCDA-KIT using 10000 samples. The best score to achieve would be the first column, top row, with a bubble as large as possible. This would indicate ranking first place in every sample evaluation. In this scenario the alternatives "Small waste 2" and "Small waste 1" scored similar slightly in favour of "Small waste 2".

Conclusion

The stakeholders were in general not used to MCDA and tools thereof, however the MCDA method as well as the tool MCDA-KIT were well received, judging the process and tool to be very helpful in long term decision making. Especially the forced discussion to come to an agreement and the transparency of the process was much appreciated. Several criteria were identified that should be used in good practise. Several others were suggested, depending on the specific scenario. Thus, a general catalogue of criteria to be considered as well as a best practises guideline was recommended to be introduced to the community. Also integrating uncertainties in the decision-making process was highly recommended, as increasing the robustness would be of high value in general.

3.5 KIT – ITAS

Authors: Martina Haase, Manuel Baumann, Laura Mesa Estrada

In this chapter, three completed case studies (ITAS1, ITAS2, ITAS3) are selected and described with respect to criteria selection, MCDA methods (including preference aggregation and uncertainty/sensitivity analysis) as well as stakeholder integration. Additionally, the ITAS focus project "MCDA for sustainability assessment of energy technologies" aiming at the further development of existing approaches for sustainability assessment is presented. A comprehensive list including ongoing projects and respective case studies related to sustainability assessment and MCDA at ITAS can be found in the Working Table (see Supplementary Material).

Case study 1: Selection of different battery types in different applications (ITAS1)

Original authors and contributors: Manuel Baumann, Jens Peters, Marcel Weil

Battery storage systems (BESS) are an option that allows it to integrate higher shares of RES on multiple grid levels to enable decarbonized electricity system. There are several technologies available, and the choice of the best energy storage technology is based on the requirements of a certain application field. At the same time, stakeholder-based expectations related to technical, environmental, economic, and social aspects (e.g., high power, long life vs. low cost, excellent safety, abuse-resistance, environmentally friendliness etc.) have to be considered. This results in a complex decision problem wherein trade-offs, different application areas and multiple stakeholder interests have to be considered.

The aim of this work is to give an overview of the role of different sustainability-oriented indicators for the selection of a suitable BESS depending on the application field. Additionally, 8 different technologies are analysed based on the given weights in a tentative way by the use of a hybrid MCDA including 4 different application fields. These application fields are wind energy direct marketing (WES), primary regulation (PR), energy time shift (ETS) and decentralized energy storage (DC). 64 experts were integrated into the MCDA to provide weights to determine the relevance of the different indicators. Batteries considered in the assessment are five different Li-Ion batteries (LIB), Lead-Acid (PbA), high-temperature batteries (Sodium-Nickel Chloride (NaNiCl)), and Vanadium redox flow (VRFB). Environmental aspects are quantified by LCA, and economic aspects by Life cycle costing (LCC). Social aspects are based on expert judgment. A comprehensive description can be found in [71, 97, 98].

Criteria selection

The four dimensions environment, economy, social aspects, and technology are integrated into the assessment. These comprise 11 sub-criteria (e.g. technology acceptance, investment cost, damage on resource availability etc.). The selection of criteria is based on a comprehensive literature review and was presented to 12 persons and discussed with these. Then, 22 external experts were contacted and asked to conduct a critical review of the given criteria in a first-round loop. From these participants, 10 were interviewed (up to one hour) to discuss and consolidate the criteria. Named criteria are quantified by a combination of different methods like LCA, LCC and other methods such as expert judgment and literature review. Uncertainties have been considered via a Monte Carlo simulation.

MCDA methods

MADM methods initially tested where ELECTRE I [99], SMART, TOPSIS [100] and AHP. The Requirements of the research for the construction as well exploitation phase made the expression of trade-offs required for outranking methods only partially possible. The tested method of ELECTRE I was not considered to be practical for a high number of participants and the limited possibility of interaction with these. Finally, a mixture of AHP and TOPSIS was considered as a most suitable approach. AHP results were used to analyse the consensus among all participating actors in respect to their perceived stakeholder group using concepts of bio-diversity (alpha and beta diversity) and Shannon entropy [101]. AHP Eigenvector method for consistency calculus was too restrictive for AHP, thus geometric mean method (RGMM) was used as inconsistency evaluation [102].

Stakeholder integration

Utility-scale BESS can be integrated into generation, network and demand within all voltage levels. There is thus a high number of potential users and business areas distributed within the entire electricity system. Choice of participants is based on different socio-technical sub-regimes dimensions relevant for energy storage identified by [103] and were classified following a concentric system view. Stakeholder involvement was relevant for alternative selection, criteria definition and weighting. The involvement is based on a pre-test phase that consisted 4 phases as follows: i) pre-test phase among 12 persons working in the broader field of energy systems (interviews, test surveys); ii) second pre-test phase including 22 selected experts in the field of energy storage and energy economics (online test survey), iii) in depths interviews with ten candidates and finally iv) distribution of the AHP online survey with direct email (106) and snow ball principle leading to 272 survey participants. From these 64 finished the survey fulfilling AHP consistency requirements.

Results

Stakeholders attributed a high relevance to economic and environmental aspects. Technology performance is ranked third and the least importance is attributed to social aspects. There also significant differences in the weights of the considered sub-criteria (e.g. LCC vs. Investment cost). It has to be mentioned that the results show that there is only poor to no common preference among included stakeholder groups regarding the mentioned indicators and there is a need for further research in this area. Finally, as a result of the tentative ranking most lithium-ion batteries can be recommended for all considered application areas (this comes also true for conducted sensitivity analysis with varying weights). In general, rankings for should be seen as rather indicative. This is due to the uncertainties related to the attributed weights as well as uncertainties related to the LCA and LCC and especially the considered social factors.

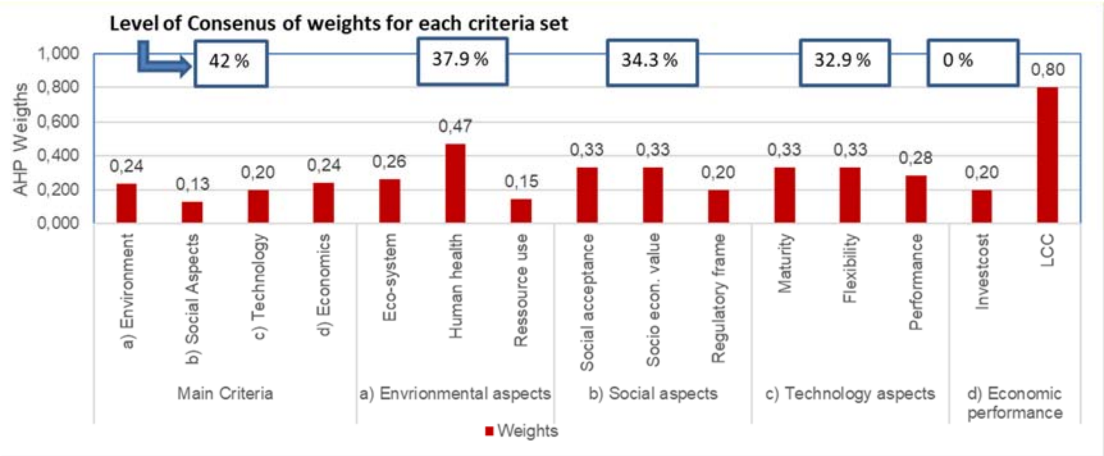


Figure 13. Overview of attributed weights from all stakeholder groups (based on [71]) .

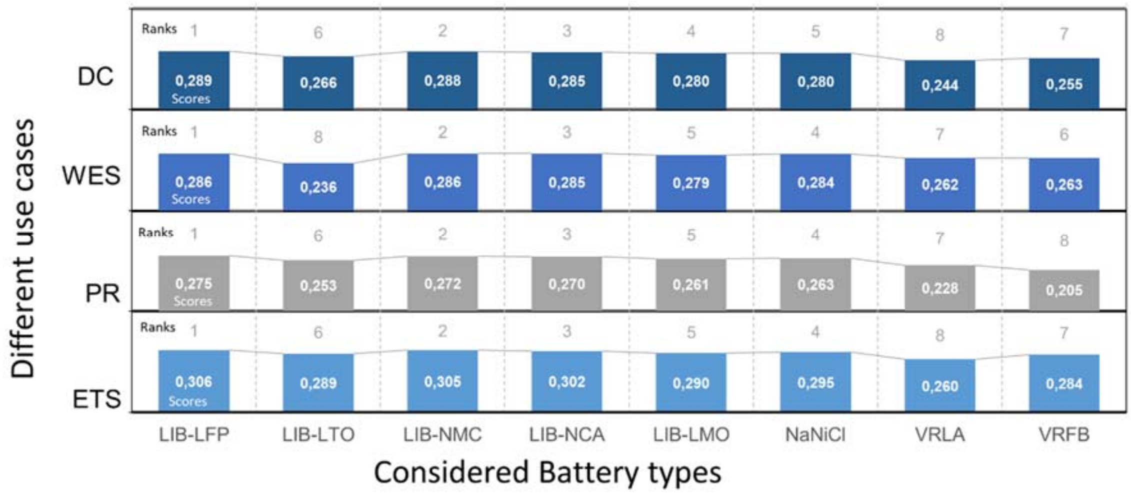


Figure 14. Indicative rankings among the different battery energy storage systems in the considered four application areas, (1 represents the best and 8 the worst rank) are given in the rows below (ETS:Energy Time Shift, DC: decentralized Grid, WES: Wind Energy Support, PR:Primary Regulation). Ranking values are indicated in grey as in most cases differences among scores can be considered as marginal (based on [71]).

Case study 2: Sustainability assessment of synthetic biofuel production in Germany (ITAS2)

Original authors and contributors: Martina Haase, Nils Babenhauserheide, Christine Rösch

Solid biomass stores energy and carbon dioxide naturally and is an important resource to compensate fluctuating availability of wind and solar power. So-called second generation biofuels are regarded as a promising renewable alternative to obtain liquid fuels for the transport sector as they do not compete with food and fodder production and at the same time bear a high potential for greenhouse gas emission reductions [104, 105]. This case study focuses on synthetic biofuel (gasoline), produced via industrial scale thermochemical conversion of lignocellulosic biomass (bioliq® process chain) [106]. In this example, synthetic biofuel from straw (*Straw*) is compared to synthetic biofuel from wood (*Wood*) and fossil gasoline (*Fossil*).

Criteria selection

For indicator-based assessment, the approach for sustainability assessment developed within the 'Energy System 2050' framework (ES2050)[107] is used. It consists of the three elements "environmental", "economic", and "social" assessment in accordance with the triple-bottom line model of sustainability. It includes established life cycle based economic and environmental indicators together with social indicators derived from the Integrative Concept of Sustainable Development (ICoS). The selection of indicators is driven by the preconditions "applicability for technology assessment", "avoidance of overlapping with established E-LCA and LCC indicators", and "feasibility and practicability of data availability, collection and analysis". In this example, 13 environmental midpoint-indicators as recommended in the ILCD Handbook of the European Commission [108] are used, one economic indicator (manufacturing costs of fuel), and one social indicator (number of employees per unit of product as a proxy for domestic value added).

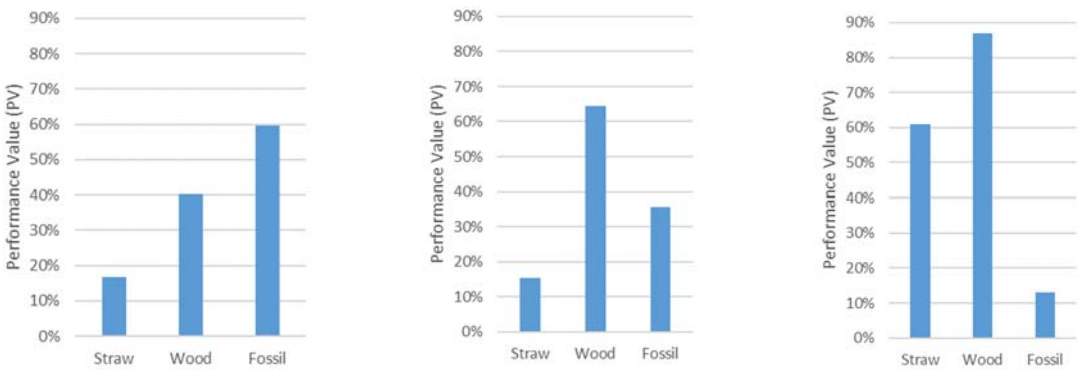
MCDA methods

Here, environmental indicators are aggregated in a first step to one environmental indicator and in a second step, three indicators, one for each sustainability dimension (Environment, Economy, Social), are aggregated. The first aggregation step, i.e. aggregation of environmental indicators, should be given attention as it might influence the overall result depending on what method and which weighting factors are used. In this example, a distance-to-target approach according to [109] including binding and non-binding EU-targets (target reference B) is applied for the aggregation of environmental indicators. For the second aggregation step, i.e. aggregation of indicator values of sustainability dimensions, the MCDA method TOPSIS (cf. [100]), belonging to the compensating MCDA methods, is chosen. This method is one of the most widely used MADM methods for cases when information on attributes is available on a cardinal scale.
For weighting of sustainability dimensions, prioritization according to standardized stakeholder profiles, i.e. Individualist, Hierarchist, Egalitarian, is carried out together with pairwise comparison 0-1-2-3. The profile Individualist, for example, prioritizes the dimension Economy, before the dimension Environment and the dimension Social while the profile Hierarchist prioritizes the dimension Ecology and the profile Egalitarian the dimension Social [23]. Time perspective, required level of evidence, manageability according to [110, 111] and resulting priority settings for the sustainability dimensions according to [112] are given in Annex 2.
Sensitivity analysis are carried out for weighting of sustainability dimensions (Economy, Environment, Social) as well as for input data, e.g. manufacturing costs of fuel. Therewith, socio-economic tipping points are assessed.

Results

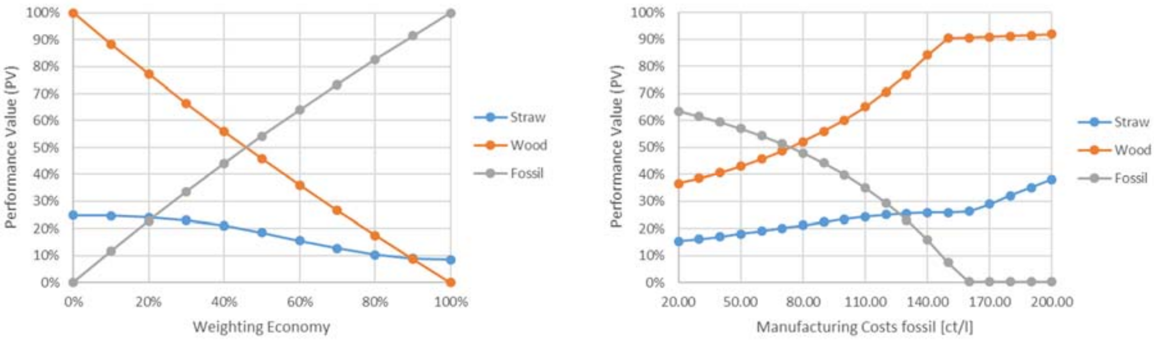
The results presented here are based on [113]. Stakeholders who prioritize the dimension Economy (Individualist) would choose *Fossil*, while stakeholders who prioritize the dimensions Environment and Social (Hierarchist and Egalitarian) would choose *Wood* (see Figure 15). While the Hierarchist would choose *Fossil* in second place, the Egalitarian would choose *Straw* in second place. These results provide evidence that different cultural profiles i.e. different weighting of sustainability dimensions, results in different rankings of the fuel production routes.

Individualist Hierarchist Egalitarian



A B C

Figure 15. Performance values of different fuel production routes (bioliq from straw – Straw, bioliq from wood – Wood, fossil gasoline – Fossil) using TOPSIS together with preferences of standardized stakeholder profiles Individualist (A), Hierarchist (B), Egalitarian (C) (based on [113])



A B

Figure 16. Sensitivity analysis: Variation of weighting of Economy (A) and variation of Manufacturing Costs of fossil gasoline (B), stakeholder profile Individualist (based on [113])

From sensitivity analysis for different weightings of the dimension Economy (Figure 16 A), one can interpret that the Individualist would choose *Wood* as a first priority if Economy is weighted with less than 45%. Sensitivity analysis for manufacturing costs of *Fossil* indicates that the Individualist would choose *Wood* as first priority if the manufacturing costs of fossil gasoline would exceed 70 ct/l (see Figure 16 B). For example, political framework conditions but also rising crude oil prices could favour this cost increase.

Case study 3: Sustainability assessment of alternative mobility in Germany (ITAS3)

Original authors and contributors: Martina Haase, Christina Wulf (FZJ), Manuel Baumann, Hüseyin Ersoy, Jan Christian Koj (FZJ), Freia Harzendorf (FZJ), Laura Mesa Estrada

In Germany, around 43% of the population uses a car every day [114]. At the same time, conventional ICEVs remain the technology of choice with a share of almost 75% of new registrations [115]. In this example, a comprehensive life cycle-based sustainability assessment using MCDA is applied for prospective and comparative sustainability assessment of different vehicle types, i.e. ICEV, BEV, FCEV, and corresponding fuel and electricity supply, i.e. fossil gasoline (ICEV-fossil), synthetic biofuel from straw (ICEV-straw), electricity production mix Germany (BEV-mix_DE) and electricity from wind power (BEV-wind, FCEV-wind). For the assessment, a consistent assessment framework, i.e. background scenario and system boundaries, and a detailed modelling of vehicle production, fuel supply and vehicle use are the cornerstones. The presented case study is based on joint research of KIT-ITAS and FZJ IEK-STE (see [116]).

Criteria selection

The selection of criteria is based on the approach for sustainability assessment developed within the 'Energy System 2050' framework (ES2050) [107] and basically corresponds to the one of case study ITAS2. In total, 15 indicators are used:13 environmental indicators according to [108], one economic indicator (total costs) and one social indicator (domestic value added).

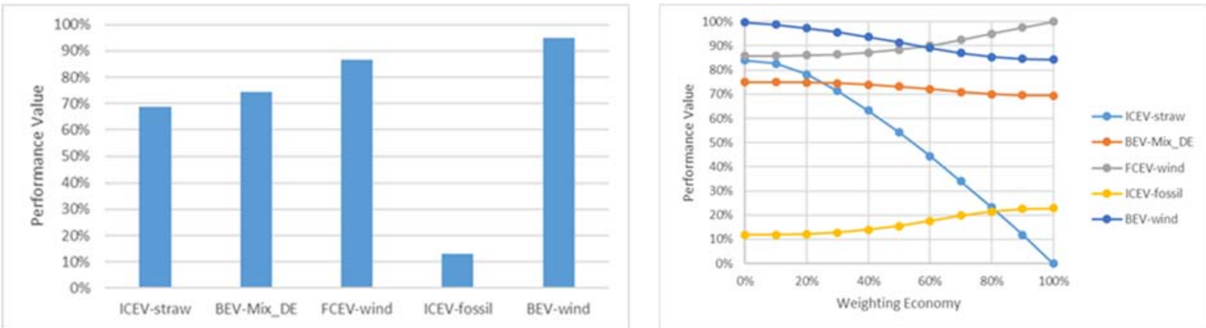
MCDA methods

In this example, the MCDA method TOPSIS (see case study ITAS2) and equal weighting of indicators is used for the aggregation of indicator values. Here, both, "hierarchical equal weighting" and "two step equal weighting" are carried out. For the former, all 15 indicators are aggregated in one step for overall performance value (PV) calculation with sustainability dimensions being weighted equally (33.33% each) and environmental indicators proportionally with 0.33/13 (2.6%). For the latter, in a first step, 13 environmental indicators are aggregated to one environmental indicator i.e. the environmental performance value (EPV) is calculated using equal weights of 1/13 (7.69%). In a second step, three indicators, one for Environment, Economy, and Social respectively, are aggregated to the overall PV using equal weights of 1/3 (33.33%).

Sensitivity analysis are carried out for technical input data (electricity mixes and vehicle mileage), weighting of sustainability dimensions, economic input data (i.e. total costs), and social input data (i.e. domestic value added).

Results

Here, results are presented for “two step equal weighting. As a result of the first aggregation step, i.e. aggregation of environmental indicators equally weighted, BEV-wind performs best from an environmental point of view with an EPV of 65%. As a result of the second aggregation step, i.e. aggregation of indicator results for sustainability dimensions equally weighted, BEV-wind exhibits the highest performance value (PV 95%), i.e. is the preferable option from a sustainability point of view (see Figure 17 A). Sensitivity analyses are carried out for the weighting of sustainability dimensions as well as for different input data (see above). The alternative BEV-wind performing best is a robust result with respect to the weighting of sustainability dimensions Environment and Social. In case that Economy is weighted with more than 60%, FCEV-wind performs better than BEV-wind (see Figure 17B).



A B

Figure 17. Performance values of ICEV-straw, BEV-Mix_DE, FCEV-wind, ICEV-fossil, and BEV-wind using TOPSIS and two-step equal weighting of indicators (A) and sensitivity analysis for weighting of Economy (B), year 2050 (based on [116])

Focus project “MCDA for sustainability assessment of energy technologies”

Original authors and contributors: Laura Mesa Estrada, Martina Haase, Manuel Baumann, Jens Buchgeister, Jürgen Kopfmüller, Christine Rösch, Volker Stelzer, Marcel Weil

The aim of the focus project is to complement and further develop existing approaches for the sustainability assessment of (emergent) (energy) technologies in order to contribute to the development of the energy system towards sustainability. The further development of the existing assessment approaches refers to three main elements: sustainability criteria, MCDA methods, and stakeholders’ integration, e.g. environmental associations, companies, citizens. Therefore, a MCDA-framework for integrative sustainability assessment of energy technologies and systems is elaborated considering three main challenges:

- Enhancement of sustainability criteria: Social and socio-technical characteristics of energy technologies and systems need to be better addressed; indicators need to adequately address cultural, ethical or resilience issues
- Guidelines for MCDA methods implementation: including model-based and non-model-based (“qualitative”) indicators; selection of (MCDA) methods considering

requirements for sustainability assessment (e.g. non-compensatory methods) and the data available; consideration of uncertainties; verification of robustness of results.
- Systematic stakeholder integration: identification of relevant stakeholders and the stages at which their integration is efficient and relevant; adaptation of participatory approaches for stakeholder integration.

To facilitate the implementation of the framework, a decision support tool (DST) for sustainability assessment of energy technologies is developed based on an existing licence-free MCDA tool/software. In order to identify and characterize existing licence-free MCDA tools, an extensive literature review has been carried out [117]. As a result, the MCDA-KIT Tool (see Case study 1: European Project CONFIDENCE (ITES1)) has been selected to be used as starting point for the development of the DST. The work on this tool can be described in two (simultaneous and independent) stages: 1) Complementing the MCDA KIT tool by adding missing features or methods according to sustainability assessment requirements [16, 17] (e.g. TOPSIS, PROMETHEE). 2) Development of stand-alone plugin(s) for sustainability assessment of energy technologies that include the elements of the framework (see Figure 18). Within the further course of the project, the tool will be applied to various use cases e.g. nearly zero energy buildings (NZEB), transport options, etc.

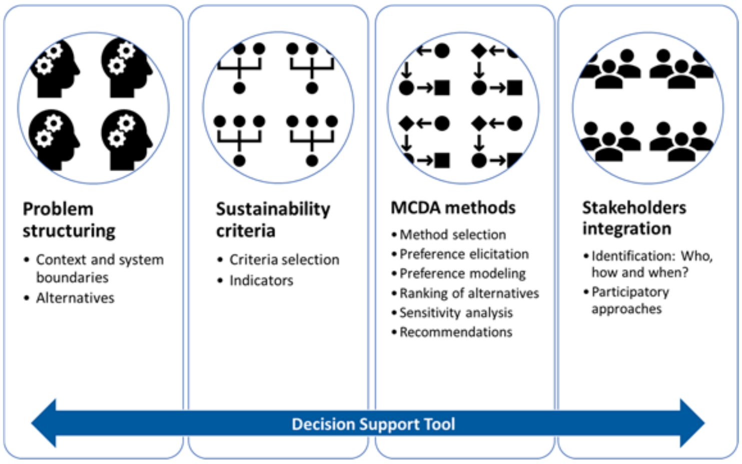


Figure 18. Elements of the decision support tool (Source: KIT-ITAS).

3.6 KIT – IIP

Authors: Raphael Heck, Andreas Rudi

For the following section two examples have been selected that demonstrate the broad applicability of MCDA-methods to very different use cases. Case study 1 is an example of the field of bioeconomy, coping with the multi-criteria-based selection of suitable locations for innovative biorefineries. Case study 2 is an example from the automotive industry regarding the selection process of suppliers, considering social, ecological and economic risks. A list of additional case studies that have already been completed, are currently carried out or are planned at the IIP can be found in the Working Table (see Supplementary Material).

Case study 1: Evaluation of biomass valorization pathways (IIP1)

Original authors and contributors: Andreas Rudi

Biomass is the only renewable resource that can provide renewable energy in the form of bioenergy such as heat and power and renewable products in the form of base chemicals e.g., to produced biobased polymers. Biomass in its variety is commonly spatially distributed and is composed of heterogeneous compounds, which characterize the type and conversion of valorisation. The biomass valorisation pathways are characterized by three main processes, i.e., the supply of biomass feedstock, the logistics processes like transport, transhipment and storage, and the conversion process. In order to implement biomass valorisation pathways a comprehensive analysis is required which takes several decisions into account such as the type, quality, quantity, location and time of supply, the type of transport and transhipment as well as the time and location of storage, and the technology of conversion, the location of the facilities, its capacities and configurations for producing a certain product. The evaluation of biomass valorisation pathways integrates economic criteria such as the net present value and is required to cover environmental issues such as GHG emissions and social aspects like acceptance as well as.

Criteria selection

The criteria selection for evaluating bio-based valorisation pathways is based on a comprehensive desk research and expert interviews. The main indicators are the profitability, the GHG emissions and from a strategic perspective the locations suitability. From a tactical and operational perspective, it is the customer satisfaction in terms of quality and time. Whereas profitability, GHG emissions, quality and time can be measured, the suitability of conversion site locations requires various quantitative and qualitative criteria. A total of twelve criteria was determined, which were grouped into three categories: infrastructure, environment, social. These twelve criteria were transferred into GIS layers in order to quantify the suitability of locations at the example of Baden-Württemberg.

MCDA methods

A GIS-based calculation of suitable conversion site locations for lignocellulose biorefineries was performed. The result is a selection of candidate biorefinery locations in Baden-Württemberg. By applying the eps-Constraint method (MODM) optimal sites out of various candidates based on techno-economic and ecological factors as well as GIS-based site suitability were determined with TOPSIS.
Starting from 13 location criteria for selecting biorefinery sites which are grouped into 3 categories, a pairwise comparison is performed to identify the most important location factors. First, the groups are compared with each other. Within one group another pairwise comparison is performed. The pairwise comparison is performed by 10 experts from industry and research. By transforming the location factors into GIS-layers and by applying a GIS-based analysis a suitability map of biorefinery locations in Baden-Württemberg is created. Several suitable locations or rather candidate locations are then used as input data for a forthcoming location

planning model. The model is further enriched with techno-economic and ecological biorefinery plant data as well as raw material locations in order to find the best location. The tradeoff between the three criteria (suitability, profit, GHG) is solved by applying the eps-Constraint method and by determining the pareto efficient frontier. At last, TOPSIS is applied to find the best location regarding the decision makers preferences.

Results

The results of the AHP suitability location analysis with GIS and a few criteria are shown in the following figure as heat maps:

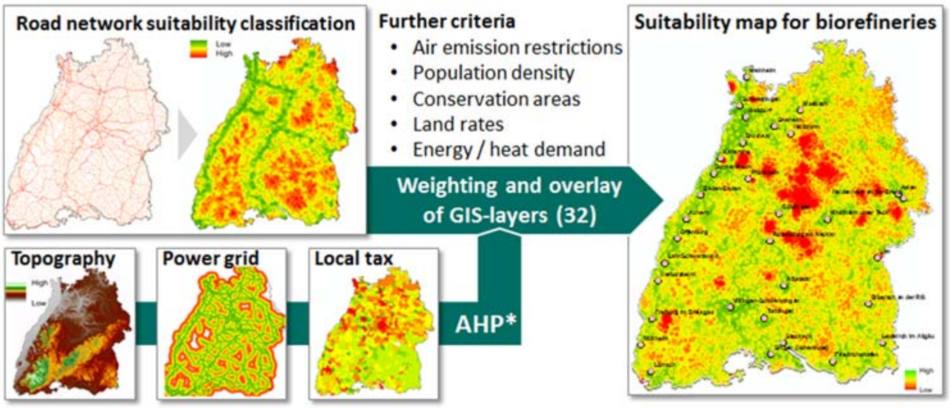


Figure 19. Results of the AHP suitability location analysis with GIS (work in progress).

The pareto frontier of the facility location problem with the three dimensions profit, suitability and GHG emissions is shown in the spider chart below (Figure 20):

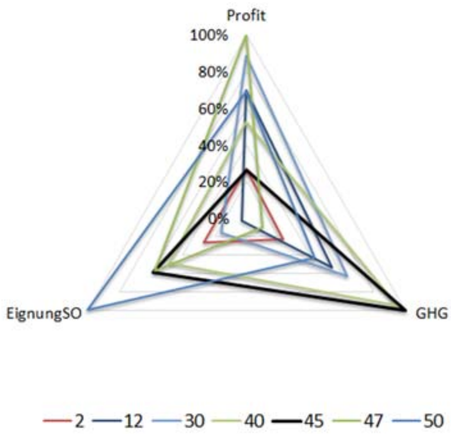


Figure 20. Pareto optimal solutions of the multi-objective MILP with the three dimensions profit, suitability and GHG (work in progress).

In the spider chart several pareto optimal solutions of the multi-objective MILP are presented. Each combines different values along the three dimensions and represents one location. No solution or rather no biorefinery location is fully dominant, but in accordance with the dimensions semi-dominant solutions exists such as location number 50 for the suitability, number 45 for GHG emissions, and number 47 for the profit criterion. The decision maker can weigh the dimensions in accordance with its preferences by applying TOPSIS. A higher weight of the profit and the GHG criteria would favour location number 30 for instance. In terms of profitability and suitability location number 47 is favourable. The according research publication is work in progress.

Case study 2: Selection and management of suppliers in the automotive industry (IIP2)

Original authors and contributors: Konrad Zimmer

The primary goal of supplier management is to strengthen the company's competitive position by optimally managing supplier-customer relationships and the supplier base. In doing so, supplier management pursues several target criteria and is thus confronted with multi-criteria decisions.

Two main challenges have to be met: First, creating transparency along the supply chain is a major hurdle. Second, the comparability of supplier sustainability performance assessments in the context of supplier management is a challenge. Even though a large number of models for decision support of supplier management considering economic, ecological and social aspects can already be found both in practice and in the scientific literature, there is still a considerable need for research with regard to the two challenges mentioned [118].

Criteria Selection

Environmental and social criteria were selected for the assessment of sustainability risk. To quantify these criteria, it was to use over 250 publicly available statistics have been used and ratings from various recognized institutions. The first step of the risk calculation was to assign each supplier to a country and an economic sector, depending on the country of the production site and its offered product.

During the research, suitable indicators were found for six ecological risk criteria (ecological commitment, material, energy, emissions, water, waste). In total, 14 indicators have been selected to quantify the manifestations of these six risk criteria.
For the social risk criteria (social commitment, child and forced labour, occupational health and safety, wages and working hours, employee education, employment relationship, discrimination, freedom of association, social responsibility), a total of 16 suitable indicators were selected for quantification.

MCDA Methods

The Fuzzy AHP (F-AHP) was used to determine the criteria weights. The AHP is basically based on performing a pairwise comparison, a structuring criteria hierarchy, and applying the eigenvalue method [119]. One criticism of the classic AHP is that frequently used expert assessments and the resulting vague or uncertain information not being adequately integrated into the process. Therefore, in order to represent the assessments as realistically as possible in the calculations, the FAHP was applied as an extension of the classical AHP to determine criterion weights [120]. So, for conducting the pairwise comparisons, instead of a scale with sharp numerical values [121], a scale with linguistic assessment levels from "much less important" to "much more important" is used.

To determine the ranking of potential suppliers, the Fuzzy-PROMETHEE method was used. For qualitative non-binary indicators requiring expert linguistic judgments, a five-point Likert scale was used. Fuzzy equivalents were used for the application of F-PROMETHEE.

Stakeholder Integration

With the aim of deriving a preference function depending on the independent variable "risk" and "award volume" to determine the overall risk and integrating it into the risk model, a regression analysis was carried out using the data from a survey of ten sustainability experts to determine the characteristics of the variable "overall risk".
The indicator system was developed in several steps. First, extensive literature-based indicator analysis was conducted to generate a list of potential indicators. In a further step, the indicator list was first roughly analysed in collaboration with two sustainability experts from an automotive manufacturer in order to remove overlapping and less relevant indicators from the list.

In order to determine the ranking of the potential suppliers with the help of F-PROMETHEE and to consider the individual importance of the indicators, criteria, areas and dimensions, weightings are needed. In order to determine the weightings of the indicators, several meetings took place with the two sustainability experts mentioned above.

Results

In order to determine the group weights of the criteria of the risk model, regional criteria weights were used and normalized with the help of a linear scale transformation, first at a regional hierarchy level and then at a global hierarchy level. In addition, the individual weightings of the sustainability experts surveyed were determined in the same way and the minima and maxima of these expert weightings were then determined so that, based on this, several scenarios could be developed to test the sensitivities of the risk model. Selected results of the group and individual weightings can be found in the following Figure 21.

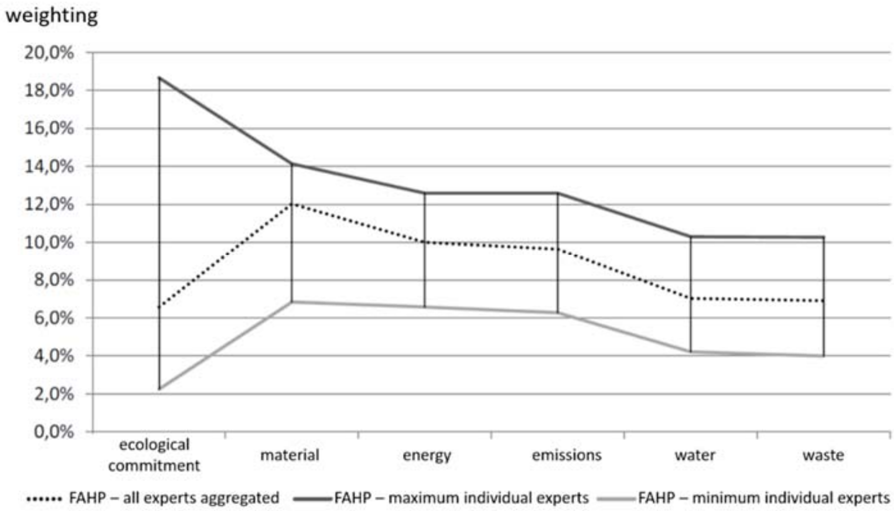


Figure 21. Span of the maximum and minimum individual weightings of individual experts compared to the group weightings of all experts [118].

The study also investigated the extent to which, besides the variable "risk", also the variable "award volume" influences the values of the dependent variable "overall risk". The results of the F-AHP were used to create a specific preference function (Figure 22).

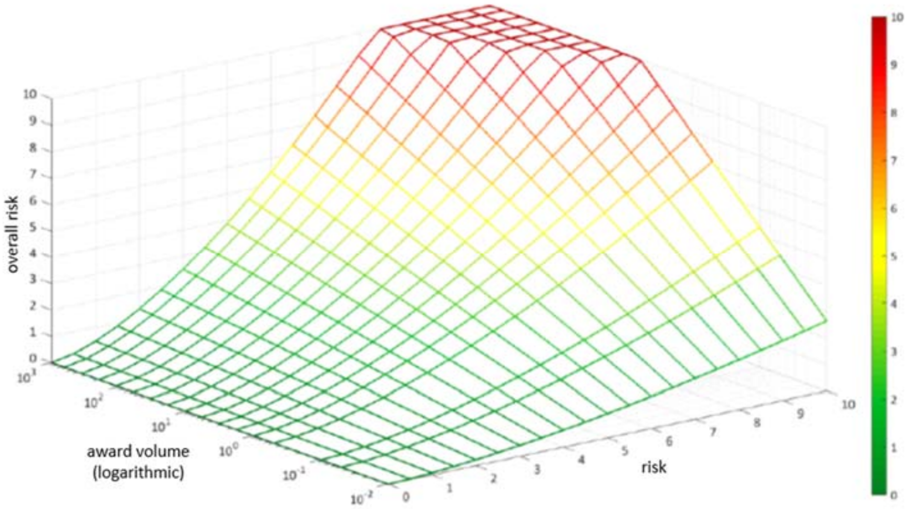


Figure 22. Plot of the preference function to be integrated into the risk model (logarithmic) [118].

4. Overview, comparison and discussion of methods and use cases

Authors: Laura Mesa Estrada, Walther Zeug, Martina Haase, Christopher Ball, Jürgen Kopfmüller, Manuel Baumann, Christina Wulf

4.1 Overview

The activities and use cases from chapter 3 and the Working Table (see Supplementary Material) are summarized in Table 3. Although most of the institutes presented their research through use cases, others like FZJ, KIT and UFZ also focused on the theory behind their methodologies. The use case of KIT-ITES is not related to sustainability assessment; however, the relevance of its work relies on the development of a generic standalone MCDA tool and uncertainties handling.

The triple-bottom line model of sustainability and rather classical MCDA applications are predominant in the activities presented. These involve mainly decision making between technology choices – e.g. between mobility technologies, BESS, different types of synthetic biofuels, biomass valorisation pathways. However, there are variations of these classical approaches, with MCDA also used to answer slightly different questions which go beyond ranking technology choices for a decision maker. MCDA has also been applied to more complex questions and decisions, e.g. (i) trade-offs and synergies in bioeconomy pathways based on the societal interests and perceptions of stakeholders (UFZ), and (ii) assessment of sustainability risks in supplier selection in the automotive industry (IIP). Moreover, MCDA has also been used to assess the drivers and barriers to the diffusion of mobility technologies (e.g. reverse MCDA) considering interaction among stakeholders (FZJ).

Table 3. Summary of activities presented in chapter 3 and the Working Table (see Supplementary Material).

Methodologies				
Institute	**Authors**	**Title**	**Scope**	**Publications**
FZJ-STE	Wulf C., Siekman F., Ball C., Kuckshinrichs W.	Indicators selection	Sustainability indicators	[122]
		Determination of weighting factors without stakeholder survey	MCDA methods	[74]
		Thresholds in PROMETHEE for uncertainty integration	MCDA methods	[75]
UFZ	Zeug W., Bezama A.	Stakeholder participation in SYMOBIO	Stakeholders	[86, 87]
		Application in holistic and integrated life cycle sustainability assessment (HILCSA)	Sustainability assessment	[88, 89, 92, 123]
KIT-ITAS	Haase M, Baumann, M., Mesa Estrada, L., Kopfmüller, J., Rösch, C., Stelzer, V., Weil, M.	Focus Project MCDA for Sustainability assessment	Framework and tool development for sustainability assessment	[117]
Use cases				
ID	**Authors**	**Title**	**Scope/boundaries**	**Publications**
DLR1[+]	Oswald M., Brand-Daniels. U	Multidimensional assessment of passenger cars: Comparison of electric vehicles with internal combustion engine vehicles	Technology	[28]
DLR2[+]	Buchgeister (ITAS), Naegler T.	Multidimensional sustainability assessment of different national energy system transformation pathways	System	[55]
FZJ1.1*	Wulf C.	Setting Thresholds to Define Indifferences and Preferences in PROMETHEE for Life Cycle Sustainability Assessment of European Hydrogen Production	Technology	[75]
FZJ1.2*	Wulf C.	Integrated Life Cycle Sustainability Assessment: Hydrogen Production as a Showcase for an Emerging Methodology	Technology	[124]

FZJ2*	Wulf C.	Sustainability assessment of hydrogen mobility in Germany	Technology	In progress
ITAS1+	Baumann M.	Selection of different battery types in different applications	Technology	[125]
ITAS2+	Haase M.	Sustainability assessment of synthetic biofuel production in Germany	Technology	[113]
ITAS3+	Haase M., Wulf C. (FZJ).	Sustainability assessment of alternative mobility in Germany	Technology	[116]
ITAS4*	Baumann M.	A combined optimisation and decision-making approach for battery-supported HMGS	Systems	[126]
ITAS5*	Baumann M.	Recycling aktueller und zukünftiger Batteriespeicher: Technische, ökonomische und ökologische Implikationen: Ergebnisse des Expertenforums am 6. Juni 2018 in Karlsruhe	Technology	[127]
ITAS6*	Gaiser J., Kraus B.	Regional sustainability assessment of energy scenarios for 2050.	Systems	In progress
ITAS7*	Rösch C., Fakharizadehshirazi, E., Haase, M.	Assessment of the sustainable land potential for solar park establishment with stakeholder involvement.	System location	In progress
ITES1+	Müller T.	European Project CONFIDENCE (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs)	Generic MCDA Tool development and uncertainties handling	[128]
IIP1+	Rudi A.	Evaluation of biomass valorisation pathways	Systems	In progress
IIP2	Zimmer K.	Selection and management of suppliers in the automotive industry	Systems	[107]
IIP3*	Heck R.	Integrating the perspective of individual agents into the modelling and evaluation of biomass-based value chains	Systems	In progress
IIP4*	Treml N.	Development of two indicator sets contributing essential parts of the pig value chain – animal welfare and meat quality.	Systems	In progress

**Case studies from the Working Table, +Case studies presented in chapter 3 and the Working Table.*

4.2 Comparison

This chapter compares the activities (methods and use cases) using three main categories: sustainability criteria, MCDA methods and stakeholder's involvement. For use case IDs and general description please refer to Table 3.

Sustainability criteria

Given the sustainability approach of the different activities, the criteria presented by the authors cover the three dimensions of sustainability "environmental", "economic", and "social". UFZ and FZJ agree on the importance of the SDGs as guidelines/starting points to select the criteria. FZJ1.2's sensitivity analysis based on two concepts/views of sustainability (i.e. three sustainability dimensions and SDGs) confirms the great influence of the concept used on the results. ITAS6 finds challenging the definition of the perspective in an integrative assessment e.g. supply vs demand, local vs global.
Several activities report challenges associated to the definition of criteria and indicators (IIP4) especially for social assessment (ITAS2), and to achieve a common understanding of criteria and their interdependency (ITAS1, ITES1, IIP5). Among the activities, the selection of criteria and indicators starts with a literature review. After that, different strategies are applied, for example, DLR1's final selection is based on the authors' experience while DLR2 proposes a systematic procedure for this purpose. For environmental and economic criteria LCA- and LCC-based indicators are commonly used (UFZ, ITAS, DLR, FZJ). The social criteria differ more among the use cases. For example in ITAS2 and ITAS3 selection of social indicators is related to ICoS [129] whereas DLR1 uses (socio-)technical indicators relevant for users. In FZJ2, indicators are selected based on the SDGs. IIP2 presents a different methodology to quantify environmental and social criteria using statistical data from recognized institutions.

MCDA methods

The reasons behind the selection of the MCDA methods (for the ranking of alternatives) within the activities presented rely mainly on two different perspectives: simplicity and level of compensation. Table 4 summarizes the information related to the MCDA methods (weighting and ranking) and techniques for handling uncertainties in the case studies.

Table 4. Summary of MCDA methods/approaches presented in chapter 3 and Working Table (see Supplementary Material).

	Weights				Ranking				Uncertainty handling				
Use case (ID)	**SMART**	**AHP/ PC**	**DCE**	**Other**	**WSM**	**TOPSIS**	**PROMETHEE**	**Other**	**Criteria/indicator values**	**Weights**	**Sustain. concept**	**MCDA method**	**Techniques according to [13]**
DLR1+				Weighting scenarios			x			x			Sensitivity analysis, scenario analysis
DLR2+			x		x								None
FZJ1.1*				Equal weighting			x					x	Sensitivity analysis
FZJ1.2*				Equal weighting			x			x	x		Sensitivity analysis
FZJ2*	x						x			x			Sensitivity analysis
ITAS1+		x				x			x	x			Sensitivity analysis, Stochastic techniques
ITAS2+		x		Stakeholder Profiles (standard)		x			x	x			Sensitivity analysis
ITAS3+				Equal weighting		x			x	x			Sensitivity analysis
ITAS4 *		x				x			x				Sensitivity analysis (Trade-off analysis)
ITAS5*		x								x			Robustness analysis
ITAS7*		x											None
ITES1	x				x				x	x			Stochastic techniques sensitivity analysis
IIP1+		x										x	Sensitivity analysis, Scenario analysis, Stochastic techniques
IIP2		Fuzzy					Fuzzy					x	F-AHP / F- PROMETHEE
IIP3*		x					x		x	x			Sensitivity analysis, Scenario analysis
IIP4*		x											Not yet defined
UFZ				Social Multi Criteria Evaluation (SMCE)				Linear aggreg.	x	x	x		Sensitivity analysis

**Case studies from the Working Table, + Case studies presented in chapter 3 and the Working Table.*

Even though literature recommends the use of non-compensatory methods to handle sustainability assessment, WSM and TOPSIS (compensatory methods) are preferred by some authors given their ease of use and understandability, or as justified by ITAS2 and ITAS3, TOPSIS requires limited subjective input. The outranking method PROMETHEE was preferred in other cases because it does not allow full compensation (DLR1 and FZJ) and facilitates the integration of uncertainties (FZJ1.2 and IIP4). SMART, AHP and pairwise comparison are the most frequent methods for weighting the criteria. In other activities, given that these methods require time, resources and could lead to uncertainties, the authors use different approaches to obtain weights. For example, FZJ proposes the "Reverse MCDA" approach in which weights of criteria are taken from existing information e.g. sales figures. ITAS2 uses standardized stakeholder profiles to represent behaviour patterns.

Handling uncertainty is an important issue across the activities. The most frequent technique applied is sensitivity analysis for criteria, weights, and input data, followed by (with a much lower level of occurrence) scenario analysis and stochastic techniques. From this, some practices have been identified to provide robust results e.g. hierarchical equal weighting in ITAS2. FZJ's methodology for the integration of method-specific thresholds (e.g. from LCIA) increases the information value of results (FZJ1.1); however, the definition of thresholds for social and economic indicators remains a challenge in the proposed methodology. ITES presents its generic licence-free MCDA tool MCDA-KIT [95], which supports the inclusion of uncertainties through distribution functions and ensembles for the criteria values of the alternatives, and sensitivity analysis of weights and criteria values.

Stakeholders' integration

This section presents the categories of the stakeholders considered in the activities, the stages of the MCDA at which they participate, and the participatory formats used for preference elicitation (Table 5). The type of stakeholders integrated in the activities are described using the following categories: *no stakeholders involved* (0), *research and development* (1), *industry* e.g. manufacturers, energy companies, network operator (2), *government* (3), *Decision makers* e.g. developers, policy makers (4), *organized civil society* i.e. interest groups including statutory (e.g. lobby groups) and non-statutory associations (e.g. trade unions, NGOs, religious communities) (5), and *broad civil society* i.e. individuals affected by or interested in a specific initiative [130] (6). The level of participation is assigned to every activity using [22] as a reference.

Table 5. Specification of stakeholders' integration (categories, stages, formats, levels) of case studies presented in chapter 3 and Working Table (see Supplementary Material).

Use case (ID)	**Category according to [130]**	**Stage of MCDA**						**Participatory format**	**Level of participation according to [21]**
		Problem definition	**Alternatives selection**	**Criteria selection**	**Weighting**	**Method evaluation**	**Communic. of results**		
DLR1⁺	0							–	–
DLR2⁺	6				x			Focus groups (qualitative)	Low-moderate
FZJ1.1*	0							–	–
FZJ1.2*	0							–	–
FZJ2*	1				x			Workshop	Low-moderate
ITAS1⁺	1,2,3,4,6			x	x			Interviews and surveys	High
ITAS2⁺	0							–	–
ITAS3⁺	0							–	–
ITAS4*	1,2				x			VBA-xls elicitation	Low-moderate
ITAS5*	1,2,4				x			Workshop	High
ITAS6*	2,3,5			x				Workshop	Low-moderate
ITAS7*	5				x			–	Low
ITES1	1,5			x	x	x	x	Delphi survey, interviews, workshops	High
IIP1⁺	1,2				x			Interviews, questionnaires, workshops	Low-moderate
IIP2	2,4			x	x			Interviews, workshops	Moderate
IIP3*	1,2,4,5,6	x		x			x	Workshops, interviews, (online-) surveys	High
IIP4*	1,2,3,4	x		x	x			–	–
UFZ	1,2,3,4,5,6			x	x	x	x	Surveys, Workshops (SMCE)	High

**Case studies from the Working Table, + Case studies presented in chapter 3 and the Working Table.*

The stages at which stakeholders are considered within the activities presented are very diverse, the majority agrees on the importance of integrating stakeholders for selecting (screening) and weighting the criteria. The authors reported the following lessons learned/challenges from the integration of stakeholders in their activities:

FZJ2 describes the selection of the participatory format as a challenging step and reports the limitations of the method SMART to handle eight alternatives. ITAS1 states that unguided surveys are not a fully adequate participatory format for weight elicitation, whereas ITAS4 found VBA-xls with elicitation and direct result visualization to be useful. The participation formats and approaches used by ITES1 allowed to have transparent discussions within the study; however, the author reports using qualitative values for the preference elicitation to be challenging.

4.3 Discussion

The previous sub-chapters show a trend towards using established MCDA methods for sustainability assessment as well as different underlying sustainability concepts. The applications include diverse topics: bioeconomy, transport technologies (vehicles and fuels), supply chain management, energy systems and technologies, and location planning (biorefineries and solar parks).

In the sustainability assessments presented, the life cycle perspective is predominant. While environmental impacts are mostly comprehensively assessed using various LCA indicators, social and economic aspects are not elaborated to the same extent, possibly underrepresenting the complexity of sustainability e.g. by using only one or two economic (mainly related to costs) and social criteria (mainly social acceptance). This might be related to the limited access to data when comparing LCA approaches with more socio-economic oriented issues and becomes in particular relevant when technologies of low technology readiness level (TRL) are assessed. Apart from LCA, use of historic or statistical data (as presented for example by IIP2) might be a feasible approach to broaden socio-economic indicators.

The methodologies used for preference elicitation concerning the different criteria correspond to the subjective weighting category based on the stakeholders' preferences [131]. Although SMART (used by FZJ2 and ITES1) and AHP (used by ITAS and IIP) are easier to use and require less resources (e.g. time and software) when compared to other weighting methods like DCE (used by DLR2), Potentially All Pairwise Rankings of all Possible Alternatives (PAPRIKA) and Conjoint Analysis (CA), the chance of bias is higher [132]. The use of fuzzy logic is a common practice within MCDA applications to consider uncertainties and facilitate the interaction with stakeholders by providing scales of valuation that are closer to the way human beings make decisions [99]. Although only one of the case studies uses fuzzy logic, it is assumed to be a promising field to explore within the work of the group. Regardless of the method used, the process of weights elicitation requires the stakeholders to be adequately *informed* about the object of study (e.g. technologies, systems, policies) including potential interrelated aspects within one sustainability dimension [133]. For example, within the dimension environment, GHG emissions and climate change can lead to eutrophication of water or desertification and erosion of arable land. If such cause-effect-chains are neglected within the problem description, it can be that the effects are of more subjective relevance than the causes and thereby setting unfavourable incentives to overcome the problem itself.

When selecting an MCDA method for aggregation, i.e. to determine preference orders of alternatives, non-compensatory effects in the sustainability context should be kept in mind, as, for example, ecological systems usually cannot compensate specific negative effects by different positive effects: Not transgressing one planetary boundary does not revoke the transgression of another, if only one planetary boundary is transgressed, a long-term reproduction of societies is at stake, independent of subjective weighting. Outranking methods (e.g. PROMETHEE, ELECTRE) allow a differentiated discussion related to the mentioned cause-effect-chains because of their partially or non-compensating nature [17]. This is the reason why some of the activities presented show different applications of the outranking method PROMETHEE (FZJ, DLR). However, these outranking methods are more difficult to apply compared to other methods, e.g. TOPSIS and WSM, in the sense that they require higher cognitive effort from stakeholders e.g. for the definition of preference thresholds. To approach this challenge, FZJ proposes a methodology to define the preference/indifference thresholds for environmental indicators based on uncertainty of LCIA. The MCDA methods implemented in the different activities allow handling uncertainties at different levels e.g. input values, thresholds, or weights. In order to facilitate the sensitivity calculations and avoid re-running the model several times, having a software available for this analysis is an advantage.

The integration of stakeholders is perhaps one of the most challenging tasks in the activities presented. Different stakeholders and social groups might see a societal-ecological transformation as assertive and necessary on a normative level to go beyond business-as-usual and claim a global responsibility to provide a good life for all within planetary boundaries [86, 87]. However, when actually eliciting preferences in complex decision-making processes, stakeholders might have their own interests creating conflicts that must be considered and discussed (UFZ). The challenges of stakeholders' integration go beyond the representation of societal groups though. The identification of particular stages of an MCDA process where their integration is most effective, and the type of participatory format that is most appropriate for the respective context, each considering optimal use of resources, must be mentioned here.

The understanding and analysis of complex systems is in most cases more than the sum of their subsystems and would mean more than just combining their parts [90, 134, 135]. Nevertheless, the basic intention of using MCDA is to reduce complexity in order to enable support, discussion and reflection for decision-making processes when a variety of different aspects and interests come together in a specific issue. Sustainability transformations are especially subject to controversial societal mentalities and values, conflicts, practices and sometimes contradictory and irreconcilable positions, interests and ideologies [136-138]. The strength of reducing complexity with technical approaches like MCDA might cut short societally controversial and contradictory aspects. In this sense, it must be understood that MCDA-assisted models for sustainability assessment, as any other model, should be constantly reviewed and updated.

5. Conclusions & outlook

This document reflects the activities and interests of the Helmholtz Working Group MCDA, developed in the context of the Helmholtz program ESD Topic 1. Such activities are related to MCDA-assisted sustainability assessment in different contexts, e.g. bio economy, transport technologies, supply chain management, energy systems and technologies. These present a collection of approaches, from the conceptualization of sustainability in different contexts, lessons learned from the use of several MCDA methods (for preference elicitation and aggregation) and participatory approaches, to the development of methodologies to facilitate preference elicitation (with and without stakeholders) and adaptation of existing MCDA approaches to handle uncertainties.

This document reveals several opportunities to support MCDA-assisted sustainability assessment within the Helmholtz Working Group MCDA such as: enhancement of sustainability criteria (e.g. elaboration of socio-economic indicators, inclusion of criteria for resilience and responsibility), diversification of MCDA methods for preference elicitation (e.g. objective and subjective weighting methods, consideration of TRL) and aggregation (e.g. towards non-compensatory methods), and systematic integration of stakeholders not only for weighting but other stages of an MCDA, e.g. the selection of criteria. For the latter, questions of relevance of criteria, handling of qualitative data, practicability, and influence of underlying sustainability concept, need to be further addressed in the future.

Using MCDA requires critical reflections and a clear recognition and definition of conflicts and contradictions avoiding compensation of impacts or levelling out of societal and political controversies. Concerning the work of the Helmholtz Working Group MCDA, the research will be especially extended by the inclusion of transdisciplinary formats and qualitative analysis in order to make societal relations and complexities more transparent.
Tackling these challenges is as complex as the problem itself; therefore, this analysis proposes to address this task with two goals: i) to gather best practices for an integrative sustainability assessment that includes criteria and indicator selection, (MCDA) methods and stakeholder integration in an appropriate way, and ii) build on existing DSTs that facilitate the implementation of such best practices in different decision-making situations. This would contribute to a substantial improvement of sustainability assessments by:

- thematically enhancing, broadening, linking and adapting criteria and indicators according to the particular societal context in a transparent and changeable way;
- facilitating the implementation and use of suitable MCDA methods;
- including and considering stakeholder views in the whole process systematically aiming towards active involvement in different stages of MCDA (co-design).

The development of Helmholtz-wide best practices for sustainability assessments using MCDA could provide a first milestone on the way to developing an MCDA framework and DST for sustainability assessment.

HELMHOLTZ

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Annex 1

Table A1.1. MADM methods commonly used for energy technology assessment (taken from [97], re-structured based on [20])

Methods	Description	Utility	Applications
Value and Utility theory approaches			
Weighted sum method - WSM	Simple linear additive models, where weights are multiplied with the performance measure of an alternative to calculate final scores. The WSM based approaches use simple, ordinal scales (1-10 and tyically Likert scale 1-5) for weight attribution.	+simple computation, transparent / -only basic estimations, only single preference	Selection of renewable sources
Multi-Attribute Utility Theory - MAUT	In MAUT utility functions are defined to convert performance values of different criteria considered. on, e.g. a 0-10 scale. An advantage of the method is its simplicity as well as robustness.	+simple computation / -Difficult to get precise information from stakeholders	Energy planning, resource allocation
Multi-attribute Value Theory - MAVT	MAVT is comparable to MAUT but also considers the importance of criteria weights. This is often carried out by direct ratings	-simple computation / -Difficult to assign utility functions	Electricity generation (power expansion alternatives)
Simple Multi-Attribute Rating -SMART	Different way to apply MAUT through the use of weighted linear averages, that give close approximations to utility functions	+ Simple computation / - weights not clearly related	Renewable energy deployment decisions
Analytic Hierarchy Process – AHP	The decision problem is structured within a hierarchy. At the top is the general objective (e.g., choice of technology or policy). Criteria are set below this goal and can be further decomposed into sub-criteria, alternatives are at the bottom of this hierarchy. Within AHP, stakeholders attribute an individual preference to each criterion by pairwise comparisons (in total (n (n-1/2).	+Simple computation, consistency threshold / -interdependence of objectives	Electricity generation (H2-natural gas), Sustainability evaluation of electricity supply
Best-Worst Method - BWM	Based on pairwise comparisons (2n-3). a) a set of criteria is determined, b) best and worst criteria are identified; c) determination of preferences of the best criterion in relation to the other criteria (1-9 scale), d) the same is conducted for the worst criterion in relation to all other criteria; e) optimal weights have to be determined by minimizing the maximum absolute differences (e.g., through linear programming).	+ less comparisons as in AHP / - no consistency measurements	Supplier selection Energy efficiency in buildings
Outranking approaches			
ELimination and Choice Expressing REality - ELECTRE	This method is based on two main procedures: i) a multiple criteria aggregation procedure including the construction of outranking relation to compare each pair of actions; ii) result are then chosen, ranked or sorted. Outranking relations are based on concordance, dis-concordance indexes, and threshold values	+ Rankings are validated / - complex to apply, less versatile	Selection of wind energy projects

Methods	Description	Utility	Applications
Preference Ranking Organization METHod for Enrichment of Evaluations - PROMETHEE	The method is comparable to ELECTRE, but uses preference functions that allow it to measure difference between two alternatives related to any criteria. Six criteria functions are used to do so. Two pre-orders of alternatives are provided; based on ingoing and outgoing flows. Rankings are based on net flow yields	+ considers interdependency of criteria / - complex method, computation efforts high	Characterization of generation technology – feedstocks
Others			
Technique for Order Preference by Similarity to Ideal Solution - TOPSIS	TOPSIS is a method built on a simple principle: the selected best alternative should have the shortest (Euclidian) distance from the positive ideal solution in a geometrical sense while it has the longest distance from the negative ideal solution.	+simple computation / -does not consider difference between neg. & pos. values	Selection of sust. electricity generation

Annex 2

Table A2.1. Time perspective, required level of evidence, manageability (according to [139], [140]) and resulting priority settings for the sustainability dimensions (according to [141]) for cultural profiles Individualist, Hierarchist, Egalitarian.

	Individualist		Hierarchist	Egalitarian
Time perspective	Short-term		In between short and long-term	Long-term
Required level of evidence	Only proven effects		Effects on a consensus basis	All possible effects
Manageability	Technology can avoid many problems		Policy can avoid many problems	Problems can lead to catastrophic events
Priority	1	Economy	Ecology	Social
	2	Ecology	Economy	Ecology
	3	Social	Social	Economy