Evaluation of Energy Scenarios

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The assessment of future options and pathways for sustainable energy systems requires considering multiple techno-economic, ecological and social issues. Multicriteria analysis methods, which are useful tools that aid decision processes involving various and even conflicting qualitative and quantitative criteria, could support such comprehensive analyses. With regard to energy policies, the key actors and stakeholders' acceptance of emerging and innovative technologies for generating, converting and storing electricity, heat and fuels is crucial for their future implementation. The multiactor multicriteria (MAMCA) methodology was developed to involve stakeholders with vastly different views and objectives when addressing complex societal problems.

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1. Introduction

The transition from the current electricity system to a renewable electricity supply poses immense economic, technological and policy challenges [1][2]. Within this process towards a more sustainable energy system, energy scenarios can be a valuable instrument [3]. Energy scenarios are representations of possible development paths towards desired future energy system states, in order to provide guidance for decisions associated with the transition process [4][5].

Allowing citizens and companies to invest in renewable energy and thereby become independent power producers has not only advanced the population's acceptance of renewable energy but has also accelerated the move towards a more decentralised and sustainable power supply [6][7]. Consequently, energy policies need to take divergent groups of key actors and stakeholders' viewpoints into account. In turn, when transforming an energy system, policy-makers need to take multiple, often conflicting, criteria and stakeholder interests into account in order to identify, evaluate and, ultimately, implement possible development paths [8].

Multicriteria analysis's (MCA) methods have been used to support decision processes involving energy scenarios and to explicitly allow for conflicting criteria (e.g., investments or emissions) [9][10][11]. In this context, these methods offer the possibility of evaluating several energy scenarios and considering path dependencies [3] but without explicitly taking different stakeholder objectives into account. See [8] for a recent overview of studies applying MCA to evaluate energy scenarios.

Without stakeholder acceptance, emerging and innovative technologies' smooth implementation to generate, convert and store electricity, heat and fuels may be unlikely [11]. Recent public reactions to projects related to energy supply have highlighted the importance of the public's acceptance of energy policy measures to ensure they support realised projects [12].

2. Application of the Multiactor Multicriteria Analysis for the Evaluation of Energy Scenarios

In this section, we present an application of the MAMCA method. The case study aims to illustrate the MAMCA method's functionalities and to highlight this method's distinctive contributions to decisions in the context of energy scenario planning. We do so by examining a bioenergy village in Lower Saxony, Germany [7][13]. The village's goal is to transition to a self-sufficient power supply by expanding the capacity of its renewable energy technologies. The village has 1000 inhabitants and an electricity demand of 8021 MWh per year. The target is to satisfy at least 94% of the electricity requirement (7518 MWh/a) through renewable energy sources. The grid can provide the remaining 6% (503 MWh/a) required for peak loads. In the following, the MAMCA framework's steps, are applied consecutively.

- **Step 1:** Identification of alternatives

There are three different renewable energy technologies available to this village. To achieve further decarbonisation and increase the village's self-sufficiency, it can utilise solar energy, wind power and biomass fermentation [13]. **The photovoltaic (PV) systems can** either be built on rooftops or installed as ground-mounted systems.

Based on this information, we define the decision problem's alternatives as the different transition paths' final states which the village should achieve within the 20-year planning horizon. Figure 1 illustrates the relevant configurations.

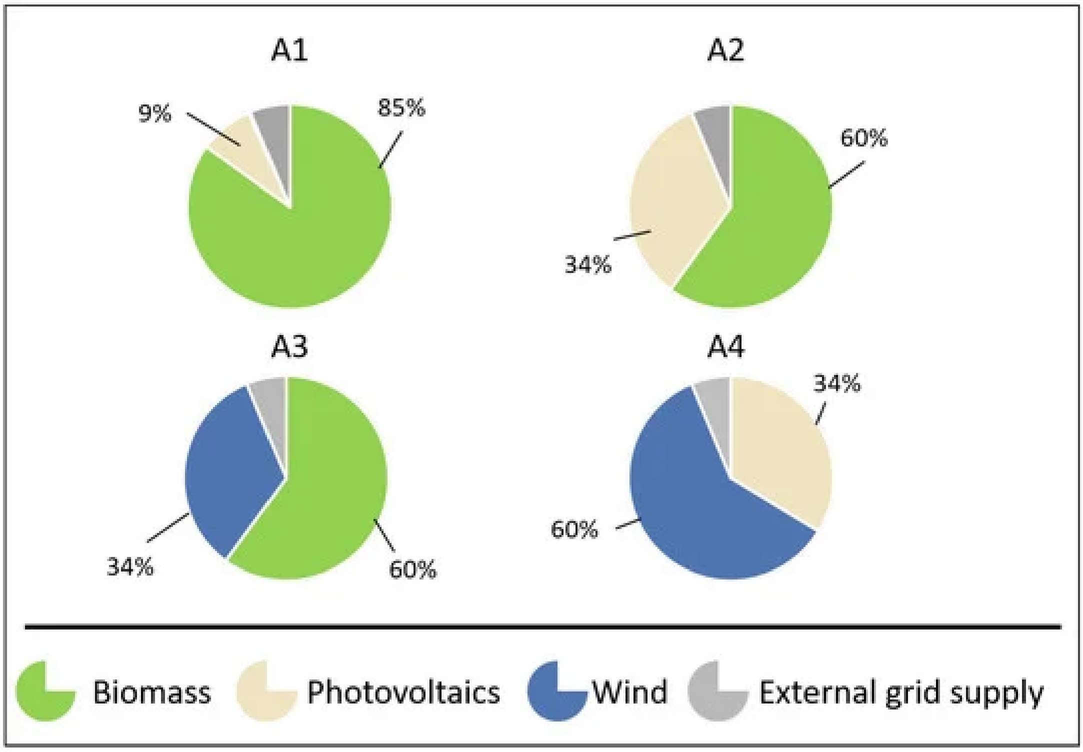

Figure 1. Alternative energy scenarios for self-sufficient electricity supply of a bioenergy village in Germany. Solar power, wind power and biomass fermentation can be utilised for the supply of electricity. The depicted scenarios represent the final states of the villages' energy system at the end of a 20-year transition process. While each alternative proposes a different utilisation of electricity from renewable sources, reliance on grid supply is required only at peak load times for up to 6% of total annual demand.

- **Status quo alternative (A1):**

  This alternative depicts the village's currently planned energy system. This scenario is included in the analysis in order to check whether altering the village's energy scenario would be at all beneficial. In this transition path's final state, biomass fermentation with additional photovoltaic systems will provide electricity. The remaining share of electricity supply is provided externally by the grid.

- **Biomass and photovoltaics (A2):**

  This path focuses on providing electricity from biomass, which amounts to 60% of the total electricity production. Rooftop photovoltaic systems cover 34% of the demand, while the grid provides the remaining 6% of the total demand.

- **Biomass and wind turbine (A3):**

  This energy scenario introduces generating electricity by means of wind turbines. This scenario's setup is quite similar to A2 but with electricity from a wind turbine replacing the share of electricity from solar energy.

- **Wind turbine and photovoltaics (A4):**

  In this path, biomass is not used and wind energy replaces the share of biomass in A2 and A3 (accounting for 60% of the village's total electricity supply), while rooftop photovoltaic systems (34%) and the grid (6%) provide the remaining energy from renewable sources.
- **Step 2:** Stakeholder analysis

Now that the alternatives have been defined, the stakeholders need to be identified and characterised. In our case study, we consider hypothetical village inhabitants and a group of experts and academics to be stakeholders. The village inhabitants are split into three demographic age groups, namely those who are 29 or younger, those between 30 and 50 years of age and those inhabitants older than 51 in order to testify the algorithm. We chose this group configuration, since we regard the inhabitants' diverging goals and criteria as closely tied to their age. However, this does not necessarily imply that the relevant groups are fully homogeneous or that there are no intersecting opinions between them. We include the expert and academic group to foster mutual learning for all stakeholders by integrating the local inhabitants' interests, values and beliefs with the technical experts' knowledge through consulting and exchanging of information, as [14][15][16][17] advise.

- **Step 3:** Determination of criteria and weights

The criteria and the stakeholder groups' respective weightings are illustrated in Figure 2 and reflect their slightly diverging interests. While some criteria are universal across all stakeholder groups, some of the criteria are either exclusive to a certain group or of different importance.

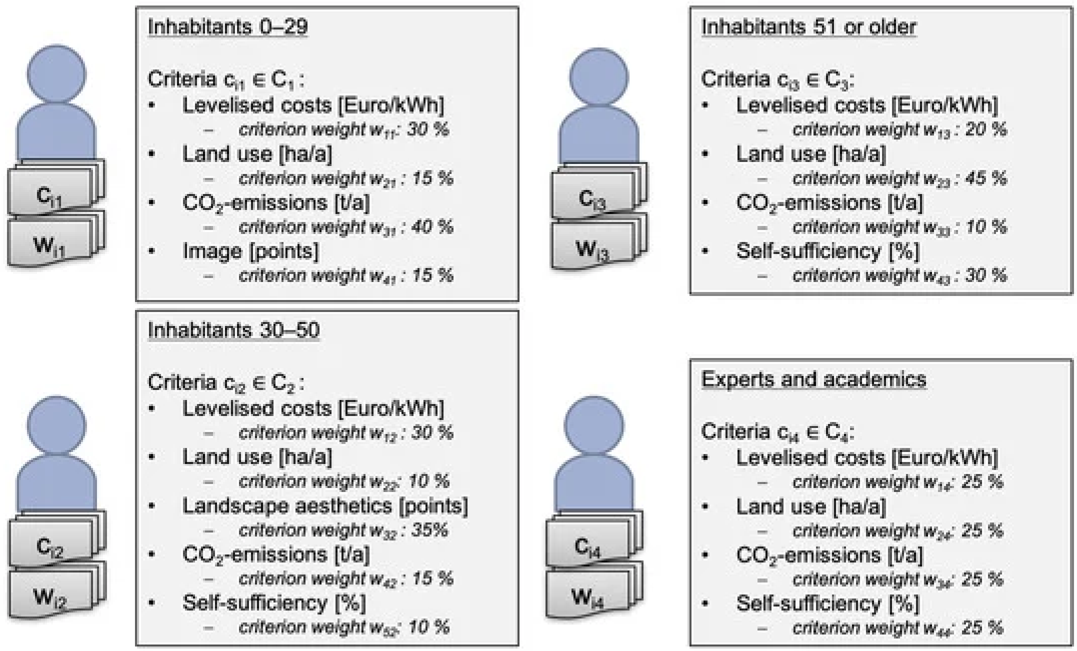

Figure 2. Criteria and criteria weights for the different stakeholder groups, which are being determined in the third step of the MAMCA method. Stakeholder groups are the village inhabitants, which are split into three demographic

age groups, as well as a group of experts and academics. Each stakeholder group is granted a separate set of criteria and criteria weights to account for diverging objectives.

The overall set of criteria assesses the alternatives with regard to their environmental, economic, social and technical aspects, finding that they are adequate [18]. The criteria are defined and measured as follows:

- **Levelised costs of electricity (LCOE)**

  reflect the average cost per unit of electricity generated. These costs are measured in Euro per kilowatt and hour [Euro/kWh].

- **Land-use**

  is measured in hectare of covered area in the village per year [ha/a]. This is the area that the power generation system covers and for biomass cultivation [19].

- **CO_2-emissions**

  are only considered in respect of the share of electricity drawn from the grid. These emissions are measured in tons per year [t/a].

- **Degree of self-sufficiency**

  measures the share of electricity the village is able to draw from renewable sources as a percentage of the total electricity demand across the transition process.

- **Landscape aesthetics**

  are measured on a point scale ranging from 1 to 10. Higher scores represent more attractive aesthetics, while lower scores represent rather unattractive visual perceptions of the employed technologies.

- **Image** refers to the perceived social acceptance of the energy technologies to be utilised [20] and is measured on a point scale ranging from 1 to 10. Higher scores indicate that a group of stakeholders links the employed technologies with a higher social acceptance and vice versa for lower scores.

- **Step 4:** Determination of performance scores

The performance scores are averaged over the transition period of 20 years and determined as follows:

The calculation of the *levelised costs* of renewable technologies is based on the studies by Nestle and Wissel et al. [21][22]. The levelised costs of electricity drawn from the grid are calculated by using the values provided by the

German Association of Energy and Water Industries [23] and supplemented by the information from the Federal Statistical Office of Germany [24].

Regarding the *land use*, we assume that photovoltaic-rooftop systems do not occupy any space. The other energy technologies' specific land requirements are taken from [19]. The highest land use is required in scenario A1, in which the cultivation of crops for the biomass plant occupies larger surface area than in the other scenarios (494.95 ha/a). Consequently, the scenario that does not consider electricity from biomass (A4) occupies the least surface area.

The *CO_2-emissions* due to the power drawn from the grid are derived from [25], while energy from renewable sources is considered carbon neutral. A linear regression was performed based on the power grid CO_2 -emissions between 1990 and 2017 from [25] to estimate those during the entire transition period in the presented case study.

Owing to solar and wind energy's volatile nature, the village's electricity demand is sometimes not matched or even surpassed. Using standard load profiles (SLP) for households and agricultural holdings [26], we extrapolated the village's annual energy demand. The resulting hourly demand was compared to the amount of electricity from renewable sources fed into the local distribution network [27] and used to calculate the degree of *self-sufficiency*. When demand cannot be fully met, additional electricity is purchased from the grid, but when there is an oversupply, the surplus electricity is fed back into the grid. Accordingly, self-sufficiency is highest in scenarios where a biomass plant is employed. Without a biomass plant, which is able to offset the variability of the more volatile energy provision from wind and photovoltaics, the lowest percentage of self-sufficiency is reached (13%), as seen in scenario A4.

Regarding the qualitative criteria *image* and *landscape aesthetics*, and given this case study's illustrative purpose, we assigned exemplary scores. For the complete performance matrix and each of the actors' scores, see Table 1.

Table 1. Performance matrix for all stakeholders based on their respective criteria. Accordingly, only the criteria to be considered vary between stakeholder groups, while the actual performance of an alternative regarding a criterion does not vary between stakeholder groups.

Stakeholder	Criteria	Unit	A1: Status quo	A2: Biomass and Photovoltaics	A3: Biomass and Wind Turbine	A4: Wind Turbine and Photovoltaics
Inhabitants	Levelised costs of electricity	[Euro/kWh]	0.1134	0.1185	0.1003	0.1117
0–29	Land use	[ha/a]	494.95	377.63	384.11	23.12
	CO_2-emissions	[t/a]	1638.83	1952.40	1952.40	2074.78

Stakeholder	Criteria	Unit	A1: Status quo	A2: Biomass and Photovoltaics	A3: Biomass and Wind Turbine	A4: Wind Turbine and Photovoltaics
	Image	[points]	2.00	5.00	4.00	8.00
Inhabitants	Levelised costs of electricity	[Euro/kWh]	0.1134	0.1185	0.1003	0.1117
30–50	Land use	[ha/a]	494.95	377.63	384.11	23.12
	Landscape aesthetics	[points]	7.00	8.00	4.00	1.00
	CO_2-emissions	[t/a]	1638.83	1952.40	1952.40	2074.78
	Self-sufficiency	[%]	19	17	18	13
Inhabitants 51	Levelised costs of electricity	[Euro/kWh]	0.1134	0.1185	0.1003	0.1117
or older	Land use	[ha/a]	494.95	377.63	384.11	23.12
	CO_2-emissions	[t/a]	1638.83	1952.40	1952.40	2074.78
	Self-sufficiency	[%]	19	17	18	13
Experts and	Levelised costs of electricity	[Euro/kWh]	0.1134	0.1185	0.1003	0.1117
academics	Land use	[ha/a]	494.95	377.63	384.11	23.12
	CO_2-emissions	[t/a]	1638.83	1952.40	1952.40	2074.78
	Self-sufficiency	[%]	18.67	16.79	17.57	13.08

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...one of the six generic types of preference functions that PROMETHEE provides [28] to each criterion. With respect to the quantitative criteria, we chose the Type III linear preference function, in which the preference increases linearly until the deviation in the performance scores between two alternatives equals the strict preference threshold. The preferences regarding the qualitative criteria *image* and *landscape aesthetics* were modelled using the Type II preference function, in which the preference only prevails if the deviation in the performance scores surpasses the indifference threshold *q*. For a further description of the six types of preference functions available in PROMETHEE, see Table A1. For illustrative purposes, the preference modelling in this case study universally applies for all stakeholders, whereas for practical applications, a separate determination for each stakeholder might be advisable.

Table 2. Preference modelling for the criteria considered in this case study. The outranking method PROMETHEE provides six different types of preference functions to model the intracriterial preferences of a stakeholder. Depending on the chosen type of preference function, the according preference parameters were calculated for this case study.

Criteria	Orientation	Unit	Preference Function	Preference Parameters
Levelised costs of electricity	Min	[Euro/kWh]	Type III: Linear	$p_{il} = 0.0812$
Land use	Min	[ha/a]	Type III: Linear	$p_{il} = 471.83$
CO_2-emissions	Min	[t/a]	Type III: Linear	$p_{il} = 435.95$
Self-sufficiency	Max	[%]	Type III: Linear	$p_{il} = 6$
[29]Image	Max	[points]	Type II: Quasi p_{il}	$p_{il} = 6$, $q_{il} = 1.2$
Landscape aesthetics	Max	[points]	q_{il} Type II: Quasi	$p_{il} = 6$, $q_{il} = 1.2$

between

Aggregating the data according to PROMETHEE yields numerical results as shown in Table 3 as a basis for the calculation of the MAMCA overall flows. Since the crucial part in the MAMCA methodology, just as in other multicriteria decision support methods, is not the generation of hard numerical values but to provide the decision maker with useful information to derive an informed decision, further processing and evaluation of these outranking flows is required.

Table 3. Assessment of alternatives for the different stakeholders according to PROMETHEE as a basis for the calculation of MAMCA overall flows.

		Alternative a_j			
Stakeholder Group s_l	**PROMETHEE Flows**	**A1: Status quo**	**A2: Biomass and Photovoltaics**	**A3: Biomass and Wind Turbine**	**A4: Wind Turbine and Photovoltaics**
Inhabitants 0–29	$\phi^{+}_{1}(a_j)$	0.3532	0.1005	0.3379	0.3225
	$\phi^{-}_{1}(a_j)$	0.3055	0.3489	0.1848	0.2708
	$\phi^{net}_{1}(a_j)$	0.04767	−0.2483	0.1489	0.05170
Inhabitants 30–50	$\phi^{+}_{2}(a_j)$	0.43328	0.2783	0.4065	0.1306
	$\phi^{-}_{2}(a_j)$	0.13077	0.2431	0.3008	0.5740
	$\phi^{net}_{2}(a_j)$	0.3025	0.0353	0.1057	−0.4435
Inhabitants 51 or older	$\phi^{+}_{3}(a_j)$	0.2500	0.1154	0.3010	0.4086

Stakeholder Group s_l	**PROMETHEE Flows**	**Alternative** a_j **A1: Status quo**	**A2: Biomass and Photovoltaics**	**A3: Biomass and Wind Turbine**	**A4: Wind Turbine and Photovoltaics**
	$\phi^{-}_{3}(a_j)$	0.2767	0.2969	0.1575	0.3438
	$\phi^{net}_{3}(a_j)$	−0.0268	−0.1816	0.1435	0.0648
Experts and academics	$\phi^{+}_{4}(a_j)$	0.3516	0.1008	0.3218	0.2486
	$\phi^{-}_{4}(a_j)$	0.1914	0.3020	0.1387	0.3907
	$\phi^{net}_{4}(a_j)$	0.1602	−0.2012	0.1831	−0.1420

extensive with wind ricity from habitants between 30 and 50. This stakeholder group rates wind turbines and photovoltaic systems' deployment (A4) noticeably worse than the other groups, given a PROMETHEE net flow of −0.4435. Using PROMETHEE's unicriterion net flows, we conducted an intrastakeholder analysis to examine the reasons for this negative assessment. Figure 4 depicts this intrastakeholder ranking of the group of 30 to 50-year-old inhabitants' alternatives and reveals how each alternative performs in terms of this group's criteria set. It is clear that the use of wind power and solar panels is evaluated remarkably negatively in terms of the criterion *landscape aesthetics*, therefore possibly requiring a sensitivity analysis of this criterion's weights. On the other hand, this knowledge is also a valuable starting point for the communication process with this group of inhabitants and allows the design and implementation of measures that specifically address the landscape aesthetics. The configuration of energy scenario A4 could also be slightly modified or another iteration of the analysis could be undertaken.

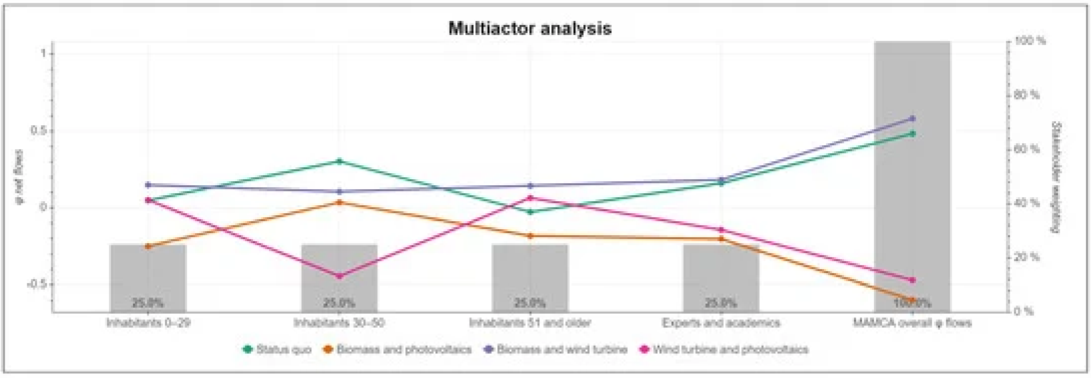

Figure 3. Multiactor view after assessment and aggregation according to PROMETHEE.

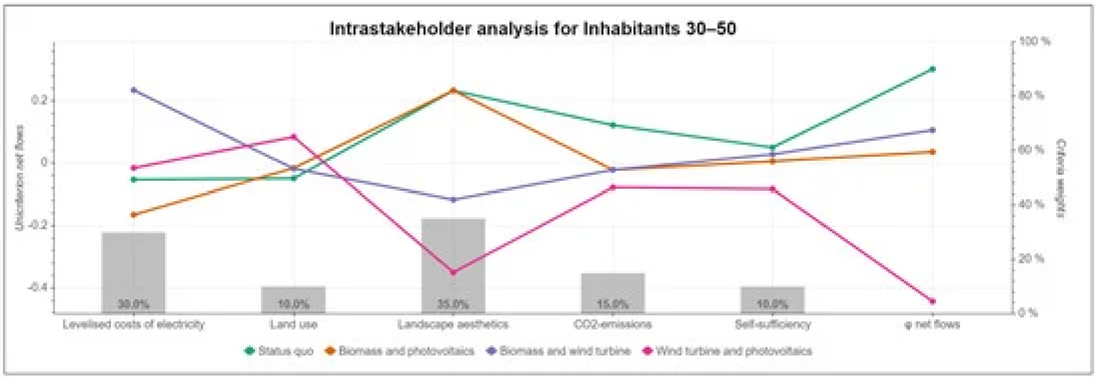

Figure 4. Intrastakeholder analysis view for the stakeholder group 30–50 years.

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