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*Article*

# Transdisciplinary Evaluation of Energy Scenarios for a German Village Using Multi-Criteria Decision Analysis

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**Abstract:** Multi-Criteria Decision Analysis (MCDA) can assist local decision processes towards selecting renewable energy systems as it is able to manage qualitative data and offers opportunities to integrate knowledge from local stakeholders. However, little experience is available regarding practical applications of MCDA in real decision processes in communities on their path towards a renewable energy supply. Within the "Bioenergy-Region Ludwigsfelde" project, an MCDA evaluation has been applied to a small village on its way to becoming a "bioenergy village". Here, MCDA has been combined with already established tools accompanying the process to becoming a "bioenergy village", such as planning workshops, citizens' meetings and best-practice trips. A comprehensive set of sustainability criteria was applied aimed at addressing the questions of local actors. An emphasis was placed on social criteria that comprise the perceived values of local impacts. In general, it was observed that MCDA provides many benefits for this application context. In particular, the group weighting using the SIMOS method demonstrated good results in the process. However, for real-world applications of MCDA, the challenge of data compilation in particular must be addressed.

**Keywords:** Multi-Criteria Decision Analysis; PROMETHEE; renewable energy systems; public participation; sustainable development

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## 1. Introduction

Renewable energy systems play an important role in the path towards sustainable development [1]. In the European Union, a goal of 20% was agreed upon in 2008 as the gross final energy consumption to originate from renewable energy sources [1]. In 2010, the German government adopted the German energy concept, which outlines the German energy strategy until 2050. In this concept, renewable energies will contribute the major share to the future energy mix: 18% of the gross final energy consumption by 2020, 30% by 2030, 45% by 2040, and 60% by 2050 [2]. However, when decisions concerning energy infrastructure investments are made, they are often more positive for traditional energy systems based on fossil fuels or nuclear power, which are associated with lower costs in the short run. By contrast, renewable energies are associated with less environmental pollution while exhibiting more local impacts [3]. To implement sustainable development in the energy sector, all of the economical, ecological, and social aspects must be taken into account. Multi-criteria decision-making can assist in this decision-making process.

Because of the different characteristics of the method, Multi-Criteria Decision Analysis (MCDA) (In this article, MCDA is used as an umbrella term for all of the different terms and methods within the field of multi-criteria decision analysis. See chapter 4.2 in [4] for details on the different approaches) is suitable for implementation and evaluation of systems aimed at sustainable development [4,5]. Depending on the MCDA method used, it is possible to consider qualitative data on the basis of ordinal scales. In this manner, social and ecological data can be integrated using qualitative data where quantifiable data are not available in the database.

Furthermore, MCDA offers participatory elements that support transdisciplinary approaches. Because of the mainly decentralized character of renewable energy systems, the perceivable local impact of the plants is more widespread compared with a conventional energy supply. More residents are directly affected by the energy systems; therefore, participatory decision-making is needed in the energy sector. In MCDA, these impacts can be integrated, for instance, by a participative weighting of criteria. Within the Multi-Attribute Decision Making (MADM) methods (In MCDA, MADM and MODM (Multi-Objective Decision Making) are distinguishable. In contrast to MADM, MODM calculates the best solution. For more details on the MCDA theory, see [6,7]), a set of finite alternatives is evaluated according to certain criteria, for example, using sustainability criteria. Stakeholders have the opportunity to assign weights to the criteria in order to be able to combine their evaluation with scientific data to achieve a ranking of the alternatives [6]. In addition, the development of alternatives and criteria from the participation of the stakeholders is possible [4].

Several different approaches to prepare a MCDA process are possible (see [4], [8], and [9] as examples). These generally include many common basic steps. However, the order of these steps may differ depending on the decision context. An outline of the steps acquired from a decision-making manual for communities and local governments in Great Britain [10] is reproduced below:

1. Establish the decision context. What are the aims of the MCDA, and who are the decision makers and other key players? (Paragraph 2)
2. Identify the alternatives. (Paragraph 3)
3. Identify the objectives and criteria that reflect the value associated with the consequences of each alternative. (Paragraph 4)

4. Describe the expected performance of each alternative against the criteria. (Paragraph 4)
5. Assign weights for each of the criteria to reflect their relative importance to the decision. (Paragraph 5)
6. Combine the weights and scores for each of the alternatives to derive an overall value. (Paragraph 6)
7. Examine the results. (Paragraph 6)
8. Conduct a sensitivity analysis of the results to changes in scores or weights. (Paragraph 6)

Other approaches perform the MCDA in cycle processes (see [4] or [9]). Depending on the decision context, undergoing the process more than one time and adjusting for instance criteria, alternatives or weights can be useful.

MCDA has been applied in the energy sector many times. Many case studies have evaluated renewable energy technologies against each other or compared renewable energies with conventional energy technologies or systems [11–16]. MCDA has been widely used for energy policy analysis, energy utility operations or environmental control and management [12]. However, in general, those case studies are described from the perspective of MCDA in a research environment and not from the perspective of a real decision context [15]. Often an ex-post analysis is absent, which could provide practice recommendations regarding the application of MCDA in the energy sector [15].

A real world application of MCDA in a bioenergy village is presented in the following paragraphs along with the steps of the MCDA process. The discussion explores the implementation of MCDA in that context and provides an ex-post analysis regarding the practice aspects.

## 2. Case Study: The Decision Context

The "Bioenergy-Region Ludwigsfelde", which began in 2009 in the federal-state Brandenburg, is part of the federal funding for "Bioenergy-Regions" available through the German Federal Ministry of Food, Agriculture and Consumer Protection. The task of this specific project in Ludwigsfelde is to establish a network in the region that supports the development of sustainable bioenergy projects. The concept of "bioenergy villages" has been established in Germany since the successful implementation of the "bioenergy village Jühnde" in 2005 [17]. This concept of consensus orientated to the use of waste heat for district heating evoked the interest of more than 200 inhabitants of a small village in the Ludwigsfelde region.

Since then, the process towards the creation of a "bioenergy village" has been successfully reproduced in five villages near Lower Saxony [18]. Using evidence from this established process, we integrated the MCDA to evaluate the outcomes for sustainability using different scenarios:

In order to introduce the concept of a "bioenergy village", several meetings and events took place. After a first meeting with the village council, a broad citizens' meeting for the residents and a best-practice trip to a nearby biogas plant were organized. After that trip, we conducted two MCDA workshops. At this stage, many concerns and questions regarding the transport, smell, noise and other disturbances of the new heating system dominated the discussion among the residents. After the MCDA workshops, further citizens' meetings were organized.

The decision-making body in the village was composed mainly of residents, as it was aimed at the collective approach from Jühnde. In this cooperative approach all heat customers and biomass suppliers are common owners of the biomass plant and the district heating [17]. The aim was to involve not only the powerful actors but also the residents who would be affected by the biogas plant in the MCDA process. In order to identify these actors, semi-structured interviews with five key actors were conducted: two farmers that were supposed to supply biomass, the local mayor, the owner of the aquaculture, and a citizen of the village who was strongly convinced of the idea of a bio energy village. The interviews further helped the project team to understand interactional patterns as well as power and trust constellations within the village.

For the MCDA workshops, all of the participants of former events and the key actors identified in the interviews were invited to participate. In the first and second workshop, 11 and 13 actors were involved, respectively.

## 3. The Scenarios

For the MCDA evaluation of alternatives, the project team identified different bioenergy and fossil fuel scenarios. Based upon the evidence gathered in the interviews, the team attempted to capture the decision of the village: Whether they supported the conversion to a bioenergy system and if so, what that would look like. Participatory development of scenarios with the group of actors was not considered useful at this stage of the project.

The scenarios described the energy supply for the 70 households (with approximately 200 inhabitants) of the village based on either a small biogas plant (biomass of one farmer) or a larger one (including the biomass of a second farmer), combined with different sizes of an aquaculture plant. The energy consumption of each household was assumed to be 4,500 kWh of electricity and 30,000 kWh of heat. The aquaculture, being a closed-loop system, is an additional heat consumer and is thus beneficial for the efficiency of the biogas plant. A certain heat demand of the aquaculture is available even in the summer such that the combined heat and power plants have a better operating grade. Three different plant sizes (50 kW, 100 kW, 150 kW thermal power) for the aquaculture component were modeled. Two fossil fuel scenarios were developed as reference scenarios. The first followed a "business as usual" (BAU) pattern of energy consumption in which all the households maintained their fossil fuel heating. The second scenario included additional central heating gas for a medium-sized aquaculture. Figure 1 provides an overview of the scenarios.

**Figure 1.** Scenarios evaluated using Multi-Criteria Decision Analysis (MCDA).

| scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| fuel feed | biogas: 2 farmers | | biogas: 1 farmer | | | fossil fuel | |
| aquaculture | medium | big | small | medium | none | none | medium |

Depending on the heat available from the biogas plant after the subtraction of the aquaculture heat demand and transport losses, the number of houses connected to the district heating was calculated. To ensure a secure heat supply, a central boiler based on woodchips was added to the district heating system. The details are provided in Table 1.

**Table 1.** Technical data of the scenarios.

| *Scenario* | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
|---|---|---|---|---|---|---|---|
| **biogas plant key data** | | | | | | | |
| cow dung input | 6,000 t | 6,000 t | 4,500 t | 4,500 t | 4,500 t | - | - |
| grass silage input | 500 t | 500 t | 500 t | 500 t | 500 t | - | - |
| corn silage input | 2,000 t | 2,000 t | - | - | - | - | |
| electrical power | 252 kW | 252 kW | 126 kW | 126 kW | 126 kW | - | - |
| thermal power | 286 kW | 286 kW | 143 kW | 143 kW | 143 kW | - | - |
| full load hours | 7,500 h | 7,500 h | 7,500 h | 7,500 h | 7,500 h | - | - |
| **peak load boiler** | | | | | | | |
| heat capacity | 988 kW | 781 kW | 567 kW | 254 kW | 867 kW | - | - |
| heat production | 1,609 MWh | 1,097 MWh | 846 MWh | 292 MWh | 1,511 MWh | - | - |
| woodchips quantity | 408 t | 278 t | 214 t | 74 t | 384 t | - | - |
| **aquaculture** | | | | | | | |
| thermal power | 100 kW | 150 kW | 50 kW | 100 kW | - | - | 100 kW |
| head demand | 873 MWh | 1,013 MWh | 437 MWh | 873 MWh | - | - | 873 MWh |
| **district heating** | | | | | | | |
| grid length | 1300 m | 800 m | 800 m | 500 m | 1300 m | - | - |
| connected houses | 63 | 42 | 37 | 8 | 65 | - | - |
| head demand | 1,890 MWh | 1,260 MWh | 1,110 MWh | 240 MWh | 1,950 MWh | - | - |
| **remaining (fossil) households** | | | | | | | |
| gas-fired houses | 7 | 26 | 31 | 53 | 5 | 60 | 60 |
| oil-fired houses | 0 | 2 | 2 | 9 | 0 | 10 | 10 |

## 4. The Set of Criteria

The set of criteria for this case study was based on a literature review, expert discussions and discussions with local actors. The main purpose was a more "holistic" evaluation of energy scenarios based on the concept of sustainable development. Sets of indicators for this purpose have been published many times. Within the framework of the EU-project REQUIRES (New Energy Externalities Developments for Sustainability), Burgherr *et al.* provide a comprehensive overview on international and national criteria sets for sustainability assessment as well as for energy assessment [19]. Furthermore, sets of indicators are available in MCDA case studies applied in the energy sector [14,16]. For bioenergy, however, notably less research is available. Buchholz *et al.* [20] present an overview based on an expert survey, and Eigner-Thiel *et al.* [21] published a detailed elaboration of criteria for the evaluation of bioenergy systems, which was used extensively in this case study.

Based on the literature review, we compiled a first set of 32 criteria. Based on internal and external discussions on data availability, a final set of 27 indicators was selected.

For better handling of criteria, two further hierarchy levels were introduced: 11 "areas of sustainable development" and three columns of sustainability. To maintain an evaluation process that was both manageable and comprehensible for the actors, "areas of sustainable development" were used for the weighting process.

The data were quantified and related to one Megawatt hour (MWh) exergy. With the help of this energy parameter, the scenario output parameters of heat and electricity were made comparable.

**Table 2.** Set of criteria applied in the case study.

| | Area of Sustainable Development | Criterion | Indicator | Criterion Description | Unit |
|---|---|---|---|---|---|
| Ecological Indicators | **air and climate protection** | protection of climate | $CO_2$ equivalent | Global warming is caused by an increased concentration of greenhouse gases in the atmosphere. The indicator "$CO_2$-equivalents" combines the global warming potential of several greenhouse gases [22]. | kg/MWh exergy |
| | | acidification | $SO_2$ equivalent | The indicator combines all acidifying pollutants. These pollutants have a wide variety of impacts on the soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings) [22]. | kg/MWh exergy |
| | | human toxicity | 1,4-dichlorobenzene equivalent | Human toxicity describes the impact of toxic substances present in the environment on human health. The toxicity results from the emissions of these toxic substances into the air, water and soil [22]. | kg/MWh exergy |
| | **protection of soil** | ecotoxicity | 1,4-dichlorobenzene equivalent | Ecotoxicity describes the impact of toxic substances on terrestrial ecosystems. This indicator combines all the emissions of toxic substances into the air, water and soil [22]. | kg/MWh exergy |
| | | local erosion | C-factor * land use | Erosion leads to a loss of functionality of the agricultural soil. The C-factor determines the relative effectiveness of the soil and crop management systems in terms of preventing soil loss [23]. | ha/MWh exergy |
| | **protection of water** | aquatic eutrophication | $PO_4$ equivalent | Aquatic eutrophication covers all the potential impacts of excessively high environmental levels of macronutrients, emitted into the air, water and soil [22]. | kg/MWh exergy |
| | | fresh water toxicity | 1,4-dichlorobenzene equivalent | Fresh water toxicity refers to the impact of toxic substances on freshwater aquatic ecosystems. The indicator combines the fresh water toxicity potential for each emission [22]. | kg/MWh exergy |
| | **protection of resources** | cumulative energy demand (non-renewable) | | Cumulative energy demand covers the total amount of primary energy used in terms of non-renewable resources. | kWh/ MWh exergy |
| | | demand of mineral resources | | The scarcity of mineral resources is understood to be an important problem especially in agriculture [21]. | kg/MWh exergy |
| | | demand of water | | The demand of water covers the quantity of water withdrawn, in particular for operating the aquaculture. | litre/ MWh exergy |
| | | land requirements | | The land area, especially in an unsealed and non-built-up state, is a scarce resource [21]. This indicator measures the total land requirements without evaluating the different types of land use. | m²/MWh exergy |

**Table 2.** *Cont.*

| | Area of Sustainable Development | Criterion | Indicator | Criterion Description | Unit |
|---|---|---|---|---|---|
| Social Indicators | **employment** | employment | | Number of long-term jobs. | average number of jobs/year |
| | **effects on personal environment** | perceived noise | | An estimation of people perceiving the noise as annoying. Noise may be considered a nuisance by one person and appreciated by another [21]. | relative scale |
| | | perceived smell | | An estimation of the emission of smell perceived as distracting. | relative scale |
| | | risk of accidents | | People often associate risks of accidents or disasters with technical plants; this association can differ depending on the type and size of the technology and plant [21]. | relative scale |
| | | transport | | The average local traffic volume caused by the biogas plant and the aquaculture. | number of transports / year |
| | **effects on local scenery** | biogas plant | | A biogas plant can be assessed as being more or less aesthetically pleasing [21]. | relative scale |
| | | energy crop cultivation | | Different cultivation concepts have different impacts on the aesthetics of the landscape [21]. | relative scale |
| | **competition to food production** | area used for energy crops instead of food production | | Potential conflict between using the agricultural soil for energy crop cultivation instead of for food production. | ha/MWh exergy |
| | **regional cohesion** | evaluation based on number of households | | Taking part in a project commonly considered as environmental friendly enhances the team spirit and group feeling of the entire group of activists [21]. | relative scale |
| Economic Indicators | **regional value added** | sum of regional investments, periodic costs and local tax revenues | | The regional value sums the amounts of all the regional investments and operative payments made over a period of 20 years and the corresponding tax revenues that remain in the municipality. | €/year and MWh exergy |
| | **heat price package** | total cost of heat for the village | | The heat price package includes the heating costs for district heating, oil and gas for the residents and the aquaculture. | €/year and MWh exergy |
| | **security of supply** | independence from fossil energy resources | Balance of energy demand of fossil fuels and replaced energy demand of fossil fuels | District heating based on biomass reduces the dependency on fossil fuel resources, which are imported from foreign and potentially politically unstable countries. | MWh/ year and MWh exergy |

**Table 2.** *Cont.*

| | Area of Sustainable Development | Criterion | Indicator | Criterion Description | Unit |
|---|---|---|---|---|---|
| **Economic Indicators** | **operational value creation** | return on assets | | The return on assets describes the relationship between income and the capital necessary to achieve this income. | percent |
| | | annual after-tax profit | | The average annual net profit (after taxes) based on the profit and loss calculations for 20 years. | €/year and MWh exergy |
| | | dynamic amortization period | | The amortization period refers to the period that is required for the return on an investment to "repay" the original investment. The dynamic method takes into account the net present value of the corresponding cash flow. | years |

In the following section, the criteria and the generation of the data are discussed; Table 2 provides an overview of the set of criteria.

### *4.1. Ecological Indicators*

The impact of the energy supply has diverse influences on the natural environment. On the one hand, all types of emissions are produced, which have impacts on the soil, water and air. On the other hand, the renewable and non-renewable environment provides resources for the energy supply such as water or carbon from fossil fuels. The protection of the natural environment and the Earth's ecosystems is mandated upon signatory nations since the "Rio Declaration on Environment and Development" [24].

The ecological criteria in this case study, which relate to sustainable development, are "protection of climate and air", "protection of soil", "protection of water" and "protection of resources". To quantify the impact on the environmental standardized impact categories, a life cycle assessment (LCA) was applied and supplemented by criteria of resource consumption. In LCA, heat and electricity consumed during the entire life cycle of the products are considered [22].

Nearly all of the ecological indicators were calculated using the GEMIS (Global Emission Model for Integrated Systems). GEMIS is an openly available life-cycle analysis program and database for energy, material, and transport systems that was developed by the "Öko-Institut". It provides life cycle data of energy sources and of different technologies for the supply of heat and electricity. For each process, all the environmental effects through the life cycle, including all relevant transports and ancillary products, are calculated [25].

The data for "protection of climate", "acidification", "cumulated energy demand", "the demand of mineral resources", "demand of water" and "land requirements" were directly generated using the GEMIS software. For the "human toxicity", "eco toxicity", "fresh water toxicity", and "aquatic eutrophication" indicators, the model provided raw data of emissions that needed to be adapted to the corresponding impact category using certain characterization factors. The CML ("Centrum voor Milieukunde", University of Leiden, The Netherlands) publishes characterization factors for the impact categories of LCA [22].

The data for the "local erosion" criterion were calculated using the factor of cultivation (c-factor). The c-factor is one of the factors of erosion in the "Universal Soil Loss Equation"; it describes the influence of the different crops and tillage management on erosion [23]. All the other influencing factors on erosion depend on local requirements. At this stage of the process, the local requirements of the area selected for the cultivation of plants were still unknown such that the estimation was based on the c-factor alone. However, the local requirements and the cultivation method should be taken into account where the data are available. Further data on global erosion should be integrated into the evaluation.

The aquaculture is modeled in the GEMIS as a "normal" but larger consumer of the heat and electricity supply. In general, this modeling implies that many effects of the aquaculture are not considered in the ecological assessment (for instance, the production and transport of feedstock), which might have a significant effect that needs to be quantified in future research and consequently incorporated in the MCDA evaluation. For the "demand of water" criterion, the impact of the aquaculture was estimated by the system operator in order to amend the GEMIS data.

### *4.2. Social Indicators*

In addition to the technical, financial, administrative and infrastructural challenges, the public perception of the biogas plant is one of the first major obstacles on the way to its implementation [26]. The causes of social resistance are diverse. According to Wüste and Schmuck, there is an expectation that the current quality of life of the local residents might be affected [18]. Furthermore, many doubts exist as to whether one should use land for energy crop cultivation while people still die of hunger in other parts of the world.

This case study evaluates the social compatibility of the scenarios with the areas of sustainable development: "Employment", "effects on the personal environment", "effects on the local scenery", "competition to food production", and "regional cohesion". Whereas the effects on employment are quite commonly assessed in MCDA evaluations of energy systems, the application of the other aspects is not widespread in MCDA case studies. An analysis of the social criteria applied in MCDA case studies in energy is provided by [14] and [16]. For the criteria of the "effects on personal environment", "effects on local scenery", and "regional cohesion" areas, relative scales were applied. The data for this qualitative assessment are mainly based upon the work of [18]. Wüste surveyed residents of local, communal biogas projects via a questionnaire regarding their general acceptance or concerns regarding bioenergy [18,27]. The study incorporates "perceived values" to capture the effects that influence the community's acceptance of the energy system [21]. In the following sections, the procedure of data generation for the corresponding aspects is described. For the results, see Table C1 in the appendix.

#### 4.2.1. Employment

When operating a bioenergy plant and aquaculture some jobs are created (for instance, the plant manager and an administrative employee). The data for the scenarios were provided by local experts.

4.2.2. Effects on the Personal Environment

In order to describe the effects on the personal environment of the local residents, we examined disturbances due to smell, noise and transport. The risk of accidents was also assessed. All those criteria except for "transport" were perceived effects of the bioenergy plant. The influences were operationalized via qualitative scales based on the survey of Wüste [18].

Knowledge gaps are present in the literature with respect to public perceptions regarding the potential effects of closed-loop aquaculture systems. In the interviews, the key actors indicated that there were no concerns regarding smell, noise and risk of accidents of the aquaculture from their point of view. This research assumes there is no impact from aquaculture on the indicators of "perceived smell", "perceived noise" and "perceived risk of accidents". More research is necessary in the future to clarify the exact nature of the effects of the aquaculture.

In addition, the frequency of transports is part of the evaluation of the effects on the personal environment. Calculations were based upon the data of local actors. Biomass delivery, collection of digestate and the delivery and collection of fish for the aquaculture are all factors when considering the local effects of transport.

4.2.3. Effects on the Local Scenery

The overall aesthetic perception of the effects of bioenergy by the local residents is influenced by the biogas plant and the cultivation of energy crops [21].

An estimation of the aesthetic detraction due to the biogas plant was achieved by consulting local experts in the community. To estimate the influence of energy crop cultivation on the detraction of the landscape, the change in cultivation due to the cultivation of energy crops had to be considered. The influence of the aquaculture on the local detraction of the landscape was considered negligible as the pools are inside buildings already in use for industrial purposes.

4.2.4. Regional Cohesion

The criterion "regional cohesion" describes the team spirit that can develop in a group of people if they have a common goal. Research conducted by Eigner-Thiel supports that a group's engagement towards a collective goal, such as climate protection, enhances the sense of unity within the group. This group dynamic has a positive influence on health and well-being and is considered more sustainable [28]. On the path to a bioenergy village, a group feeling can originate with a participatory and cooperative development of the bioenergy project. Especially in the cooperative concept for a bioenergy village, community members can participate in the planning process and financing of the project [21].

The influence on the regional cohesion within each of the scenarios is based on a qualitative assessment supported by best practices and leading research in the field. The main assumption for the evaluation is that the regional cohesion increases with the number of households connected to the district heating system [28]. The influence of the aquaculture on regional cohesion was considered to be insignificant.

### *4.3. Economic Indicators*

For the economic evaluation of the scenarios, the "regional value added", "heat price package", "security of supply", and "operating income" areas of sustainable development were considered. The economic indicators were calculated from the perspective of a cooperative based on the experiences in Jühnde [17].

A profit and loss calculation as well as a balance sheet for each scenario was developed, providing data for the economic criteria. Data of the investment costs for the balance sheet were mainly generated with the KTBL biogas calculator [29]. Using this calculator, the biogas plant could be approximated through the provision of a comprehensive catalogue of the corresponding investment costs and operating expenses. Further assumptions on the investment costs for the district heating, the site and the logistics were made with the help of local experts.

For the profit and loss calculations, all of the revenues for the heat and electricity supply of the cooperation were calculated for a period of 20 years. This period is based on the allowance horizon of the German Renewable Act 2009. The same constraints were applied for the operating expenses, combined with depreciation, interests and taxes. In addition, the profit of the aquaculture was estimated and included in the calculation.

Values for the criteria "regional value added", "heat-price package" and "operating income" were generated based on these calculations.

#### 4.3.1. Regional Value Added

The criterion "regional value added" became popular for the evaluation of renewable energy systems because it is assumed that the income for the municipality is larger than for traditional energy systems. Basic calculations for renewable energies have been published by [30]. The assumptions made for the calculations in this case study are listed in Appendix B.

The defined area of the "region" is approximately 40 km. Estimations were made based on what resources were available in that region and what resources needed to be traded in a larger area through the assessment of the input of local experts.

#### 4.3.2. Heat-Price-Package

For the calculation of the criterion "heat-price-package", we examined the annual costs of heat supply for the three energy carriers, district heating, oil and gas. The costs of the district heating supply were derived from the example of the cooperative in Jühnde [17]. The same costs were calculated for the oil and gas supply based on data from local suppliers.

#### 4.3.3. Operational Value Creation

The aspect "operational value creation" has been described with the three criteria "return on assets", "annual net profit" and "dynamic amortization period". The average annual net profit was derived directly from the profit and loss calculation. The two other operating figures were deduced correspondingly based on a widely used formula.

#### 4.3.4. Security of Supply

The area "security of supply", pertaining to long-term economic stability, is described by the criteria "number of possible suppliers" and "independence from fossil fuels". A corresponding increase in the security of the supply and an increase in the number of farmers or other biomass suppliers were assumed. The second criterion "independence from fossil fuels" describes the long-term stability and security of the energy system resulting from the finite supply of fossil fuels.

As this research was part of a real-world process, the selection of criteria was based not only on the sustainability criteria available in the literature but also on actual questions posed by the local actors. In particular, the column of the economy addresses questions that are important for the decision-making process of the inhabitants such as "heat-price-package" or "operational income". However, concerning sustainable development, future research should also address the life-cycle aspects in the economic criteria by considering life-cycle-costing [31].

## 5. Weighting

In the weighting process in MCDA, weights are assigned to the criteria or indicators to enable an aggregation of the data and thus a ranking of the alternatives. Both subjective and objective weighting methods are available [14]. In this case study, a subjective weighting method was selected to provide the actors with an opportunity to participate. Despite the risks of participative weighting, such as its difficult elicitation [5], it can produce positive effects on the process; for example, participation can increase trust in the decisions as the actors have the opportunity to bring in their point of view. Furthermore, participative weighting can create more understanding of the viewpoints of other participants [32].

In our case study, the SIMOS method combined with "silent negotiation" was applied for the group weighting. The simplicity of the SIMOS method was easily grasped by the actors. In this method, the actors express their preferences by ranking criteria in the form of cards [33]. To avoid long discussions without any results, Picted and Bollinger separated the decision part from the discussion part; people act in a silent negotiation without discussing their arguments (see [34] for further details). This facilitates a democratic decision-making process where everyone has an equal input.

The weighting process in the case study was performed in the first workshop. Time constraints did not permit researchers to perform an individual ranking as presented in other case studies (see e.g., [35]). However, to provide the actors with an opportunity to make up their mind about their own preferences, they were given a list of the criteria with an explanation before the survey. For the ranking procedure, cards were arranged in a horizontal row on a large table. To simplify this process, the number of cards was reduced from 13 to 11 by aggregating some areas of sustainable development. In the beginning, all of the cards had the same importance. In the first part of the process, people needed to move the cards from the horizontal arrangement to a more vertical one by moving cards one row up or down. This process was repeated three times depending on the time schedule and the number of actors. In the first round, three moves were allowed; in the second, two moves were allowed; and in the last round, one move was allowed to obtain rapid results in the beginning that could not be significantly changed later during the process. The results obtained are presented in Table 3.

**Table 3.** Results of the criteria ranking and corresponding weights.

| Areas of sustainable development | Rank | Weights |
|---|---|---|
| Security of Supply | 1 | 15.21 |
| Operating Income | 2 | 14.07 |
| Heat Price Package | 2 | 14.07 |
| Effects on the Personal Environment | 3 | 12.93 |
| * | 4 | 0.00 |
| * | 5 | 0.00 |
| Regional Cohesion | 6 | 9.51 |
| Protection of Water, Soil | 6 | 9.51 |
| * | 7 | 0.00 |
| * | 8 | 0.00 |
| Competition to Food Production | 9 | 6.08 |
| Employment | 10 | 4.94 |
| Regional Value Added | 10 | 4.94 |
| Protection of Climate and Air | 10 | 4.94 |
| Protection of Resources | 11 | 3.80 |

Developments occurring at the ground level of the project at this stage indicated that people considered the "security of supply" criterion as very important. At that time, only one farmer was ready to supply biomass, so the entire demand of biomass was not secure. In general, one could observe that all the criteria with direct effects on the actors' financial situation and personal environment were weighted higher than more removed criteria such as the ecological ones.

## 6. Ranking Scenarios Using PROMETHEE

To achieve a ranking of the scenarios, scientific data and weights were aggregated using an aggregation method of MCDA. After this, a sensitivity analysis was conducted to analyze the stability of the results.

### *6.1. Aggregation of the Data*

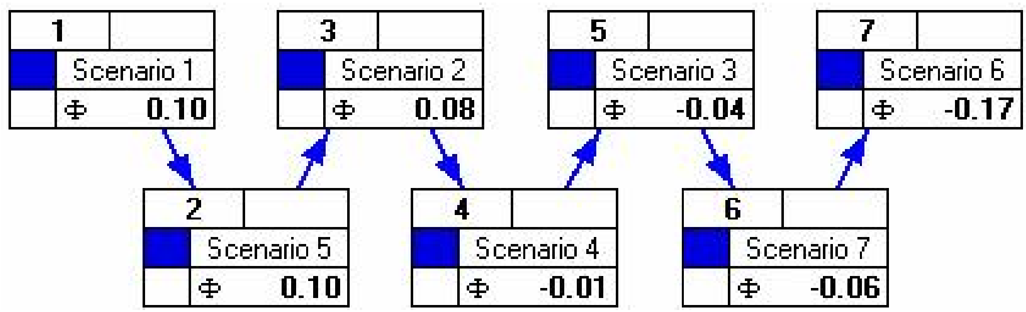
In the literature, many different methods and terms for multi-criteria decision analysis are present (see [7] for details on the different methods). The two main categories of MCDA methods are "utility-based methods" and "outranking methods" [3]. The utility-based methods require a well-structured mathematical decision problem with clear preferences of the decision maker. Those methods rank the alternatives according to a single value that represents the aggregated performance of all criteria. Methods including "Multi-Attribute Utility Theory" (MAUT), "Multi-Attribute Value Theory" (MAVT) and the "Analytical Hierarchy Process" (AHP) belong to this category. The outranking methods such as "PROMETHEE" or "ELECTRE" find a ranking of alternatives by a pair-wise comparison of criteria performance. It is not the performances of the criteria itself that are aggregated but the preferences provided by the decision maker on the performance of the criteria. Thus, the outranking methods provide less compensation (Compensation in MCDA means that, for instance, poor performance under one criterion can be counterbalanced by good performance under a different criterion) than the value-based methods and are more suitable for a strong sustainability approach [3]. As a strong sustainability approach was supported, the MCDA method "PROMETHEE" [36] was selected for this case study.

For each criterion, PROMETHEE compares the performance of alternatives using a pair-wise comparison. With the help of preference functions and thresholds, whether a preference for alternative a over alternative b exists can be determined for each criterion. Those evaluations are aggregated in a positive and a negative outranking flow. The positive outranking flow $\Phi^+$ expresses how much an alternative outranks the other alternatives, *i.e.*, for which criteria it exhibits a better performance compared with the alternatives. The negative outranking flow $\Phi^-$ expresses, respectively, how much this alternative is outranked by other alternatives, *i.e.*, those criteria where it exhibits a weaker performance. In PROMETHEE I, the results of the positive and the negative outranking flow are presented separately. In PROMETHEE II these outranking flows are aggregated in a net outranking flow $\Phi$ [36]. The results presented in the case study are based on PROMETHEE II as it allows for a complete ranking and is easier to visualize and discuss [3].

The data of the scenarios and the weights were compiled using a comprehensive impact matrix (Appendix C) and the MCDA software "Decision Lab". Due to time constraints, the thresholds were primarily based on uncertainty estimations. However, in future research, the determination of criteria should reflect human sensitivity to and the perception of the impact measured by the criterion [37].

The scenario ranking based on the weighting of the group is presented in Figure 2. One week after the first workshop, the results and the sensitivity analysis were presented to the group in the second workshop.

**Figure 2.** Results of scenario ranking based on group weighting.




### *6.2. Sensitivity Analysis*

With the help of sensitivity analysis in which different sets of weight are applied to the data, the stability of the results was demonstrated to the group. Several different sets of weight were applied to the data: "Equal weights on columns" (the weights were distributed in a way that the three columns of ecology, economy and social aspects obtained the same weights) or "50% Economy" (the weights were distributed in a way that the economic criteria obtained half of the total weights, and the remaining 50% were distributed equally between the other two columns), "50% Ecology" or "50% Social" (see Figures D1 to D4 in the appendix).

Scenarios 1, 2, and 5 were always observed to be first in the ranking; therefore, it was recommended that the village should decide in favor of the large biogas plant (scenarios 1 and 2) or the small biogas plant without aquaculture (scenario 5). As the fossil fuel scenarios 6 and 7 always ranked last, it was further concluded that, concerning sustainability, modification of the energy systems towards bioenergy systems would be beneficial for the village.

## 7. Discussion

The "principle of participation" ensures that the broader community will participate in searching for, evaluating and implementing sustainable ways of life. Without implementing that principle, sustainability processes at different levels of society have little uptake. Therefore, many chapters in Agenda 21 call for the implementation of this principle: "The primary objective is … to achieve, as soon as possible, substantial improvements in … participation of people in setting priorities and in decision making relating to sustainable development" ([24], chapter 35.6) and "The objective is to promote broad public awareness as an essential part of a global education effort to strengthen attitudes, values and actions which are compatible with sustainable development. It is important to stress the principle of devolving authority, accountability and resources to the most appropriate level with preference given to local responsibility and control over awareness-building activities" ([24], chapter 36.9). Violating the principle of participation may result in protest movements against certain developmental paths on the national level (for instance, the anti-nuclear movement in Germany) as well as on the regional level. The massive resistance of citizen initiatives in Germany against the building of high currency cable nets or factory farming projects demonstrated the high costs of excluding people from the development process. For this case study, elements of the principle of participation were included in a local planning process because implementing sustainable solutions presupposes that people of a region or a village collectively reflect about the restructuring alternatives to find one that is shared by the majority of citizens [38].

In the process of transitioning to a bioenergy village, the implementation of MCDA has demonstrated many benefits but also some challenges that must be addressed. According to the experience of the case study, the following conclusions can be drawn:

The evaluation of the different scenarios based on scientific data served to resolve the questions of the participants for a preferable manner of restructuring their village. In the first citizens' meetings conducted before the MCDA workshops, a lot of time was spent on discussions about transport, noise, smell and other issues. Having had presented the data that helped to address those questions, the following discussions concentrated more on solving the open challenges such as how to motivate other residents for the project. While those questions could have been addressed in another manner, the structured, comprehensive data sets used in the MCDA evaluations seemed to have a beneficial influence on the on-going process.

Furthermore, the MCDA presents an opportunity to address all open questions, doubts and prejudices. Throughout the interviews, key actors, especially antagonists of the project, were identified and later involved in the process. The MCDA workshops offered a platform for controversial discussion such that conflicts could come to the surface instead of ending in citizens' initiatives against the project. However, it was difficult to overcome the initial resistance of some antagonists to attend the two informative MCDA workshops.

Both the weighting procedure and the development of alternatives and criteria provided opportunities to let actors participate in the decision process towards sustainable development [4]. Due to time constraints, the set of criteria and the scenarios were almost finalized by the project team before the first workshop occurred. In this preparation phase, the residents had no strong influence on the process. To achieve more comprehensive participation, it would be beneficial to involve the actors in those preparatory steps. The villagers would have possibly developed more or different alternative scenarios than those that were developed. Developing the scenarios with the participation of actors in a workshop would have meant a long break in the process because of the extensive data compilation required. A long break between the workshops may have been counterproductive because we anticipated that some of the actors in the village may have changed their decision under the pressure to make a decision or that many variables in the context might have changed. A new decision context would have meant a new MCDA application with different alternatives. Research is necessary on the flexibility of the MCDA process such that short-term modifications are possible and thus more participatory elements are involved.

The application of the "silent negotiation" weighting process confirmed the positive experience of Picted and Bollinger [34]. The separation of weighting and discussion allowed every participant to participate in the process. This tool helped the facilitator/moderator to receive the input of all of the participants and not only of the powerful actors. It was noted that as people shared their experiences, they were caught up in the process and remained focused. In the workshops, the facilitators aimed at creating an informal, fun atmosphere that had been proven in former studies to be a successful factor in sustainability projects [39]. In the case study, this atmosphere helped to change the mood of the group from "very skeptical towards the biogas plant" to "we will give it a try". In terms of the results of the weighting, the weights were observed to be strongly affected by the stage of the project. In the discussion it became clear that the "security of supply" attracted the highest weight, as the issue of biomass supply was still open at that time.

It could be deduced from both the weighting results and in the discussion that consideration of the social criteria was very important for the residents. In addition, the presentation of "perceived values" based on the experience of other residents in other bioenergy villages seemed to address the persisting doubts. However, from a scientific perspective, the quality of data can be enhanced by further research. The results of the survey by Wüste and Schmuck [18] helped to find a difference between bioenergy and fossil fuel-based scenarios but not between the bioenergy scenarios themselves. Thus, only the difference between fossil fuel-based and bioenergy scenarios is illustrated in the assessment. This problem could be solved by using surveys based on the scenarios that were evaluated in the MCDA, which would extend the period of data compilation that is required.

In general, an emphasis was made on criteria that were able to address the questions of the local actors. For instance, we examined the after-tax profit of the cooperative or the heat-price-package for the heat consumers, as this information was highly requested. However, regarding sustainable development, evaluation criteria such as "life cycle costs" would have been more meaningful as they represent the total costs over the life cycle (31). Further research is necessary to bridge the gap between scientific and practical requirements.

Furthermore, the quality of the data must be improved by considering the LCA of closed-loop aquaculture. Consideration of "heat sinks" is necessary as the aquaculture in our case study created a challenge for the evaluation of energy systems. To provide a fair evaluation of the project, all processes linked to it must be considered and assessed completely. Otherwise, there is a danger of supporting "heat sinks", as they increase the efficiency of the biogas plant without considering its price (in our case, the environmental burden resulting from fish-feed for the aquaculture). A general solution for the problem of how to manage those side processes without further extending the period of data compilation is necessary.

In general, the effort of data compilation is immense in that there is a real risk that decisions are made before the data are available. Data generation depends highly on the point of time when MCDA is implemented in the process. If MCDA evaluation occurs early in the decision process, when scenarios are still very unclear, data from the literature can be useful for the actors to gain an idea of what influences could be generated by the scenarios. However, if the decision context is advanced, people require an answer on real alternatives. In this case it might not be sufficient to evaluate any biogas plant; at that point in time, data on the actual biogas plant should be presented. Those data in general are available only from manufacturers and operators and are difficult to obtain. Additionally, the amount of data makes the entire process very inflexible, such that short-term amendments of alternatives are difficult to consider. Further work should be performed on standardized procedures and databases for the evaluation of energy systems that allow flexible data generation. Further work must be performed on the compatibility of LCA and MCDA. According to the experience of this case study, LCA and databases such as GEMIS are suitable data sources for MCDA, especially concerning ecological criteria. In LCA, much research has been performed to capture all columns of sustainability as life-cycle costs and social LCA are improved [40]. The effective application of those assessments for assisting decision makers aiming at a sustainable energy supply must be analyzed in future research.

## 8. Conclusions

Although many issues remain, MCDA is considered a very useful tool in supporting communities on their path towards a renewable energy supply because it accounts for the advantages and drawbacks of renewable energy systems that are difficult to quantify. Therefore, the effects that are usually excluded from the evaluation due to a lack of data can be integrated to provide a better understanding of the complexities involved.

In the selected case study in a village transitioning to a "bioenergy village", the participation of community members in the decision-making process achieved obvious positive outcomes: The MCDA process offers a platform for the exchange of arguments and different perspectives; provides data that are able to answer the questions of the residents; and combines scientific data with the perspectives of actors such that well-balanced decision making is possible. The "silent negotiation" weighting procedure is highly applicable to this evaluation process as it was easy to under represent the actors and seemed to make the process more "fun". Stable rankings of the energy scenarios could be achieved by convincing the group that the bioenergy scenarios were more sustainable for the village than those based on non-renewable energy sources. However, the data compilation was comprehensive and thus very time intensive. As a result, the procedure can be inflexible and have difficulties adapting to change in the decision context, thus requiring further research.

An overall conclusion from the case study that is in line with the conclusions drawn by other researchers [4] is that MCDA can achieve good results on the path to sustainable development if the focus is on the process and not only on results. If the researcher restricts his role to the calculating process and disregards the social context of the process, then the probable uptake of the data for assisting the decision-making is low. The ways in which the participatory elements of the method are used and implemented in the decision context have a strong influence on the success of the method as a whole. Greater attention must be given in future research to combine methods from operations research and psychology in a fruitful manner to support sustainable development projects [41,42]. The evidence presented in this case study may provide insights that can help to chart this path.

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## Conflict of Interest

The authors declare no conflicts of interest.

## References

1. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0028:en:NOT (accessed on 14 January 2012).
2. *The German Government's Energy Concept*; Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: Bonn, Germany, 2010. Available online: http://www.bmu.de/english/energy_efficiency/doc/46516.php (accessed on 14 January 2012).
3. Polatidis, H.; Haralambopoulos, D.; Munda, G.; Vreeker, R. Selecting an appropriate Multi-Criteria Decision Analysis technique for renewable energy. *Energy Sources Part B* **2006**, *1*, 181–193.
4. Omann, I. Multi-Criteria Decision Aid as an Approach for Sustainable Development Analysis and Implementation. Ph.D. Thesis, University of Graz, Graz, Austria, 2004.
5. Munda, G. Multiple Criteria Decision Analysis and Sustainable Development. In *Multi Criteria Decision Analysis: State of the Art Surveys*, 1st ed.; Figueira, J., Greco, S., Ehrgott, M., Eds.; Springer: Berlin, Germany, 2005; Volume 3, pp. 953–986.
6. Zimmermann, H.J.; Gutsche, L. *Multi-Criteria Analyse-Einführung in die Theorie der EntscheidungenbeiMehrfachzielsetzungen*; Springer: Berlin, Germany, 1991.
7. Figueira, J.; Greco, S.; Ehrgott, M. *Multiple Criteria Decision Analysis: State of the Art Surveys*; Springer: Berlin, Germany, 2005.

8. Diakoulaki, D.; Grafakos, S. Externalities of Energy: Extension of Accounting Framework and Policy Applications—Multicriteria Analysis; Technical Report; National Technical University Athens: Athens, Greece, 2004.
9. Buchholz, T.; Rametsteiner, E.; Volk, T.; Luzadis, V.A. Multi-criteria analysis for bioenergy systems assessments. *Energy Policy* **2009**, *37*, 484–495.
10. Dogson, J.; Spackman, M.; Pearman, A. *Multi-Criteria Analysis: A Manual*; Department for Communities and Local Government: London, UK, 2009.
11. Huang, J.; Poh, K.; Ang, B.W. Decision analysis in energy and environmental modeling. *Energy Policy* **1995**, *20*, 843–855.
12. Zhou, P.; Ang, B.; Poh, K. Decision analysis in energy and environmental modeling: An update. *Energy* **2006**, *31*, 2604–2622.
13. Pohekar, S.; Ramachandran, M. Application of multi-criteria decision making to sustainable energy planning—A review. *Renew. Sustain. Energy Rev.* **2003**, *8*, 365–381.
14. Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. Review on Multi-Criteria Decision Analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278.
15. Braune, I.; Pinkwart, A.; Reeg, M. Application of Multi-Criteria Analysis for the Evaluation of Sustainable Energy Systems—A Review of Recent Literature. In *Proceedings of 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems*; Dubrovnik, C., Guzović, Z., Duić, N., Ban, M., Eds.; Faculty of Mechanical Engineering and Naval Architecture: Zagreb, Croatia, 2009; p. 165. Available online: http://www.evur.tu-berlin.de/fileadmin/fg45/Publikationen/SDEWS2009_050509_Braune_Pinkwart_Reeg.pdf (accessed on 16 November 2011).
16. Oberschmidt, J. *MultikriterielleBewertung von TechnologienzurBereitstellung von Strom und Wärme*; FraunhoferVerlag: Karlsruhe, Germany, 2010.
17. Ruppert, H.; Eigner-Thiel, S.; Girschner, W.; Karpenstein-Machan, M.; Roland, F.; Ruwisch, V.; Sauer, B.; Schmuck, P. *Wege zum Bioenergiedorf—Leitfaden für eine eigenständige Wärme- und Stromversorgung auf Basis von Biomasse im ländlichen Raum*; Fachagentur Nachwachsende Rohstoffe: Gülzow, Germany, 2008.
18. Wüste, A.; Schmuck, P. Social Acceptance of Bioenergy Use and Success Factors for Communal Bioenergy Projects. In *Sustainable Bioenergy Production—An Integrated Approach*; Ruppert, H., Kappas, M., Eds.; Springer: Berlin, Germany, 2012; in press.
19. Burgherr, P.; Hirschberg, S.; Brukmajster, D.; Hampel, J. *Survey of Criteria and Indicators. New Energy Externalities Developments for Sustainability (NEEDS), Deliverable D1.1—Research Stream RS 2b: Energy Technology Roadmap and Stakeholders Perspective*; Project co-funded by the European Commission within the Sixth Framework Programme (2002–2006); Paul ScherrerInstitut (PSI): Villigen, Switzerland, 2005.
20. Buchholz, T.; Luzadis, V.; Volk, T. Sustainability criteria for bioenergy systems: Results from an expert survey. *J. Clean. Prod.* **2009**, *17*, 86–98.
21. Eigner-Thiel, S.; Schmehl, M.; Ibendorf, J.; Geldermann, J. Assessment of Different Bioenergy Concepts Regarding Sustainable Development. In *Sustainable Bioenergy Production—An Integrated Approach*; Ruppert, H., Kappas, M., Eds.; Springer: Berlin, Germany, 2012; in press.

22. Guinée, J.B.H.; de Bruijn, H.; van Duin, R.; Huijbregts, M.A.J.; Lindejer, E.; Roorda, A.A.H.; van der Ven, B.L.; Weidema, B.P. *Handbook of Life Cycle Assessment. Operational Guide to the ISO Standards*; Kluwer Academic Publishers: Dordrecht, Netherlands, 2002.
23. Wischemeier, W.H.; Smith, D.D. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains. In *Agric Handbook 282*; United States Department of Agriculture (USDA): Washington, DC, USA, 1965.
24. *Report of the United Nations Conference on Environment and Development (UNCED), Annex I: The Rio Declaration on Environment and Development*; UNCED: Rio de Janerio, Brazil, 1992. Available online: http://www.un.org/esa/dsd/agenda21/ (accessed on 3 May 2011).
25. Fritsche, U.R.; Schmidt, K. *Handbuchzu GEMIS 4.5*; Öko-Institut: Darmstadt, Deutschland, 2008. Available online: http://www.oeko.de/service/gemis/de/index.htm (accessed on 20 June 2011).
26. Roesch, C.; Kaltschmitt, M. Energy from biomass—Do non-technical barriers prevent an increased use? *Biomass Bioenergy* **2008**, *16*, 347–356.
27. Wüste A.; Schmuck, P. Bioenergy villages and regions in Germany: An interview study with initiators of communal bioenergy projects on the success factors for restructuring the energy supply of the community. In *Proceedings of the Conference Changing the Energy System to Renewable Energy Self-Sufficiency (RESS)*, Freiburg, Germany, 15–16 September 2011.
28. Eigner-Thiel, S.; Schmuck, P. Gemeinschaftliches Engagement für das Bioenergiedorf Jühnde: Ergebnisse einer Längsschnittstudie zu psychologischen Auswirkungen auf die Dorfbevölkerung. *Umweltpsychologie* **2010**, *14*, 98–120.
29. KTBL: KuratoriumfürTechnik und Bauwesen in der Landwirtschaft, KTBL bio gas calculator. Available online: http://daten.ktbl.de/biogas/startseite.do (accessed on 24 November 2011).
30. Aretz, A.; Hirschl, B.; Prahl, A.; Böther, T.; Heinbach, K.; Pick, D.; Funcke, S. *Kommunale Wertschöpfung durch Erneuerbare Energien*; Institutfürökologische Wirtschaftsforschung: Berlin, Germany, 2010.
31. Papadopoulos, A.; Karagiannidis, A. Application of the multi-criteria analysis method ELEVTRE III for the optimisation of decentralised energy systems. *Omega* **2008**, *36*, 766–776.
32. Garmendia, E.; Stagl, S. Public participation for sustainability and social learning: Concepts and lessons from three case studies in Europe. *Ecol. Econ.* **2010**, *69*, 1712–1722.
33. Figueira, J.; Roy, B. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. *Eur. J. Oper. Res.* **2002**, *139*, 317–326.
34. Picted, J.; Bollinger, D. The silent negotiation or how to elicit collective information for group MCDA without excessive discussion. *J. Multi Crit. Decis. Anal.* **2005**, *13*, 199–211.
35. Kowalski, K.; Stagl, S.; Madlener, R.; Omann, I. Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis. *Eur. J. Oper. Res.* **2008**, *197*, 1063–1074.
36. Brans, J.-P.; Mareschal, B. PROMETHEE Methods. In *Multi Criteria Decision Analysis: State of the Art Surveys*, 1st ed.; Figueira, J., Greco, S., Ehrgott, M., Eds.; Springer: Berlin, Germany, 2005; Volume 3, pp. 163–195.
37. Rogers, M.; Bruen, M. Choosing realistic values of indifference, preference and veto thresholds for use with environment criteria within ELECTRE. *Eur. J. Oper. Res.* **1998**, *107*, 542–551.

38. Diefenbacher, H. *Gerechtigkeit und Nachhaltigkeit—Zum Verhältnis von Ethik und Ökonomie*; Wissenschaftliche Buchgesellschaft: Darmstadt, Germany, 2001.
39. Eigner, S.; Schmuck, P. Motivating Collective Action: Converting to Sustainable Energy Sources in a German Community. In *Psychology of Sustainable Development*; Schmuck, P., Schultz, W., Eds.; Kluwer Academic Publishers: Boston, MA, USA, 2002; pp. 241–257.
40. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–95.
41. Cervinka, R.; Schmuck, P. Umweltpsychologie und Nachhaltigkeit. In *Enzyklopädie der Psychologie, Band Umweltpsychologie*; Linneweber, V., Lantermann, E., Klas, E., Eds.; Hogrefe: Göttingen, Germany, 2008; pp. 595–641.
42. Schmuck, P.; Vlek, C. Psychologists can do much to support sustainable development. *Eur. Psychol.* **2003**, *8*, 66–76.


## Appendix

### A. Results of Ecological Criteria

The results are presented in the following figures. The results are plotted on the basis of criteria. The criteria of one "area of sustainable development" are always compiled in one figure. The data are visualised in percent compared with the BAU-scenario (scenario 6), which equals 100 percent (except Figure A2).

**Figure A1.** Results for the "Protection Climate and Air" area.

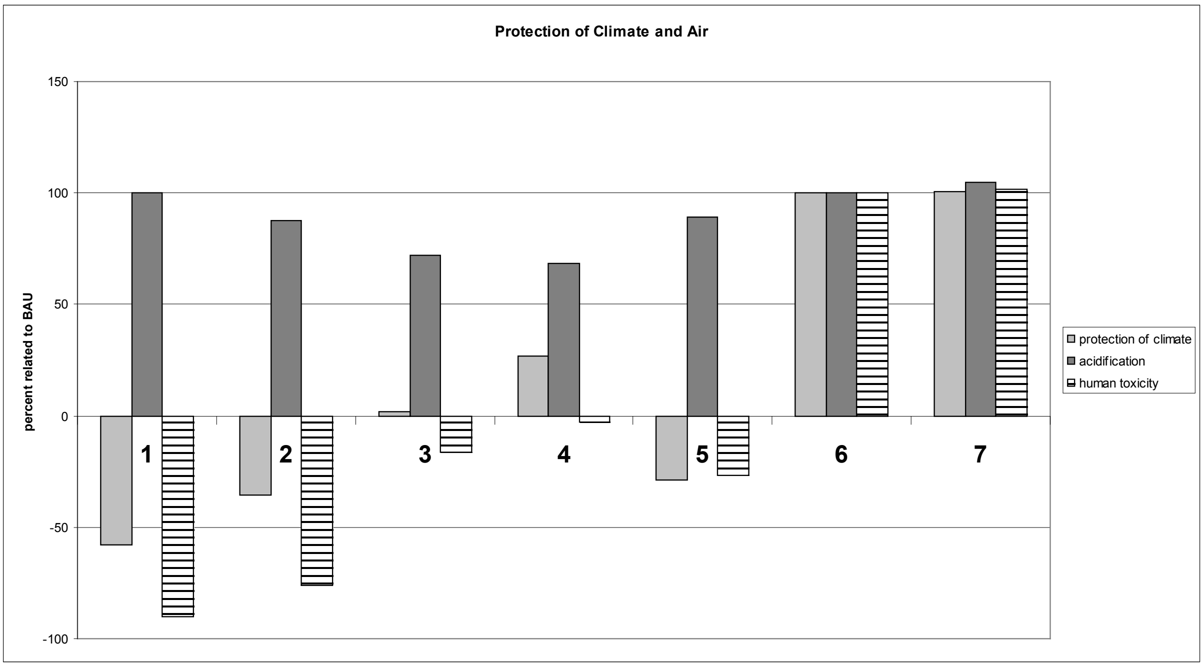
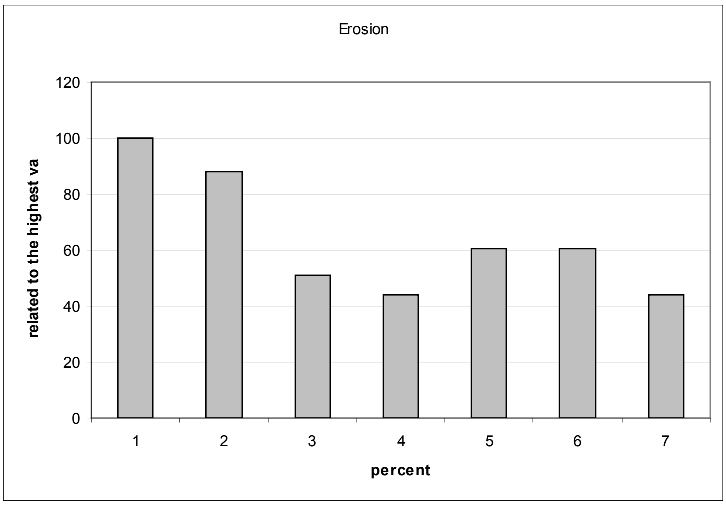
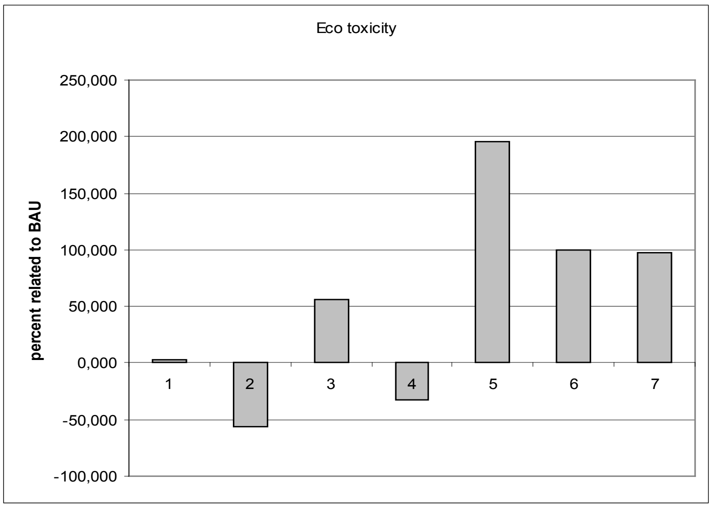


**Figure A2.** Results for the "Protection of Soil" area: (**a**) Erosion; (**b**) Ecotoxicity.




(**a**)




(**b**)

**Figure A3.** Results for the "Protection of Water" area.

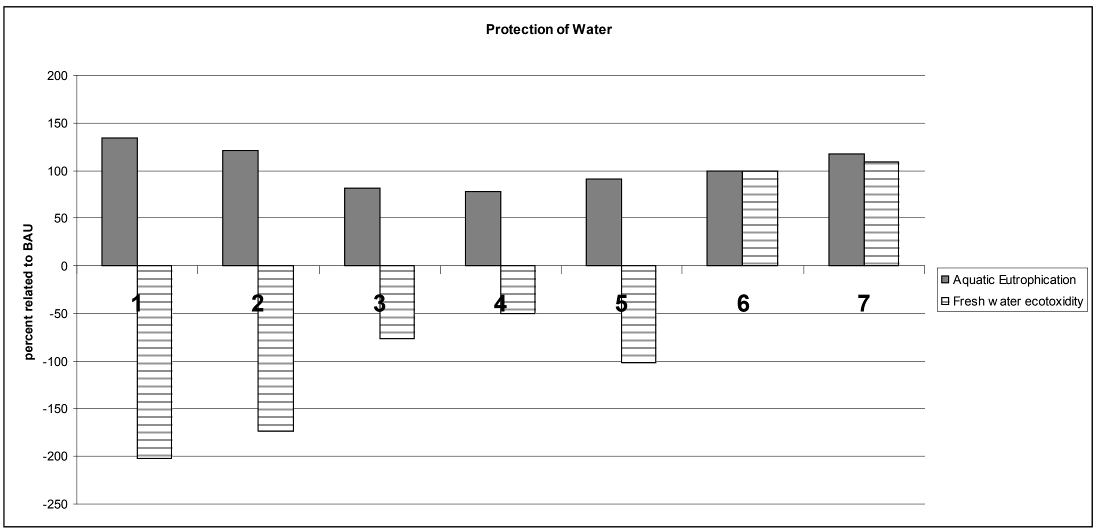
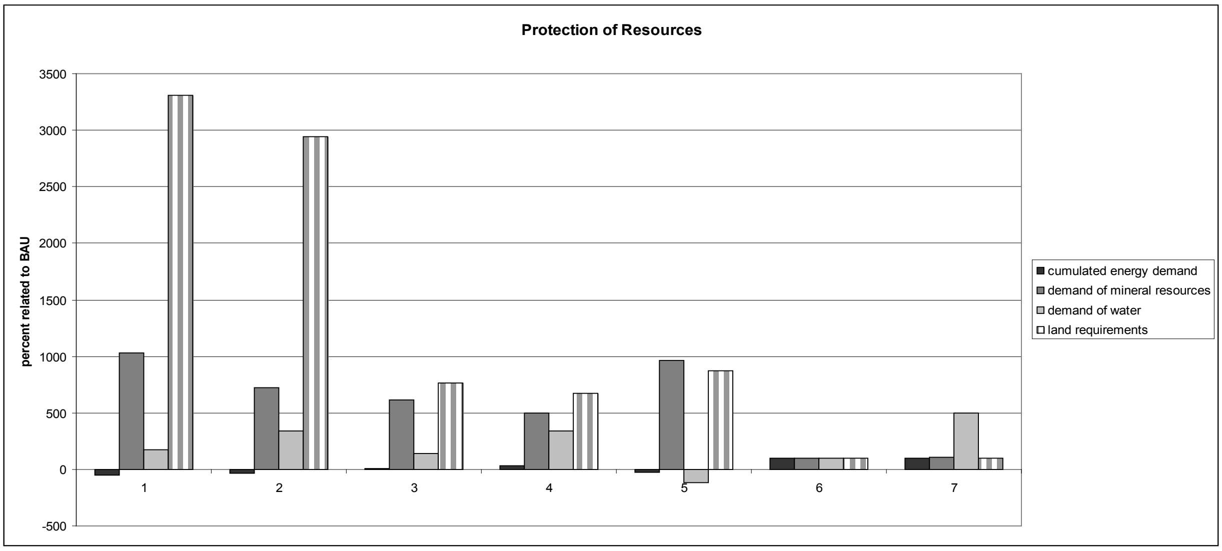


**Figure A4.** Results for the "Protection of Resources" area.




## B. Regional Value Added: Items and Corresponding Assumptions

**Table B1.** Results for scenario evaluation.

| | |
|---|---|
| **Investment costs** | |
| aquaculture | planning and realisation mainly by the later owner and operator; local factor of the total investment costs: 50% regional |
| planning biogas | all "incidental costs" by KTBL, including planning and approval (100% regional) |
| site development | local building company in charge of the site development (100% regional) |
| construction work | casting basement and concrete walls created by local construction firm (100% regional) |
| district heating | 30% of total costs for main and ancillary pipe, connection works |
| peak-load boiler | planning and layout designed by engineering firm (10% of total investment costs) |
| **Periodic payments** | |
| employees' wages (biogas) | 100% of total net wages of the employees |
| employees' wages (aquaculture) | 100% of total net wages of the employees |
| net profit (biogas) | 100% of average after-tax profit |
| net profit (aquaculture) | 10% of average after-tax profit |
| concession | reduced value added for municipality through reduction of gas concession fees (100%) |
| woodchip peak load | 100% local value added costs; provided by local supplier |
| business tax (biogas) | business tax, in consideration of tax allowance (88% remain in municipality) |
| business tax (aquaculture) | business tax, in consideration of tax allowance (88% remain in municipality) |
| income tax (biogas) | local portion (15%) of income tax [30] |
| income tax (aquaculture) | local portion (15%) of income tax [30] |

## C. Impact Matrix

**Table C1.** Results for scenario evaluation.

| Area of Sustainable Development | Criteria | Criteria Description 1 | 2 | 3 | 4 | 5 | 6 | 7 | Unit |
|---|---|---|---|---|---|---|---|---|---|
| **air and climate protection** | protection of climate | 643 | −394 | −394 | 300 | −322 | 1.114 | 1.123 | kg/MWh exergy |
| | acidification | 0.9488 | 0.8309 | 0.8309 | 0.6458 | 0.8462 | 0.9464 | 0.9924 | kg/MWh exergy |
| | human toxicity (min) | −2.9159 | −2.4533 | −2.4533 | −0.0852 | −0.8720 | 3.2333 | 3.2932 | kg/MWh exergy |
| **protection of soil** | ecotoxicity | 0.0002 | −0.0037 | −0.0037 | −0.0022 | 0.0130 | 0.0067 | 0.0065 | kg/MWh exergy |
| | local erosion | 0.0336 | 0.030 | 0.0171 | 0.0148 | 0.0203 | 0.0203 | 0.0148 | ha/MWh |
| **protection of water** | aquatic eutrophication | 0.1512 | 0.1372 | 0.1372 | 0.0883 | 0.1029 | 0.1129 | 0.1331 | kg/MWh exergy |
| | fresh water toxicity | −0.0062 | −0.0053 | −0.0053 | −0.0015 | −0.0031 | 0.0030 | 0.0033 | kg/MWh exergy |
| **protection of resources** | cumulated energy demand (non-renewable) | −2,612 | −1,531 | −1,531 | 1,424 | −1,271 | 4,787 | 4,868 | kWh/MWh exergy |
| | demand of mineral resources | 157 | 110 | 93 | 76 | 146 | 15 | 16 | kg/MWh exergy |
| | demand of water | 2,699 | 5,196 | 2,213 | 5,185 | −1,759 | 1,534 | 7,657 | litre/MWh exergy |
| | land requirements | 304 | 271 | 71 | 62 | 80 | 9 | 9 | m²/MWh exergy |
| **employment** | employment | 3 | 4 | 1.75 | 2.75 | 0.75 | 0 | 2 | average number of jobs/year |
| **effects on personal environment** | perceived noise | 1 | 1 | 1 | 1 | 1 | 0 | 0 | relative scale (0–2) |
| | perceived smell | 1 | 1 | 1 | 1 | 1 | 0 | 0 | relative scale (0–2) |
| | risk of accidents | 1 | 1 | 1 | 1 | 1 | 0 | 0 | relative scale (0–2) |
| | transport | 1,334 | 1,334 | 826 | 826 | 826 | 0 | 64 | number of transports/ year |
| **effects on local scenery** | biogas plant | 2 | 2 | 1 | 1 | 1 | 0 | 0 | relative scale (0–2) |
| | energy crop cultivation | 2 | 2 | 1 | 1 | 1 | 0 | 0 | relative scale (0–2) |
| **competition to food production** | area used for energy crops instead of food production | 0.069 | 0.061 | 0 | 0 | 0 | 0 | 0 | ha/MWh exergy |
| **regional cohesion** | evaluation based on number of households | 3 | 2 | 2 | 1 | 3 | 0 | 0 | relative scale (0–3) |

**Table C1.** *Cont.*

| Area of Sustainable Development | Criteria | Criteria Description | | | | | | | Unit |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| **regional value added** | sum of regional investment, periodic costs and local tax revenues | 274 | 280 | 175 | 184 | 171 | 21 | 92 | €/year and MWh exergy |
| **heat price package** | total costs of heat for the village | 177 | 182 | 186 | 194 | 177 | 204 | 190 | €/year and MWh exergy |
| **security of supply** | independence from fossil energy resources | −1.515 | −1.113 | −0.709 | −0.266 | −1.297 | 0.842 | 0.850 | MWh/year and MWh exergy |
| | number of supplying farmers | 0 | 0 | 1 | 1 | 1 | 2 | 2 | relative scale (0–2) |
| | return on assets | 5.4 | 7.0 | 4.9 | 7.1 | 3.0 | 4.0 | 4.0 | percent |
| **operational value creation** | annual after-tax profit | 102 | 113 | 55 | 63 | 45 | 26 | 38 | €/year and MWh exergy |
| | dynamic amortisation period | 12.9 | 11.0 | 13.7 | 10.7 | 17.8 | 0.0 | 6.4 | years |

## D. Sensitivity Analysis of Scenario Ranking

**Figure D1.** Results of scenario ranking based on equal weight of columns.

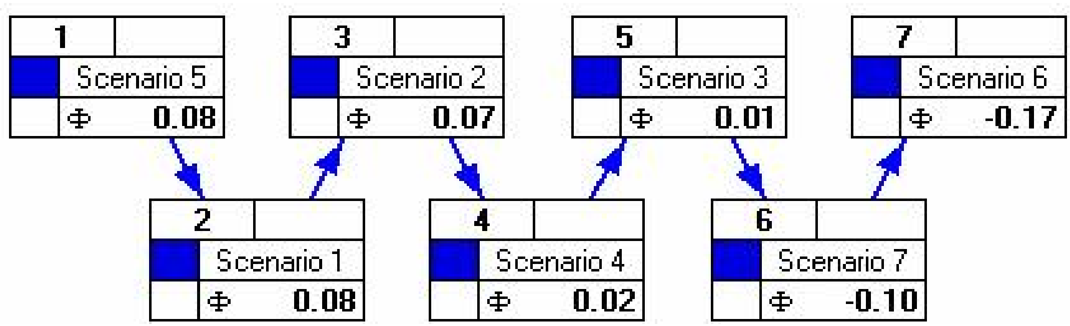



**Figure D2.** Results of scenario ranking, 50 percent weight on economy criteria.

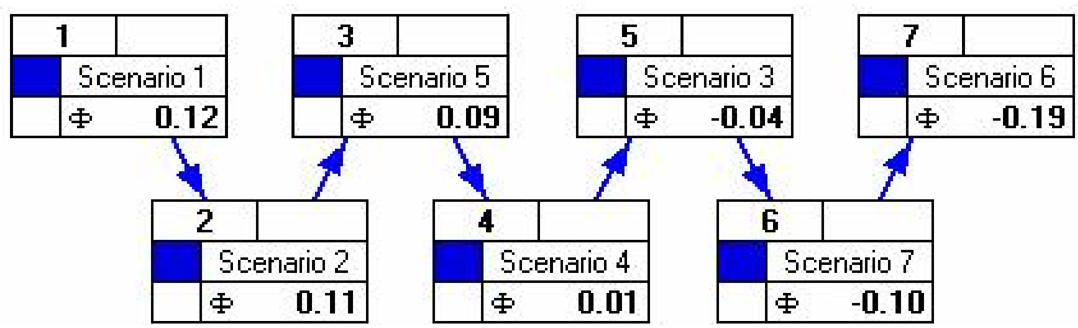


**Figure D3.** Results of scenario ranking, 50 percent weight on ecologic criteria.

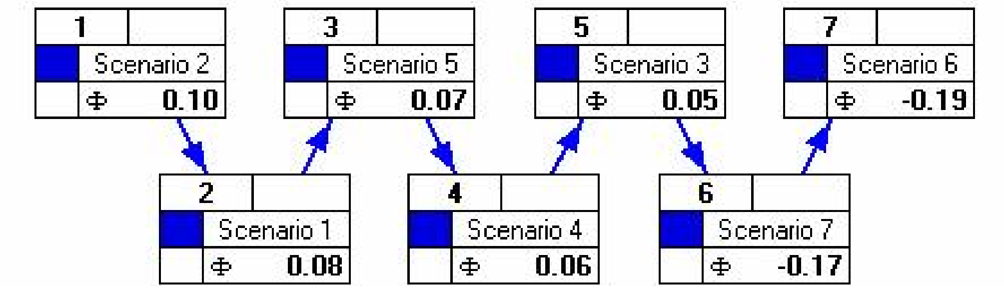



**Figure D4.** Results of scenario ranking, 50 percent weight on social criteria.