

More Sustainable Bioenergy by Making Use of Regional Alternative Biomass?

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Abstract: Bioenergy is a building block of the ongoing transformation toward renewables-based energy systems. Bioenergy supply chains are regionally embedded and need to be seen in a place-based context with specific characteristics and constraints. Using a German case study, the potential of regionally embedded bioenergy chains in the past and the future is analyzed and discussed in this paper. The analysis integrates socio-ecological data and applies sustainability criteria in a multi-criteria decision analysis (MCDA) using the Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE) methodology. The case study is focused on an industrial biogas fermenter in northwestern Germany, which currently uses predominantly maize as a substrate for bioenergy. Objectives for future development according to the ambitions of the UN Sustainable Development Goals and the EU Renewable Energy Directive (RED II) discussion are set and include the involvement of the farmer as biogas plant operator and other regional stakeholders. Since the focus of the research is put on the contribution of alternative biomass, such as grass, for the optimization of bioenergy settings, the question concentrates on how different mixtures of alternative biomass can be embedded into a sustainable management of both the landscape and the energy system. The main findings are threefold: (i) bioenergy supply chains that involve alternative biomass and grass from grasslands provide optimization potentials compared to the current corn-based practice, (ii) with respect to more sustainable practices, grass from grassland and alternative bioenergy supply chains are ranked higher than chains with increased shares of corn silage, and, more generic, (iii) optimization potentials relate to several spheres of the social–ecological system where the bioenergy structure is embedded. To conclude, sustainable enablers are discussed to realize optimization potentials and emphasize the integration of regional stakeholders in making use of alternative biomass and in making regional bioenergy more sustainable.

Keywords: regional supply chain; MCDA; PROMETHEE; biogas; SDG; sustainable management; stakeholders

1. Introduction

The transformation of energy systems toward renewables-based energy structures encompasses societal, economic, technical, and environmental dimensions and implies a more decisive role for citizens and communities [1]. This becomes even more important where bioenergy is a major part of a regional energy supply [2]. The purpose of this paper is to assess whether alternative, residual

biomass can improve regionally embedded bioenergy supply chains and contribute to a more sustainable regional development. In general, bioenergy supply chains are regionally embedded and need to be seen in a place-based context with specific characteristics and constraints [3–5]. In this paper regional impacts of bioenergy production are examined in both aspects: on the one hand, bioenergy is influenced by the regional characteristics such as soil quality and climate conditions finally affecting the availability of biomass. On the other hand, a region itself is influenced by existing bioenergy chains, e.g., by providing work, becoming manifest in the landscape, and increasing the general income of a region.

The complexity of ambitions and implications of bioenergy correspond to the UN Sustainable Development Goals (SDGs) with its targets as announced in the 2030 Agenda for Sustainable Development “Transforming our World” [6]. Subsequently, the SDGs have been of growing relevance at regional and national levels, providing both aims and advice for taking action. Although the SDGs have been formulated for universal application, their implementation and indicator assessments need to reflect specific circumstances of a given national and regional context [7]. Energy represents one SDG (Affordable and Clean Energy) with priorities on renewables. Bioenergy can make a significant contribution in that respect [8]. Biomass production and its use for energy supply interfere with several other SDGs, i.e., Life on Land, Zero Hunger, or Responsible Production and Consumption. Bioenergy is part of a nexus of societal needs and calls for fair balance with other dimensions of sustainable development [9]. The SDG indicators have potential to play a decisive role in that respect and enable a wide range of stakeholders and decision-makers to plan and act in progressing toward the goals and targets [8].

A stepwise approach is recommended according to the SDG-based assessment and optimization framework for bioenergy solutions. Biomass is often used in multiple ways. For example, animal manure can be used for biogas production and can still be used as fertilizer on the field after being treated in a biogas fermenter. This concept of cascade use is essential for a beneficial bioenergy solution in the regional context and has also been acknowledged by other researchers [10–13]. This also implies a cross-sectoral collaboration of stakeholders for bioenergy improvements. Hence, landowners, farmers, and the owners of bioenergy plants need to act in symbiosis, since all are interested in their supply chains. This becomes even more important if there is a strong competition for either biomass supply or even land. By means of an extended bioenergy network with more participants than farmers only, biomass can be used in a more sustainable way, as shown by others [14–20]. Recently, bioenergy and cascading of the use of biomass have been integrated in bioeconomy concepts and their realization in various settings [21].

The controversial discussion of bioenergy production in Germany is a good example of how the debate is strongly related to available regional biomass, especially with regard to maize (or here also called corn). According to the literature and laboratory results, maize is known as the most efficient energy crop concerning the gas yield and used to be the main fermentation substrate in Germany for biogas production [22]. Up to 73% of the renewable substrate input (excluding manure) of German biogas plants in 2015 was covered by silage maize [23]. This was due to the high incentives deriving from the German EEG (Renewable Energy Sources Act). A decrease in wildlife and plant biodiversity and arable land for food or fuel production as well as groundwater pollution by non-site-specific fertilization are the main concerns mentioned within the biogas discussion. However, there has always been competition for land due to the food-versus-energy discussion. In addition, there is also competition for areas to apply fertilizers since there are more fertilizers available than areas to fertilize.

A binding European Union (EU) target for the total share of renewable energies in the gross final energy consumption of the EU is anchored in the Renewable Energy Directive (RED II): by 2030, the share should be at least 32% (Art. 3, Para. 1). Each member state sets national contributions to achieve the EU’s overall binding target within the framework of the integrated national energy and climate plans [24]. Concurrently, the updated EU bioeconomy strategy aims to encourage the substitution of fossil carbon with biomass feedstock in the industry and in energy production while preserving ecosystem services [25]. Links between the EU bioeconomy strategy and the SDGs are inherent.

Synergies and lock-ins of a future bioenergy as part of a future bioeconomy and related SDG targets are numerous and diverse [26]. Because of the biodiversity discussion and the food competition discussion, bioenergy is a less accepted energy in German society, compared to other established renewable energy carriers. Although the acceptance of renewable energies in society is generally high, aspects such as the so-called “NIMBY mentality” (Not In My Backyard) lower the acceptance of bioenergy as energy source. Most reasons for the low acceptance are the odor of the fresh biomass (especially if animal slurry is used) and the high traffic on the road with the accompanying noise. A detailed discussion of the public acceptance of bioenergy can be found in the review of the European Framework for the Diffusion of Biogas Uses [27]. The more tangible the projects of bioenergy plant installations become and the closer they are installed to the environments of peoples’ concerns, the lower will be the acceptance of those projects [14]. However, this is in accordance with the review [27] that public acceptance increases when information is given early, i.e., during the planning phase of a biogas plant. Often there is also active participation taking place with the involvement of more than one stakeholder where all partners see benefits for everyone. In contrast, other researchers can confirm that especially for bioenergy villages the prospectively involved inhabitants of such a village have very positive opinions on the participation in such a project: “An early involvement of villagers in the planning and organization process increases the chances of success. The inhabitants can contribute their own competencies and knowledge, and the tasks can be spread across many shoulders” [28].

The production of bioenergy in general is linked to the use of biogenic raw materials and involves farmers or owners of biogas fermenters. The raw materials “only” have to be “developed” and transported to the energy producer, who then generates energy when it is needed. It must be clarified which raw materials are most suitable for producing bioenergy, and how they can be developed and made accessible. Despite the fact that maize achieves the highest gas yield, residual biomass can also be considered for bioenergy usage for the case study area [20,29]. Residual biomass is defined in this paper as unused grass from grassland, municipal and industrial (process) waste (e.g., biowaste), agricultural side products (e.g., cow dung, liquid cow manure, and plant material from landscape conservation). Since these biomass types are not part of the usual bioenergy chain, the bioenergy farmer in our case study (cf. Section 2.1) is required to ask local administrative bodies and water authorities to get access to the residual biomass. Often this alternative biomass is available at no costs if the bioenergy farmer is taking care of the transportation.

Our research question is to assess how different mixtures of alternative biomass can be embedded into a sustainable management of both the landscape and the energy system in line with the Sustainable Development Goals? To answer the question, a multi-criteria decision analysis (MCDA) using the Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE) methodology is applied. The research is focused on a specific case study area in northern Germany. The focus of this research is on the contribution of alternative biomass to regional bioenergy solutions. The system boundary is set on a regional sustainable development approach within a socio-ecological context. This involves the interaction of different stakeholders who did not interact in the past, such as, for example, public water body authorities and biogas plant owners. Because of the high competition of acquiring raw materials as feed for the fermenter, a closer view is set on the raw material supply chain for the fermenter along with former unused material. Furthermore, we assess how different mixtures of alternative biomass can be embedded into a sustainable management of both the landscape and the energy system. These alternative biomass scenarios are compared with the baseline scenario and a scenario with increased usage of corn silage.

2. Materials and Methods

In order to answer the research question, a stepwise approach in the multi-criteria assessment of best options was followed. This was to ensure optimized regionally embedded bioenergy value chains within the selected region (cf. Section 2.1) and in the vicinity of an operating biogas plant by making use of available alternative biomass. The baseline for this assessment was established through interviews with regional experts in order to evaluate the unused potential of the “alternative

substrates” in this region. Therefore, in addition to the local farmers and plant operators, water body authorities, municipalities, landowners and local decision-makers participated.

The approach was as follows and is described in the following sections:

- (a) Identification of the regionally available biomass potentials in a bioenergy region typical for both natural and socioeconomic conditions of established German regional bioenergy structures (agriculture and grassland areas as typical regions in the rural northwestern area of Germany, cf. Section 2.1). This step established an inventory of the regional preconditions for a sustainable bioenergy production.
- (b) Analysis of the socio-ecological context of bioenergy supply chains for the assessment of the potential of so far unused biomass (cf. Section 2.2). This step introduced a generic framework for the analysis of the regional bioenergy structure, using the criteria of economic, social, and environmental conditions for all phases of the bioenergy process chain.
- (c) Participatory definition of realistic options for optimized biomass mixtures (cf. Section 2.3). Bioenergy producers together with regional stakeholders identified options for modified bioenergy chains at this step. They aimed at the integration of alternative substrates that could be made available for bioenergy purposes at high levels of feasibility.
- (d) Gathering of site-specific data and reference data sets (cf. Section 2.3). Quantitative and semiquantitative data on the criteria of the analytical framework were gathered from bioenergy plant owners and literature at this step.
- (e) MCDA according to the socio-ecological context and data with a preference analysis of the identified options according to PROMETHEE outranking method (cf. Section 2.4). The final step aimed at the identification of alternative bioenergy chains that could optimize the current regional bioenergy structures most.

2.1. Identification of the Regionally Available Biomass Potentials for Bioenergy

The following approach was taken to identify the biomass to be integrated into potential regionally embedded alternative bioenergy chains. The regional focus was set on a region in the vicinity of an operating biogas plant in the northwest of Germany (Figure 1). This rural area has less fertile sandy to silty soils or peaty soils. A total of 58% of the area is used for agriculture. Prominent is a grassland-dominated agriculture (pasture as well as hay and grass silage production) for dairy farming. Horticultural activities, mainly tree nursing, are of minor relevance. The soil and climate allow for crop production over the entire vegetation period [14].



Figure 1. Case study location. The area of Ihausen is located in the northwestern part of Germany. (own figure).

The gap between the biomass potentials and the biomass currently used for bioenergy in the region was assessed in geographic information systems (GIS) analyses and by interviews with regional actors. Accordingly, the use of biomass in the case study region depends on five aspects in particular: (i) the supply chain of biomass is normally defined by operators of bioenergy plants and their access to local farmers' biomass; (ii) a feedstock of a biogas plant is normally made up by the prevailing biomass or manure in the region; (iii) the competition for arable land to grow energy crops, including alternative biomass like grass, is high [30]; (iv) very few farmers currently align with local landscape management associations to acquire alternative biomass [14]; and (v) the availability of primary produced biomass is limited, in contrast to a high availability of manure.

This current situation marks a transition of regional bioenergy driven by changing European and German legal settings. The competition for biomass is very high in this region and was even intensified due to the incentives of the German Renewable Energy Sources Act (EEG). By giving high incentives for feeding-in electricity at the beginning of the EEG's history, subsequently the maximum amount of maize used in biogas fermenters was gradually reduced. The latest version of the EEG from 2017 restricts the use of maize to up to 44% of the total mass of substrate [23]. As the market for biogas plants was nearly saturated by the time of this last EEG revision, there are only very few biogas plants operating under this revised EEG. Hence, most of the biogas plants are allowed to use up to 60% maize, and therefore, this number was taken for one of the scenarios later in this chapter. Therefore, biogas plant operators in the case study region will be forced to reduce the amount of maize as biogas substrate in their plants when their EEG subsidies are running out. However, because of the high gas yield of maize [22], many biogas plant operators still grow maize in these regions. More recently, RED II as part of the EU's "Clean energy for all Europeans package" came into force. This directive asks for a broader view. With respect to bioenergy, it requires consideration of the

socioeconomic conditions of bioenergy chains. It is worth mentioning that a concurrent directive on the Governance of the Energy Union and Climate Action (EU 2018/1999) discusses aspects of bringing together local authorities, civil society, businesses, investors and other stakeholders to establish a multi-level energy dialogue. This context was considered in this study to highlight the benefits of new stakeholder alliances to make the regional bioenergy supply chain more sustainable and to conform to the new EU regulations.

2.2. Analysis of the Socio-Ecological Context of Bioenergy Supply Chains for the Assessment—Definition of Criteria

Any optimization of bioenergy supply chains has to take regional conditions into account [14]. This includes considering socio-cultural, economic conditions and legal regulations that provide the framework for the generation and use of bioenergy. It also relates to the involvement of actors from different stakeholder groups [31–34]. In this assessment, socio-ecological data were integrated and applied to sustainability parameters in a multi-criteria decision analysis (MCDA) using the PROMETHEE methodology to outrank optimization scenarios. As the focus was set on socio-ecological data, most environmental indicators such as CH₄ and N₂O emission occurring during the whole bioenergy supply chain were not included in this assessment and were reduced to CO₂ emissions during transportation and production of biomass. However, the topic of emissions has been discussed in many other references [35–38]. Resulting from the authors' experience in biomass-related projects, criteria for the evaluation of biogas in a regional context were developed. The traditional supply-chain operations reference model (SCOR) was modified with the involvement of project partners to meet the challenges of the production of bioenergy, resulting in the identification of the processes: material supply, logistics, production, and usage [39]. The distribution of converted energy and its accompanying emissions was not part of this study and is excluded here. Each process was specified by the definition of targets. Since different stakeholders participated in this process the best possible targets for the region were formulated and were therefore relative to this specific region. Subsequently all located targets were expressed within suitable criteria [40,41]. The criteria were elaborated together with the plant operator.

Figure 2 identifies criteria alongside targets for processes in the regional production of bioenergy, as assessed by our local partners. Therefore, these targets fit into the area of northwestern Germany and may not be transferable to other regions, countries, and continents. Targets for the optimization of different steps of bioenergy chains were defined with the regional stakeholders. A set of criteria were attributed to the targets. Quantitative or semiquantitative data in the indicated unit were compiled for each criterion from literature, official statistical data, and regional bioenergy operators. Criteria values were then calculated for each alternative action based on: (i) data from operators directly, (ii) data and indicators from literature (e.g., the Federal Statistical Office of Germany [42], the Bavarian State Research Institute for Agriculture (LfL) [43], the Association for Technology and Structures in Agriculture (KTBL) [44]), (iii) software tools (e.g., cost efficiency calculator KTBL [45], feed-in tariff calculator German Biomass Research Centre (DBFZ) [46], basic data from DungInfo [47] for the calculation of humus balance), and (iv) for criteria with insufficient data the values were introduced based on expert knowledge.

TARGETS	CRITERIA		
		unit	weighting (avg)
1. Material supply			
• Usage of potentials which do not compete with food or animal feed production	• Use of material not directly competing with food production	[%]	0.042
• Minimize material costs	• Material costs	[cent/kWh _{el}]	0.042
• Promote ecosystem based farming	• Soil quality (change in humus balance)	[t _{hum.c} /a]	0.042
• Raise social acceptance of energy crops cultivation	• Fuel consumption agriculture	[L/MWh _{el}]	0.042
• Provide and secure employment	• Share of maize plants in area	[%]	0.042
	• Working hours agriculture	[hours/a]	0.042
2. Logistics			
• Reduce transport costs	• Transport costs	[cent/kWh _{el}]	0.06
• Reduce environmental impacts	• Avg transport distance	[km]	0.06
• Minimize infrastructure usage	• CO ₂ balance transport	[g _{CO2} /kWh _{el}]	0.06
• Provide and secure employment	• Working hours transport	[hours/a]	0.06
3. Production			
• Minimize operational costs	• cost per production unit	[cent/kWh _{el}]	0.08
• Assure high materials efficiency	• CO ₂ balance production	[g _{CO2} /kWh _{el}]	0.08
• Reduce environmental impacts	• Working hours plant	[hours/a]	0.08
• Provide and secure employment			
4. Usage			
• Maximise profit	• Total income p.a.	[€/a]	0.25

Figure 2. Correspondence of criteria to targets for supply chain processes in the production of bioenergy.

The weighting of the individual criteria was applied in the outranking of options in the participatory assessment (MCDA–PROMETHEE). In addition to criteria values the PROMETHEE methodology requires information on the weighting of criteria. Therefore, the assessment followed an approach to give equal importance (0.25) to each target: material supply, logistics, production, and usage. In weighting each criterion it was assumed that all elements had the same importance for the decision-maker [48]. For each criterion the average weighting is presented in Figure 2. For all criteria a Gaussian preference function was applied, since it was proved to be stable [49]. For this function the parameter σ needed to be determined. The input data were normalized from 0 (worst value) to 1 (best value), therefore, σ of 0.3 was applied as in [50]. Calculations of some criteria were repeated, e.g., the calculation for working hours was taken from a cost efficiency calculator instead of a calculation based on performance indicators for fixed and variable working hours. Furthermore, the methane yield of the plant was taken as reference rather than the total mass of substrate.

In the case study, Target 1, Material Supply, aims at using substrates that do not compete with food or animal feed production. It tries to minimize the material costs and promote ecosystem-based farming. Energy crop cultivation will be socially accepted and at the same time bioenergy will provide secure employment. These sub-targets are expressed through different criteria. The Use of material not directly competing with food production describes the use of substrates that are not primarily used for generating biogas. First, the amount of energy crops used in an area has direct influence on other local agricultural activities. Less energy crop cultivation means less pressure on agricultural food production. Second, this will help keeping permanent grassland in the region, which has an overall positive effect on the region's ecology. Third, using agricultural and other organic waste products as a substrate allows to close the loop of the bioenergy supply chain. Material Costs describes the price for the individual substrates such as corn silage or liquid manure, excluding transportation costs. Material costs were calculated based on information from an operator survey. Corn silage was available in the region for 30 EUR/t. Liquid cow manure was partly available from own cattle and additionally bought from farmers in the region for 4.5 EUR/t. Alternative substrates such as plant material from landscape conservation and biowaste were available at no costs; however, the owner of the plant had to provide transport for the substrate himself. The same is applicable to

Soil quality (change in humus balance), reflecting that the cultivation of land induces a change in humus balance. Maize, for example, has a negative impact on the humus balance; in contrast, grassland has a positive effect. Key figures on the change of humus balance for the cultivation of different substrates are given in [47]. The Fuel consumption agriculture criterion specifies the fuel consumption at harvest time. It is based on the use of a field chopper consuming 65 l diesel and a tractor consuming 14 l diesel to harvest 2 ha/h. This criterion does not include fuel-consuming processes during other agricultural processes such as plowing, sowing, and fertilizer application due to the lack of data. Share of maize plants in area describes the amount of cultivable land in a region that is used for energy crops. The share of farmland for cultivation of corn/maize is reduced by the usage of alternative substrates and increased by the usage of corn silage as a substrate. The current state equals the current share of maize plants in the region, according to the statistical data [51]. Working hours agriculture assesses the working hours invested in cultivating biomass substrates. In this case study working hours in agriculture only occurred for the cultivation of corn, and 7.6 h/ha for corn silage was assumed based on the literature [52].

Target 2, Logistics, aims at reducing transport costs and the regional environmental impact but it also tries to increase secure employment in the sector. Therefore, Transport costs describes the costs for shipping substrates from the farm area to biogas plants. Transport costs were calculated with a linear model, giving specific transport costs depending on the transport distance [53]. For all substrates, distances were taken either from an operator survey or calculated based on GIS results from previous studies [14]. Up to 50% of the current usage of corn silage was available at a very short distance of less than 1 km. However, additional corn silage needed to be bought from distances up to 15 km. Plant material from landscape conservation was only available decentralized, and therefore transport distances of up to 20 km were taken into account. The Avg. transport distance reflects the average distance of getting the substrate from its source to the biogas plant. The criterion CO₂ balance transport determines the greenhouse gas (GHG) emissions occurring during transport of substrates and digestates. Working hours transport describes transporting substrates or digestate, thereby also reflecting the time for loading and unloading. Similar to the CO₂ balance transport, work hours transport are directly influenced by the transport distances of the substrate. Greenhouse gas emissions for the return trip of the transport vehicle were taken into account.

Target 3, Production, aims at minimizing the operational costs, achieving a high material efficiency, thereby reducing the environmental impacts. Cost per production unit, i.e., the electricity generation costs, are made up of the variable cost, fixed costs, indirect costs, and the actual supply of electricity to the grid. The CO₂ balance production criterion reflects the output of CO₂ emissions at different stages of biogas production such as cultivating plants, the actual biogas generation, and digestate utilization. The CO₂ balance production takes into account greenhouse emissions for the (i) provision of substrates in the form of soil cultivation, fertilizers, pesticides, and direct emissions (N₂O emission from soil) as well as the (ii) biogas production in the form of the provision of the biogas plant, operating material, leakage, and processing of biogas in a cogeneration unit. Working hours plant relates to “loading” the plant with solid or liquid substrates and tasks such as control, sample taking, documentation, or maintenance and repair. Finally, the Working hours plant mainly depends on the ratio of liquid and solid substrate, since solid substrate requires substantially more time for treatment and feeding of the plant [54].

Target 4, Usage, aims at maximizing the income. Total income p.a. describes the annual income/loss before taxes. It was calculated based on a cost efficiency calculator from the Association for Technology and Structures in Agriculture [45]. Since the annual mass was taken as reference in this case study the gas yield varied across the scenarios directly influencing the income. The gas yield assumed for alternative substrates (e.g., plant material from conservation areas 102 m³/t) was substantially smaller than the gas yield of corn silage (197.6 m³/t).

2.3. Participatory Definition of Realistic Scenarios of Options for Optimized Biomass Mixtures with Applicable and Regional-Specific Options

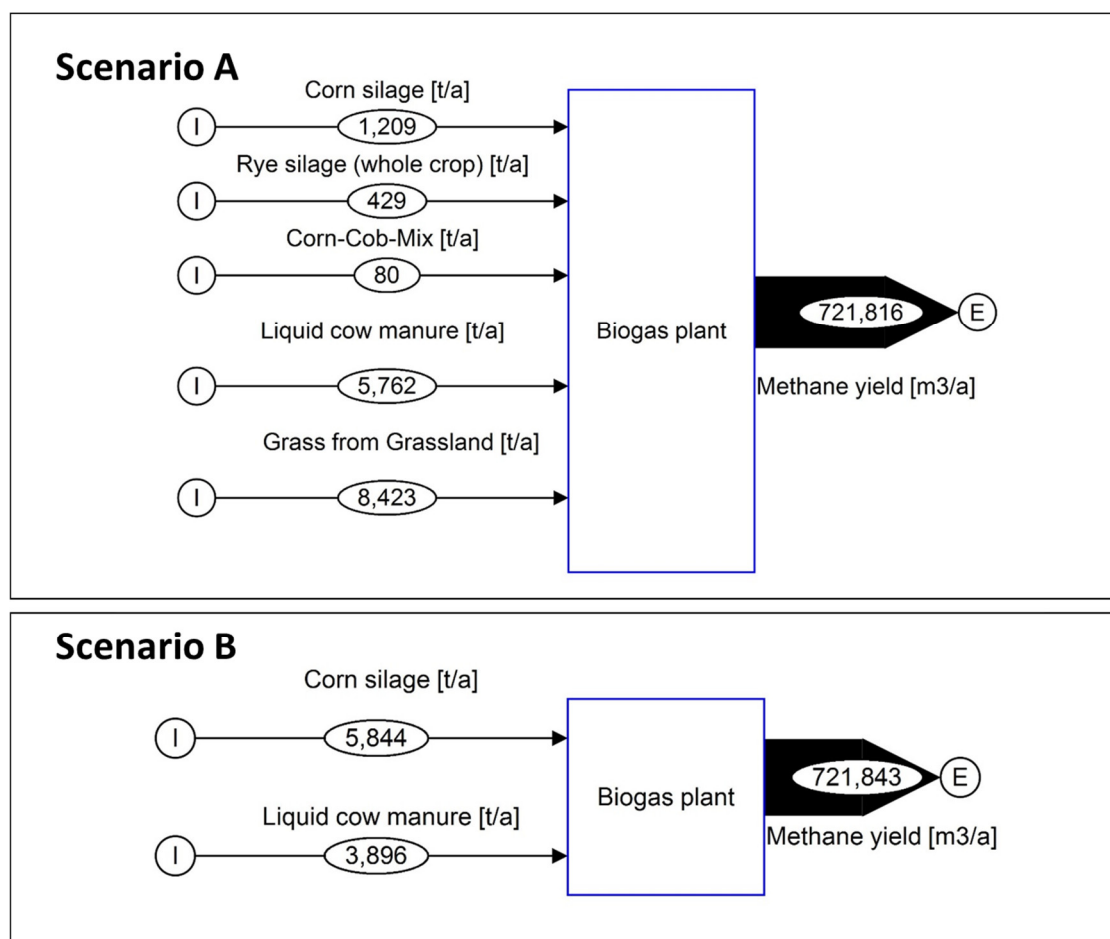
The analysis included several alternative scenarios. The different scenarios are described by the usage of alternating substrates within those mixes. In order to provide a comparability of the alternative actions, either (i) the annual total mass of substrate $[t/a]$ or the (ii) annual methane yield of the mix of substrate $[m_{CH_4}^3/a]$ can be defined as constant. In this study both approaches were investigated for the biogas plant in Ihausen.

The following subsection gives a brief overview of the scenarios that were used to derive the substrate mixes:

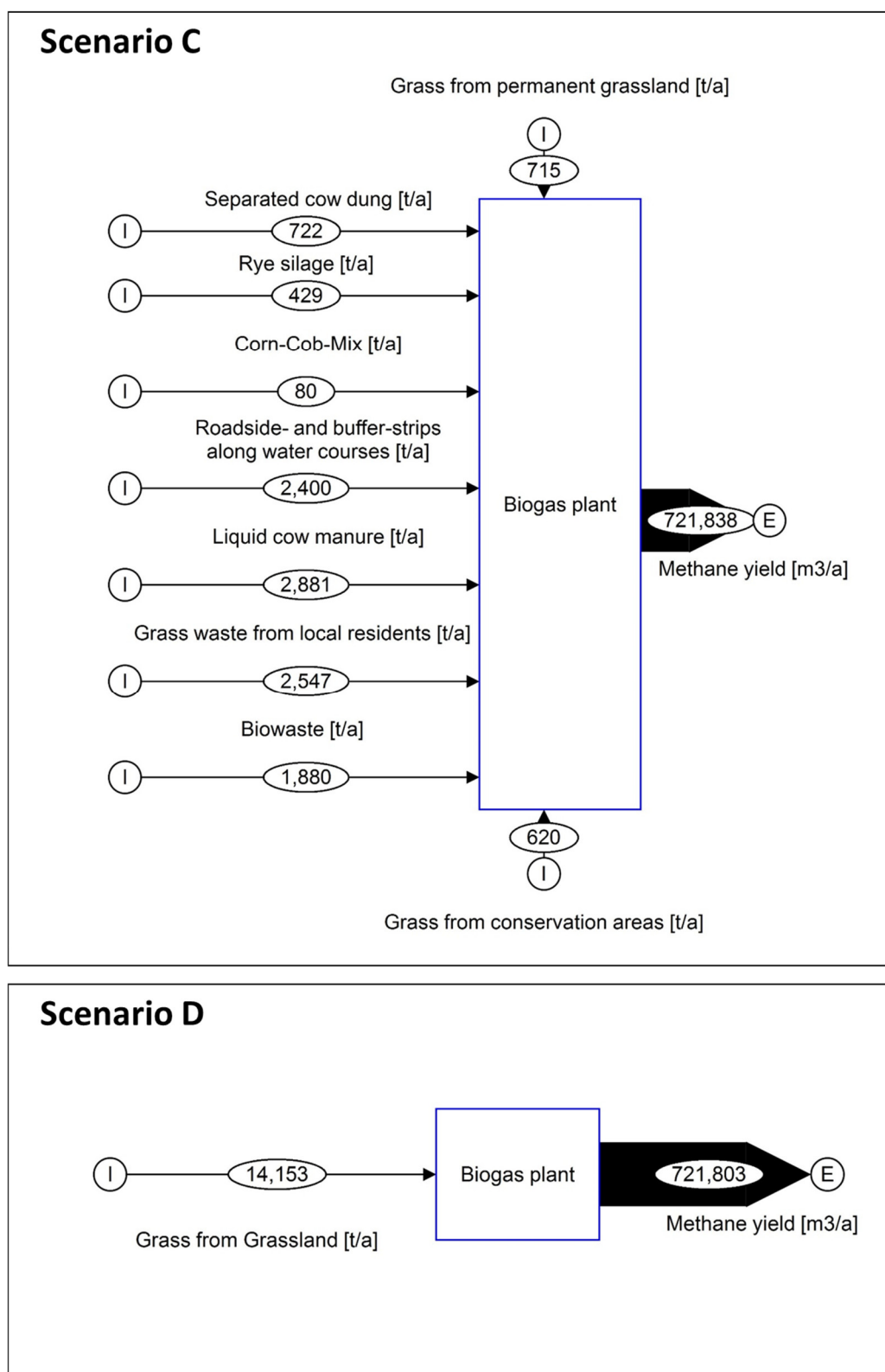
- a. Scenario A—Baseline: The current mix of substrate is based upon an operator survey executed within a project performed on cross-country borders in Germany and the Netherlands (GroenGas-DELaND, EU-project, Dutch-German cross-border program).
- b. Scenario B—Max 60% corn silage: The German Renewable Energy Sources Act (EEG) 2012 used to allow farmers a maximum usage of corn silage of 60% (EEG § 27 Biomasse Abs. 5 Nr. 2, 2012). As discussed in the introduction, because the EEG 2012 applied to the majority of biogas plants, this value was preferred to the latest version of EEG in 2017. Since corn silage has a very high gas-yield-to-material cost ratio many operators can maximize the revenue of the plant by using the highest possible amount of corn silage. However, this always has to be considered within the regional context and the increased usage of corn silage is connected to negative social and ecologic impacts on biodiversity in the region.
- c. Scenario C—Alternative substrates: Alternative substrates to biomass are available in the region that are not yet considered for bioenergy production and are mainly provided by external stakeholders outside the classic bioenergy supply chain (e.g., municipalities, water body authorities, etc.). Besides energy crops, a detailed observation of substrates that are not produced for the target of biogas production was conducted. Alternative substrates were classified within the groups of (i) municipal and industrial (process) waste (biowaste), (ii) agricultural side products (cow dung, rye silage, corn-cob mix, liquid cow manure, roadside and buffer strips along water courses, and grass waste from local residents), and (iii) plant material from landscape conservation (grass from permanent grassland and conservation areas). Potentials were calculated with the support of geographic information systems (GIS) [14] and data from the Federal Statistical Office of Germany [51]. For the scenario of the potential of alternative substrates several assumptions were made. Firstly, all alternative substrates are available for usage in the case study biogas plant. Therefore, no competition with other industries (e.g., direct usage of cow dung) is considered. Secondly, alternative substrates from group (iii), plant material from landscape conservation, can be used free of charge in this region, excluding the costs for transport. Emissions and costs resulting from the process of landscape conservation were not considered within this study. It should be noted, that these alternative substrates are fully in line with the emission reduction targets of RED II and these substrates are generally not in conflict with land-use change. Material costs for substrates other than grass are specific to the considered region. Thirdly, the usage of a diverse mix of alternative substrates requires technical adjustments of the plant and could lead to instable operation. This was not considered as extra costs.
- d. Scenario D—100% Grass from Grassland: The northwestern area of Germany is covered by a huge amount of grassland, and therefore, biogas farmers tend to use grass from grassland as feed to the biogas plant as well. On average, material costs for grass from grassland is zero in this area, therefore, their actual costs represent the harvesting costs, including transportation, since the operator of the plant can use the substrate as long as he harvests the area on own expense.

2.4. Substrate Compositions

The different types and masses of substrates resulted in similar annual methane yields in the Ihausen region for the three defined scenarios (Table 1). The numbers were either generated by GIS analysis and derived from a former analysis published in [14], or were provided by the plant operator itself or provided by the municipality. Figure 3a,b show the material flows of each Scenario.



(a)



(b)

Figure 3. (a) Material flows of Scenarios A and B. (b) Material flows of Scenarios C and D.

Table 1. Substrate composition case study area Ihausen.

Substrate in t/a	Scenario A	Scenario B	Scenario C	Scenario D
Corn silage	1209	5844	-	-
Rye silage (whole crop)	429	-	429	-
Corn-Cob Mix	80	-	80	-
Liquid cow manure	5762	3896	2881	-
Separated cow dung	-	-	722	-
Grass from grassland	8423	-	715	14,153
Plant material from				
(a) Conservation areas	-	-	620	-
(b) Roadside and buffer strips along water courses	-	-	2400	-
(c) Grass waste from local residents	-	-	2547	-
Biowaste	-	-	1880	-
Annual mass of substrate [t/a]	15,903	9740	12,274	14,153
Annual methane yield [$m^3_{CH_4}/a$]	721,816	721,843	721,838	721,803

The current state substrate composition comprises corn silage, rye silage (whole crop), corn-cob mix, liquid cow manure, and grass from grasslands.

The max 60% corn silage substrate composition represents Scenario B with the legally highest possible corn silage amount, according to EEG 2012. As mentioned before, the increased usage of corn silage is expected to enable the biogas plant owner to increase the annual income. Next to corn silage, liquid cow manure is used and available at no extra cost to the biogas plant owner in this region due to the high volume of dairy farming in the region. The use of liquid manure reduces the solid matter percentage and guarantees a stable fermentation. As a result, Scenario B shows the lowest annual mass of substrate, followed by Scenarios C and D, and finally, Scenario A with the highest annual mass.

Scenario C, Alternative substrates, represents potentially available substrates and again not all of them are usable in a biogas plant due to legal restrictions or other uses of the substrate. The substrate composition includes plant material from roadside (central reservation and verges) and buffer strips, local residents' and organic household waste. Furthermore, separated cow dung is used. In order to reduce transport costs regular cow manure is refined in a compaction process, separating the solid phase of the substrate. According to the owner of the biogas plant this allows to reduce 85% of the mass, while retaining 60% of the gas yield of the substrate.

Grass from grassland is abundantly available to the biogas plant owner as long as he collects and transports the substrate himself. The sole usage of grass from grasslands is considered in a variant of the alternative substrate composition as Scenario D, 100% Grass from grassland.

2.5. Multi-Criteria Decision Analysis (MCDA) According to the Socio-Ecological Context and Data with a Preference Analysis of the Identified Options According to PROMETHEE Outranking Method

The Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE) was applied in this study to assess the best suitable solution within the regional bioenergy production. It is a methodology within the multi-criteria decision analysis (MCDA) family [55]. Based on an outranking approach it allows practitioners and researchers to rank a finite set of alternative actions among criteria and is increasingly used in a wide range of applications [56]. Furthermore, MCDA can be utilized to evaluate problems in the context of sustainability, since it is regarded as a flexible method with the possibility of facilitating the dialogue between stakeholders, analysts, and scientists [57].

PROMETHEE is based on pairwise comparisons of alternatives in order to identify dominance of one alternative over another [58]. The outranking method PROMETHEE is applicable in cases of incomplete and contradictory information. In contrast to other MCDA methods, complete compensation of criteria is possible to a limited extent within outranking methods [50]. In the real world, decision-making problems are uncertain to some extent [59]. This research is applied to a real world case, a biogas plant in Ihausen, Germany. Therefore, PROMETHEE was chosen as the most

suitable method. Also, this MCDA procedure has been proven to be efficient and widely applied in the research field of bioenergy [60–62]. PROMETHEE I involves the calculation of negative net flow ϕ^- and positive outranking flows ϕ^+ for each scenario. The net flow describes how much a scenario was preferred over all other scenarios. PROMETHEE II provides a complete ranking of the alternatives by calculating the net flow ϕ . The higher the net flow, the better the alternative [55]. In this study PROMETHEE II was applied. The net flow for each scenario was calculated and is presented in the Results section. To perform the analysis, the Visual PROMETHEE 1.4 Academic Edition software (Marechal, Brussels, Belgium) was used [63].

3. Results

This section presents the results of the multi-criteria decision analysis using the PROMETHEE methodology. The section begins with a presentation of the criteria values and then provides the preference ranking (net flow) for the biogas plant.

3.1. Criteria Values

Following the description of the different substrate compositions, this section presents and assesses the criteria values for the case study Ihausen. A general description of the criteria was presented in Section 2.2. Therefore, the criteria values for the Ihausen case study were calculated as previously described. However, as mentioned before, the annual methane yield of the plant was defined as constant across the scenarios to make a comparison possible. The total mass of substrate needed to achieve the same methane yield was significantly higher in scenarios with alternative substrates (see Table 2).

Table 2. Criteria values of case study region.

Criteria	Unit	Scenario A Baseline	Scenario B Max 60% Corn Silage	Scenario C Alternative Substrates	Scenario D 100% Grass from Grasslands	Reference
1. Material						
1.1 Use of material not directly competing with food production	%	89.20	40	95.85	100	
1.2 Material costs	cent/m ³ CH ₄	14.20	32.38	6.81	5.88	[64]
1.3 Soil quality (change in humus balance)	t _{Hum.C} /a	−6.70	−93.50	−21.36	62.44	[47,65]
1.4 Fuel consumption agriculture	L/t	1.19	6.64	0.46	0	[53,66]
1.5 Share of maize plants in area	ha	24	117	0	0	[42]
1.6 Working hours agriculture	hours/a	1491	888	1974	1549	[52,67]
2. Logistic						
2.1 Transport costs	EUR/t	5.29	4.60	7.80	6.42	[53,64]
2.2 Avg. transport distance	km	10.57	13.00	16.35	10.00	[68,69]
2.3 CO ₂ balance transport	g _{CO2} /m ³ CH ₄	15.64	11.79	18.68	13.18	[45]
2.4 Working hours transport	hours/a	1683	897	1916	1816	
3. Production						
3.1 Costs per production unit	cent/kWh _{el}	17.00	18.78	14.01	15.97	[64,70]
3.2 CO ₂ balance production	g _{CO2} /kWh _{el}	47.2	26.1	24.3	63.6	[54]
3.3 Working hours plant	hours/a	876.30	786.90	798.40	921.40	[54,71]
4. Usage						
4.1 Total income p.a.	EUR/a	124,496	40,938	145,004	169,712	[70]

Table 2. shows that Scenario D, Grass from Grassland, and Scenario C, Alternative substrates were more profitable and had less negative impact on the biodiversity in the region, compared to other scenarios. The fuel consumption depends on the percentage of material received from agricultural activities and was a reason for a higher number in Scenarios A and B with higher inputs of corn and rye. In contrast, the soil quality showed the best results in Scenario D as grasslands are known for carbon capture, whereas maize and rye cultivation resulted in a negative scenario and reduced the soil quality. This echoed the much discussed and well researched critique of maize cultivation, resulting not only in a negative impact on the soil quality but also in the high competition with material for food production. Moreover, grass is known for a positive humus balance and caused therefore the only positive value in category 1.3, Soil quality. Furthermore, longer working hours in agriculture for Grass from Grasslands were determined since the operator of the plant could only use the substrate as long as he cut and collected the substrate from the field. Compare to maize, which is harvested once in a season, grass is harvested up to five times in a season and caused, therefore, longer working hours. This explained the low value in 2.4., Working hours transport, in Scenario B and the high value in Scenario D. Scenario C showed the longest average transport distance as material from municipal cultivation areas was also included; however, it was not always available close to the biogas plant. As grass cultivation is naturally related to its substrate-specific emissions it related to the high value in 3.2., CO₂ balance production. Noticeable was also the difference in material costs between Scenarios A and B and C and D. It should be noted that material costs underlie permanent fluctuation and that this indicator may vary within a range related to weather conditions during the season. Details on the calculation method and the values are provided in the Supplementary Materials (Tables S1–S15) to this article.

3.2. Preference Rankings

The preference rankings shown in this chapter represent the results of the performed PROMETHEE analysis. The results are presented in a vector graph to visualize the obtained net flows ϕ . The net flow describes how much a scenario was preferred over all other scenarios. Therefore, the scenario with the highest net flow value would have the best criteria values under the consideration of the applied weighting.

Figure 4 shows the preference rankings for the case study Ihausen. The annual methane yield of the mix of substrate [$m^3_{CH_4}/a$] was the defined constant for all scenarios in this case study.

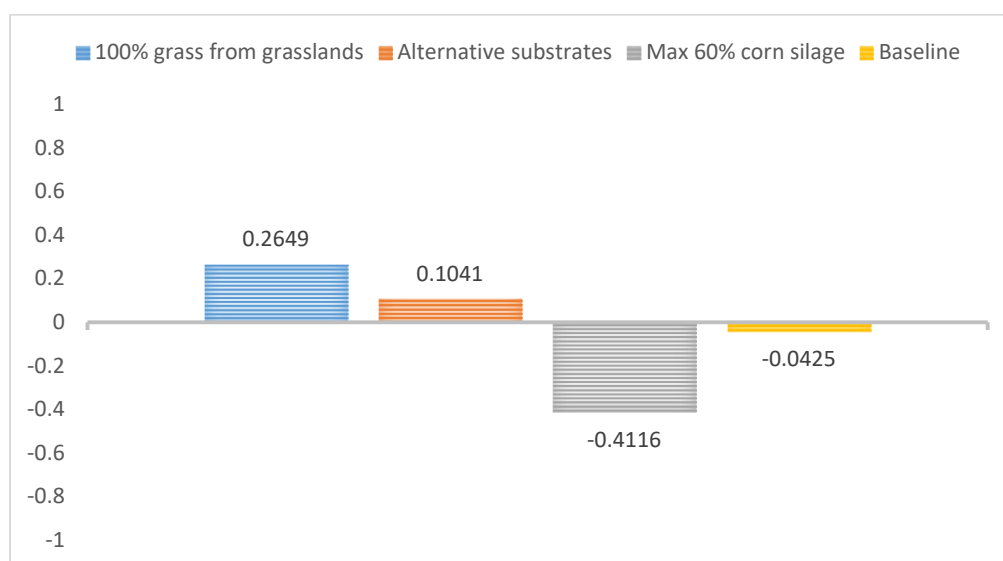


Figure 4. Results of Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE-II) analysis for the four scenarios adapted to the case study region Ihausen (net flow ϕ).

The 100% Grass from grassland scenario showed the highest net flow among all considered scenarios, followed by the Alternative substrates scenario. This was mainly caused by the usage of either free or cheaply available substrates such as liquid cow manure, separated cow dung, and plant material from roadside and buffer strips as well as grass waste from local residents. This resulted in low material costs that caused low costs per production unit and a high total income. Furthermore, the substitution of corn and rye silage resulted in no change in soil quality and fuel consumption for agriculture. Disadvantages of the usage of the potential alternative substrates were again the loss of working hours in agriculture as well as increased transport costs and CO₂ emissions for transport.

Furthermore, no costs for technical adjustments of the plant were taken into account, but there was a need for technical adjustment of biogas plants to be able to process alternative substrates (e.g., grass from grasslands). However, this was out of the scope of this study for the sake of simplification. The next section discusses the results and their implications in detail.

4. Discussion

Since the focus of this research was on the contribution of alternative biomass to the challenges of regional bioenergy settings related to the future fate of bioenergy in Germany, this article followed the question of how different mixtures of alternative biomass can be embedded into a sustainable management of both the landscape and the energy system. We can answer the question in three directions.

(i). From mono-substrates to diverse substrates with alternative biomasses

Against common belief [22,23,72] corn silage cannot be confirmed as the substrate that always gives the most economic benefits or the highest gas yields. In other words: the usage of alternative substrates is especially useful in regions with high competition for land and is now favored in RED II. However, RED II lacks a default value for grass silage, and therefore the assumptions are different from region to region. Other researchers have already come to the same conclusion [20].

Accordingly, scenarios with usage of both potential and usable grass from grasslands and alternative substrates as well as a scenario with increased usage of corn silage were compared to the current state of the case study plant. The main findings are threefold: (i) grass from grassland and alternative bioenergy supply chains are ranked higher than chains with increased shares of corn silage, (ii) bioenergy supply chains that involve alternative biomass and grass from grasslands provide optimization potentials compared to the baseline scenario and, more generic, (iii) optimization potentials relate to several spheres of the social–ecological system where the bioenergy structure is embedded. The latter is clearly dependent on topical legal frameworks, i.e., EU RED II and the EEG in Germany in the future. The approach and results of this study demonstrate that alternatives to realize optimization potentials can be identified and emphasize the need for integration of regional stakeholders in making use of alternative biomass and in making regional bioenergy more sustainable according to EU goals [24].

Shifting baselines with respect to legal frameworks constantly challenge bioenergy structures and pose optimization needs. An example provides the sub-goal that has been set for the transport sector: each member state must require fuel providers to ensure that the share of renewable energy in the final energy consumption of the transport sector is at least 14% by 2030 (Art. 25). Furthermore, a number of sustainability criteria and criteria for greenhouse gas savings for biofuels, liquid biofuels, and solid and gaseous biomass fuels are defined (Art. 29). The biofuels, liquid biofuels, and biomass fuels produced from agricultural biomass must not be produced from raw materials that come from areas of high biodiversity value and with a high carbon stock. The problem of indirect land-use changes has also found its way into RED II: there are two different measures for dealing with indirect land-use changes (Art. 26). On the one hand, the proportion of biofuels produced from food and feed crops, liquid biofuels, and biomass fuels used in the transport sector in each member state may contribute a maximum of 7% to the final energy consumption in the transport sector (Art. 26, Para. 1). On the other hand, national limit values are set for biofuels, liquid biofuels, and biomass fuels derived from food and animal feed crops with a high risk of indirect land-use changes, in which case

a significant expansion of the production area to areas with a high carbon stock can be observed, which will be gradually reduced to zero by 2030. To this end, the European Commission adopted a delegated act [24] that defines the criteria for the determination of raw materials for the production of biofuels with a high indirect land-use (iLUC) risk.

- (ii). From sectoral bioenergy to multi-faceted bioeconomy (the lock-ins of former bioenergy and bioeconomy as an open way out of it)

Germany had the luxurious situation over the last decades where bioenergy operators could benefit from the subsidies for the feed-in electricity and a bonus on energy crops as regulated by the EEG. This has shifted nearly the whole bioenergy industry in Germany toward the monoculture of maize or corn for biogas production and its transformation into electric energy, causing conflicts with regard to food supply. After implementing the indirect land-use (iLUC) discussion on the European level, the EEG has also shifted away from energy crops toward alternative substrates with no land conflict or even waste, as the incentives for energy crops were reduced to zero.

Biogas supply chains always need to be considered in a local context. For example, the case study showed that the high competition for land with the dairy industry increases material costs for corn silage to 40 EUR/t. Therefore, a biogas plant that uses 60% corn silage as substrate would not be able to generate income (see Table 2). On the other hand, the usage of alternative substrates could—in some cases—actually increase the total income (without taking into account the CO₂ benefit) as shown in the usable alternative substrate scenarios.

The main drawbacks of the usage of alternative substrates observed in the case study were twofold: the usage of alternative substrates caused (i) high transport costs and CO₂ emissions in the case study. However, stress on a region's road network can be avoided by reducing peaks in transportation. Furthermore, the (ii) substitution of corn and maize leads to a decrease of working hours in agriculture for a plant operator. On the contrary, an increase of working hours in transport was observed. In general, beneficial effects of the usage of alternative substrates need to be balanced against the described disadvantages. In addition, the change of fuel for transportation would also have an impact on the CO₂ emissions during production.

The key observation of our assessment resulted in a high influence of alternative substrates in a regional context. Also, both positive and negative impacts could be identified that were always regionally specific. In this case study the positive impacts for the region outweighed the negative ones, as shown in the net flow (Figure 3). A Finnish case study using only grass silage as a substrate when the grass is cultivated exclusively for energy purposes, concluded that the emission reduction targets set in RED II are not easy to achieve. The reduction targets can be achieved though, if the grass is cultivated due to an improved crop rotation and if only the emissions from harvesting are included [20]. However, there are still more potential substrates to assess and discover, for example, biomass from water bodies and their maintenance. This implies more discussion among stakeholders and other biomass alliances that might not be existent today in these regions. More information and adapting the overall policy framework might be necessary.

At the regional level, bioenergy systems may be integrated with the cascade biorefinery models or offer waste management solutions [9]. Such approaches are politically promoted by the EU and the stimulus given by the EU Bioeconomy Strategy [25]. In redesigning the bioenergy sector, local knowledge, public health, and the community's resilience should not be neglected, while social–environmental benefits should be considered in addressing the viability of bioenergy plants [1]. For the time being, integration of bioenergy in a broader bioeconomy is an ambition rather than a substantiated way [7–9]. This study has already demonstrated the diversity of options and implications of bioenergy. Links to other domains of bioeconomy are likely to make value chains even more complex, synergies and trade-offs with SDG targets more numerous, and decision-making more difficult.

- (iii). Bioenergy as part of regional actions toward sustainable development (bioenergy as an element of solutions and SDGs guiding the way)

In a regional context, any realized bioenergy supply chain (using biomass for bioenergy production by certain producer(s)) is embedded in a wider social–ecological context, providing both alternative biomasses and related potential regional partners. In this study, we compared the realized baseline scenario with three potential scenarios. In order to define sustainable measures for regional development, this context becomes relevant in the analysis and realization of optimized supply chains, which also need to be nested into a full set of societal settings and the overall biomass of a region. It is important to understand local needs and constraints to find an optimum within the regional bioenergy chain in favor of all parties. MCDA approaches are capable of analyzing such options, acknowledging the interdependencies of a certain value chain and the context with a set of stakeholders and actors and environmental prerequisites [10]. This has to be based on measurable sustainability indicators as shown in Section 3. Careful selection of targets and related enablers and indicators of MCDA is both a crucial and a difficult task. Innovations to realized bioenergy structures are likely to increase complexity and modification of criteria. The mentioned integration of bioenergy into bioeconomy, for example, implies covering a sustainable bioenergy supply chain that includes all kinds of biomass and its transformation. Feed-in electricity and the combined usage of heat and electrical power might shift toward a higher usage of gas for sustainable transportation. This way, collaboration and cooperation among different actors regarding the provision of substrates can be made. Mowing times, cut length, storage times, etc., are only a few aspects that need to be taken into account. Sustainable approaches are about creating synergies that foster and contribute to regional value creation, but at the same time keep an eye on user demands and attitudes regarding types of energy. A holistic approach to the “bioenergy production” system is therefore important and should also include an optimized usage of residual heat, for example.

Other recent developments will demand managing more options in both the design of bioenergy options in bioeconomy cycles and tools like MCDA to assess them thoroughly. The technical production of biogas is not only dependent on substrates. Another important factor to optimize the efficiency of a biogas plant and the utilization of residual biomass is technology. Here the continuum of available technologies is wide and often directly related to the substrate that is being used in a biogas plant. Each regional bioenergy solution must fit into regional characteristics. This relates to the composition of substrates as well as the usage of end products—biogas and digestate. Improvements along the bioenergy supply chain are only possible when partnerships along that chain are created and when central actors cooperate. This may require a central agency to lead the dialogue, and this could be, for example, local authorities, landscape management associations, or biogas plant managers. Biomass does not equal biogas, not only from a technological point of view but also from a legal perspective. Biogas can only be produced from organic material if it is currently licensed by laws and regulations. In order to foster a sustainable biogas production based on residual biomass and in order to comply with new political requirements more research is needed. Co-benefits are added benefits and could occur when successfully setting up a sustainable bioenergy supply chain. A good example is the provision of heat for a local public swimming pool from a biogas plant. Providing local people or schools with heat from a biogas plant will increase the acceptance of the plant and the technology in general as they benefit from it. Sourcing substrates locally and regionally does not only increase the regional added value but also creates jobs (transport, maintenance).

All of the mentioned facets relate to targets of global SDGs as set by the UN (2015). Considering SDGs and targets provides a framework and items to create scenarios for regional development and to define criteria for assessing promising options. Ongoing discussions and studies on the interrelationship of certain SDGs [9,21,26,72,73] will also provide guidance to local actors to identify and handle the benefits and risks as well as the synergies and trade-offs in making use of bioenergy in the future.

5. Conclusions

The focus of this research was on the contribution of alternative biomass to the challenges of regional bioenergy settings. In our case study we compared different scenarios of biomass substrate use for a case study biogas plant. We showed that the scenarios 100% Grass from grassland and

Alternative substrates were ranked higher than chains with increased shares of corn silage. Moreover, bioenergy supply chains that involved alternative substrates and grass from grasslands provided optimization potentials, compared to the baseline scenario. We also showed that biomass optimization potentials related to several spheres of the social–ecological system in which the bioenergy structure is embedded. Hence, continuous knowledge exchange between research, politics, and business in a region is one crucial aspect in that respect. Research provides relevant knowledge regarding crop and soil qualities, methane outputs, or the latest trends in public participation and governance. Politics shapes legal frameworks and legitimizes bioenergy. Businesses, including farmers and biogas plant owners, can give feedback on the business case for bioenergy and their experiences with technology and substrates. Hence, our study was based on an equilibrium of social, ecological, and economic indicators with a focus on supply chains and material flows, and less emphasis was put on the environmental impacts of the biogas process itself. Therefore, this study pointed out the need to balance the interests and roles of regional actors as another important aspect. The SDGs have the potential to catalyze such fair balancing and to provide serious targets for the regional process of sustainable development. However, this study showed that even in a post-EEG era in Germany the bioenergy sector will not disappear totally, instead, it might shift from electricity and heat production toward the biofuel sector for transportation. Biomass, especially biowaste and animal slurry, will not disappear in the future, hence providing enough availability of biomass.

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