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Energy production from grassland – Assessing the sustainability of different process chains under German conditions

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ABSTRACT

In many regions of Europe, grassland shapes the landscape and fulfils important functions in protecting nature, soil, and water. However, the traditional uses of grassland for forage production are vanishing with progress in breeding and structural adaptations in agriculture. On the other hand, the demand for biomass energy is rising due to political sustainability goals and financial measures to support renewable energy. Against this background, the Institute for Technology Assessment and Systems Analysis investigated the applicability, economic efficiency, and sustainability of different techniques for energy production from grassland as well as from grassland converted into maize fields or short-rotation poplars under German conditions. The results show that despite relatively high energy prices and the financial support for bioenergy, the effects of energy production from grassland on employment in agriculture and farmers' income are modest. What is beneficial are savings in non-renewable energy, reductions in greenhouse gas emissions, and local provision of energy carriers. If grassland biomass (grass silage or hay) is used for energy purposes, this brings the further advantages of preserving biodiversity and the cultural landscape and protecting of soil and groundwater. Negative impacts on sustainable development result from an increase in emissions, which leads to acidification, eutrophication, and risks to human health. The overall evaluation indicates that short-rotation poplars are comparatively advantageous from the economic and ecological point of view. Therefore, a development plan for grassland is required to identify areas where grassland could be used as an energy resource or where it would be favourable to install energy plantations with fast-growing perennial plants.

1. Introduction

Grassland forms a substantial part of the cultural landscapes in Central Europe and some regions of Germany. Meadows and pastures contribute to nature and environmental protection, tourism, and regional economy. Producing roughage for feeding dairy cattle is the primary use for permanent grassland. However, an increasing portion of the grassland is no longer needed for this purpose. This is due to progress in breeding and production technology and to

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structural adjustments in agriculture. In some regions of Germany, almost one-quarter of the grassland is not used in animal husbandry [1]. This 'surplus' grassland could be converted into arable land, afforested, or left for succession. However, there is ecological and sociopolitical interest in stopping the ongoing decline of grassland. In Germany, there are primarily two regulations which support the preservation of grassland: First, under Cross-Compliance regulations, a maximum of only 8% of existing permanent grassland may be converted compared with 2003 [2]. Second, area-based agricultural payment entitlements are also granted for grassland. These premiums will rise to around 300 €/ha by the year 2013. Furthermore, at the federal state level, there are agricultural environmental programmes funding the maintenance of grassland.

Against this background and with regard to the rising demand of biomass feedstock for energy purposes and the political and financial support for renewable energy, 'surplus' grassland biomass could be used as an additional energy resource. Grassland biomass which is no longer needed for feeding cattle, horses or sheep can be used either as a substrate for biogas plants or for combustion devices. At present, the use of hay bales and hay pellets occurs hardly at all. By contrast, the utilisation of grass silage as substrate in biogas plants is already state of the art in Germany. Among the energy plants which are used as substrate for biogas plants, grass silage is the second-best feedstock after maize silage, which represents approximately 80% of the biomass (in terms of tons of fresh matter) especially produced for biogas plants [3].

The number of biogas plants in Germany has increased rapidly to 3750 in 2007 with an installed electrical capacity of 1250 MW_{el} overall [3]. The amount of electricity provided from biogas plants in 2007 reached 7.5 TWh_{el}. To generate this amount of energy, large volumes of manure are required as well as an agricultural area of 500,000–550,000 ha planted with energy plants. This corresponds to around 5% of the agricultural crop land in Germany. The increase in biogas plants fed with biomass has been conditioned by the German Renewable Energy Sources Act [4] which forces power-supply companies to take over electricity from renewable sources and to pay guaranteed minimum prices for it. In order to promote the extension of bioenergy production, an additional bonus is paid for the conversion of renewable primary products into electricity.

To investigate the impacts of using grassland biomass to produce heat or electricity, the Institute for Technology Assessment and Systems Analysis (ITAS) analysed different technologies for the production of bioenergy from grassland biomass from the perspective of sustainable development. Since the conversion of grassland into arable land is still possible within Cross-Compliance up to a certain limit, the production of energy plants on converted 'surplus' grassland – maize silage as substrate for biogas plants and short-rotation poplar chips for combustion devices – was also included in the investigation. This article presents the concept and indicators used for assessing the sustainability of energy production from 'surplus' grassland biomass and energy plants grown on converted 'surplus' grassland as well as results of this sustainability analysis.

2. Approach

Sustainability was assessed according to the integrative concept of sustainable development designed by ITAS, which provides a conceptual and analytical framework for the task. This global sustainability concept was adapted to analyse the relevant sustainability aspects related to energy production from grassland biomass. Against this background specific indicators were selected to assess the different process chains . The criteria used for the selection of indicators were the adequate reproduction of the core ideas of the preconditions of sustainability, the option of setting quantitative goals or to recognise whether sustainability was increasing or decreasing, and finally the availability of suitable data.

2.1. *The integrative sustainability concept*

The integrative concept of sustainable development was developed by a group of scientists from different disciplines and research institutions in Germany [5,6]. Since then the concept has been implemented in more detail and applied to different objects and contexts, mainly in Germany. The prime feature of the integrative sustainability concept is that no prior distinction is made between economic, environmental and social dimensions. The general model is based on a dynamic understanding of sustainability and conceived for various societal systems and cultures in a context-independent manner.

Three constituent elements of the integrative concept have been emphasised. The first refers to the 'postulated intra- and intergenerative justice', i.e. all current generations shall satisfy their needs without jeopardising the ability of future generations to satisfy theirs. The two components are considered to be equal and united in principle. According to second constituent element, 'the global perspective', global or globally transmitted causes of national problems as well as global With regard to nature and the environment, the third constituent element of the integrative concept is application of the 'anthropocentric approach'. That is to say, in addition to available resources or the bearing capacity of ecosystems, the clearly human interests have to be taken into account.

The major components of the integrative sustainability concept are three general objectives: 'securing human existence', 'maintaining society's productive potential' and 'preserving development and action options'. These objectives are operationalised by 15 substantial preconditions assigned to them and ten instrumental preconditions supplementing the substantial preconditions (these constitute basic procedural requirements).

2.2. *Preconditions and indicators of sustainability*

Adaptation of the integrative sustainability concept to the scientific questions of the energy production from grassland biomass or converted grassland led to the number of relevant preconditions of sustainable development being reduced from 15 to seven substantial sustainability objectives (Table 1). To operationalise these sustainability targets in the context of

Table 1 – Preconditions for sustainable development and sustainability indicators.

Preconditions for sustainable development	Sustainability indicators
Sharing the use of natural resources fairly	• Substitution of non-renewable energy resources • Emissions of greenhouse gases
Sustainable use of non-renewable resources	• Substitution of non-renewable energy resources
Sustainable use of the environment as a sink	• Emissions of greenhouse gases • Greenhouse gas reduction costs • Emissions affecting eutrophication • Emissions affecting acidification
Protection of human health	• Emissions of particulate matter • Emissions of NO_x • Emissions of CO • Emissions of substances producing summer smog • Development of fungal spores
Sustainable use of renewable resources	• Biodiversity • Soil • Groundwater and surface water
Conservation of the cultural function of nature	• Nature of the landscape
Securing an autonomous existence	• Employment • Wage compensation

energy production from grassland biomass or converted grassland, 16 indicators were chosen.

Where possible, quantitative goals were formulated for the selected indicators. These were either adopted – in cases of already existing political decisions – or chosen in view of current debates. On the basis of this set of goals and indicators, the sustainability of different techniques for using grassland biomass or energy plants grown on converted grassland as a source of energy was analysed.

2.3. *Definition of bioenergy production chains and reference systems*

In the evaluation process, nine different process chains for the conversion of biomass from grassland or converted grassland into energy were analysed. The types of technology were distinguished here into those that could be used to convert biomass from high-input grassland and others for biomass from low-input grassland. With regard to the quality of the grassland biomass harvested, the production of hay bales or hay pellets and their use in small combustion devices were taken into consideration for low-input grassland. The process chains analysed were: the combustion of high-pressed hay bales in a device manufactured by REKA (Maskinfabrikken REKA A/S, Aars, Denmark) (30 kW_{th}) that includes a filter for the retention of particulate matter, of round hay bales in a device manufactured by Herlt (Herlt SonnenEnergieSysteme, Vielist, Germany) (89 kW_{th}) and of hay pellets in a device manufactured by Agroflamm (Agroflamm Feuerungstechnik GmbH, Overrath-Untereschbach, Germany) (40 kW_{th}). Furthermore, the use of hay together with maize silage as a substrate for a dry fermentation biogas process was investigated. As it was assumed that low-input grassland was not fertilised, the residues from the fermentation process could be used completely as manure for the maize plants. The surplus residues resulted in a bonus for the hay-bale process chain (Table 2). For grassland on more productive soils, the production of grass silage as feedstock for biogas plants with conventional wet fermentation process was assumed. To reflect differences in soil productivity the grassland biomass for the silage was harvested from grassland where three (83%) and two (17%) cuts a year were possible.

Due to the fact that the conversion of grassland into arable land is still possible within a certain limit, two energy-generation chains based on the production of energy plants with high yields were also analysed: on the one hand, the production of maize silage for biogas plants on fertile soils and, on the other hand, the plantation of short-rotation poplars on highly productive as well as on poorly productive soils and the combustion of the harvested poplar chips in regular and low-emission devices. Since the combined fermentation of maize silage, grass silage and manure is the state of the art, this has also been taken into account in this paper (maize/grass/manure substrate mix). In addition, the biogas produced was used in combined heat and power plants of different sizes – 100 kW_e, 250 kW_e and 500 kW_e. The main assumptions from the analysed bioenergy process chains are specified in Table 2. More detailed information on the bioenergy production systems analysed can be found in [7].

In order to assess the findings of the sustainability analysis, the results are shown in comparison to a system of reference values. It was assumed that if grassland is not used for the production of roughage for ruminants, simple and inexpensive maintenance of the grassland through mulching is applied in order to receive the agricultural payment entitlements for 'surplus' grassland. The following were used as reference values for energy generation from non-renewable energy: the electricity mix from non-renewable energy sources in Germany, combined heat and power plants fuelled with natural gas and oil-fired heating.

2.4. *Life-cycle assessment*

The impacts of the different bioenergy process chains described above were analysed for half of the 16 sustainability indicators by means of the Global Emission Model for Integrated Systems (GEMIS) Version 4.3 [8]. This is a life-cycle assessment programme and database for energy, material, and transport systems, which is freely available as public domain software. GEMIS includes the total life cycle in its calculation of impacts – i.e. fuel delivery, materials used for construction, waste treatment, transport and auxiliaries. To meet the requirements of calculating the life-cycle assessment of the process chains investigated for grassland biomass and energy plants grown on converted grassland, the GEMIS

Table 2 – Main assumptions on the bioenergy process chains analysed.

	Process chains	Field area, ha	Yield dry matter, $t\,ha^{-1}\,a^{-1}$	Energy yield[a], $GJ\,ha^{-1}\,a^{-1}$	Mineral fertiliser, $kg\,ha^{-1}\,a^{-1}$	Diesel, $L\,ha^{-1}\,a^{-1}$
Reference for grassland utilisation	Mulching	1/5/20	–	–	–	8.9/9.2/9.6
Low-productivity soil	Hay HP[b], REKA	1	3.9	66	–	40.3
	Hay RB[c], Herlt	5	3.9	66	–	32.8
	Hay pellets, Agroflamm	20	3.9	66	–	31.1
	Hay DF[d]	5	3.9	66	N: −37 P: −150 K: −244	32.8
	SRP[e] low yield	1	5.6	100	P: 76 K: 64	47.4
High -productivity soil	Grass WF[f], 2 cuts	5	6.4	76	–	51.2
	Grass WF[f], 2 cuts, substrate mix	5	6.4	76	–	52.4
	Grass WF[f], 3 cuts	5	10.0	119	–	77.9
	Grass WF[f], 3 cuts, substrate mix	5	10.0	119	–	79.8
	Maize WF[f]	5	15.0	195	N: 70	98.8
	Maize WF[f], substrate mix	5	15.0	195	N: 111	91.3
	Maize DF[d]	5	15.0	195	–	105.4
	SRP[e] high yield	1	9.4	166	P: 127 K: 106	59.2

a Based on the lower heating value of bales/chips/silage.
b High-pressed bales.
c Round bales.
d Dry fermentation; combined fermentation of hay and maize silage only.
e Short-rotation poplars.
f Wet fermentation.

bases of calculation was extended to include input of grassland-specific data assessed within the project. With this adjusted module, the relevant stock and energy flows of the different process chains were computed. Results calculated with the enlarged GEMIS module are related to energy efficiency, direct air pollutants (SO_2, NO_x, halogens, particulates, CO, non-methane volatile organic compounds) and greenhouse gas emissions (CO_2, CH_4, N_2O, CF_4, C_2F_6).

The results of the life-cycle assessment are related to the impacts of energy generation from fossil fuels. The findings were additionally calculated to relate to 1 ha; for this, a method was developed for converting results pertaining to energy yield into results pertaining to 1 ha. As a reference value for the use of grassland biomass and energy plants grown on converted grassland and the corresponding energy production, the process chain 'mulching' (mowing without using the cuttings) combined with the corresponding energy-generation reference value were assumed. Using this method, the limited availability of agricultural land as an important criteria for decision-making processes is included in the analysis. However, it must be pointed out that only areas with similar growing conditions can be compared.

3. Results

In line with the availability of data and methods to combine single emissions into dimensions that would have an impact, the sustainability analysis includes different types of results: quantitative emissions and impact results computed with the life-cycle assessment programme as well as qualitative evaluations based on analysis of the literature and discussions with experts.

3.1. *Substitution of non-renewable energy resources*

Despite the higher biomass yield of high-input grassland than of low-input grassland, the savings of primary energy related to the combustion of hay from low-input grassland is within the same range as the savings from the fermentation of grass silage from high-input grassland (Fig. 1).

The relatively low energy yield from grass silage compared with biomass yield harvested is due to the fact that a significant part of the energy of the biogas substrate is not converted during the fermentation process and thus remains in the fermentation residues, which are brought back to the grassland. By contrast, the energy conversion rate through the combustion of hay is much higher. Another reason for the similarities in energy yields from high-input and low-input grassland is the energy loss caused by not using the heat produced by the generation of electricity from biogas. The majority of the heat produced from biogas plants can normally not be used due to the lack of suitable heat customers in the neighbourhood. Thus an important part of the energy produced from grass silage is lost. However, the ranking changes if a significant part of the heat produced from biogas can be put to good use. The highest energy savings per hectare can be obtained from the combustion of short-rotation poplar chips from converted grassland. This is

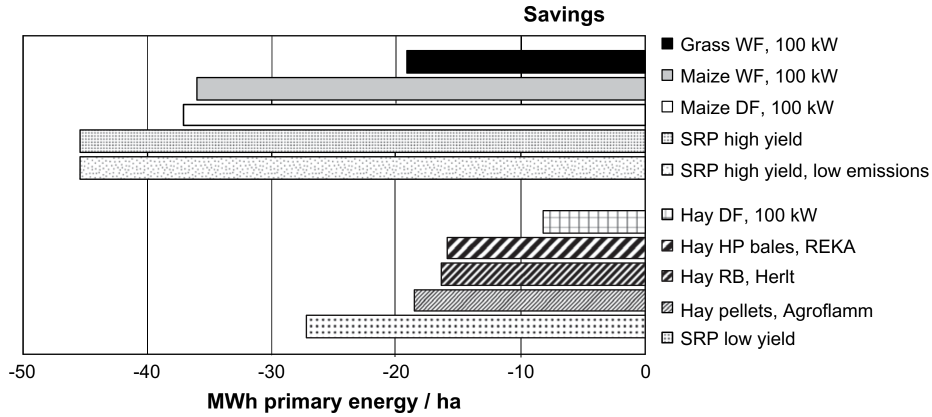

Fig. 1 – Area-related substitution of non-renewable energy (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

due to the high dry-matter yields of fast-growing trees (Table 2), the high energy conversion rate of the combustion process, and the low energy demand of the short-rotation poplar process chain.

All bioenergy chains analysed – grass silage form high-input grassland, different hay bales and hay pellets from low-input grassland as well as maize silage and short-rotation poplar chips from converted grassland – show significant potential for providing a substitute for non-renewable energy resources. The highest savings of non-renewable energy related to the energy unit generated can be achieved with the dry fermentation of hay and maize silage (Fig. 2) because this process results in a reduced demand for mineral fertiliser whose production has quite a high energy demand. The savings on fertiliser are based on the assumption that low-input grassland is not fertilised and thus the total residues from the dry fermentation process can be used for the fertilisation of maize.

3.2. *Reduction of greenhouse gas emissions and reduction costs*

Although all uses of grassland biomass and energy plants grown on converted grassland have positive effects on the reduction of greenhouse gas emissions, there are great differences in the reduction rate. The potential of the process chains to reduce greenhouse gas emissions is illustrated from two perspectives: First, the potentials are referred to the area because the availability of 'surplus' grassland is limited. Second, the potentials are related to the energy unit generated. If one considers the area-specific results, it can be seen that the production of short-rotation poplars on converted grassland has the highest potential for reducing greenhouse gas emissions, followed by maize silage (Fig. 3).

The dry fermentation of hay indicates the lowest reduction potential. The good performance of short-rotation poplar production chains is due to the assumptions that, in the long run, the additional greenhouse gas emissions which are released by the partial conversion of grassland will be counterbalanced by their higher energy yields compared with grassland. Furthermore, it seems that it will become increasingly difficult in the long term to preserve the grassland carbon stocks in an altered climate with high temporal variability and under high atmospheric CO_2 concentrations which may saturate the carbon sink in soils [9]. Relating to the energy generated, the combustion of hay and short-rotation poplar chips shows much better results than the fermentation chains (Fig. 4).

If one considers the costs of avoiding greenhouse gas emissions by energy production from grassland biomass, the

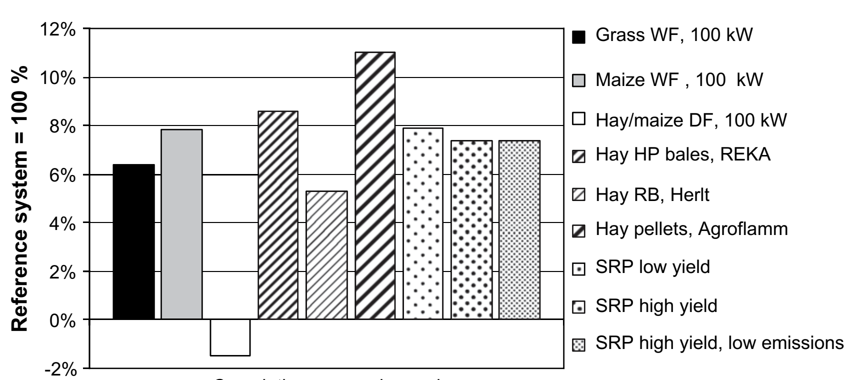

Fig. 2 – Substitution of non-renewable energy compared to the reference value (mulching and fossil fuels) (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

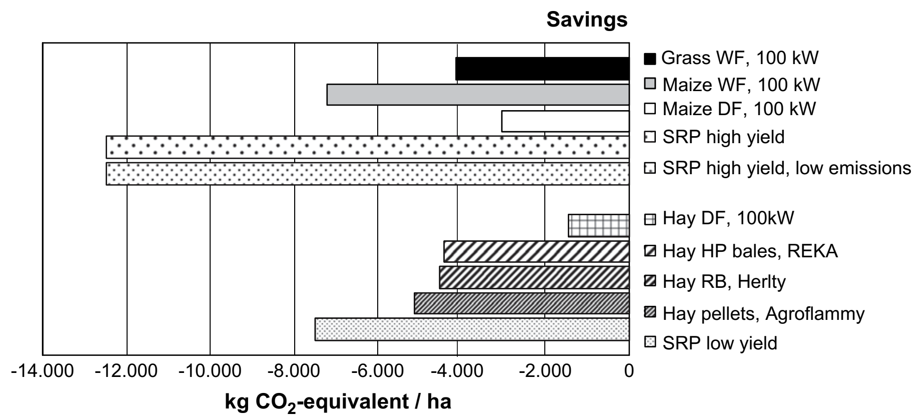

Fig. 3 – Area-related reductions in greenhouse gas emissions (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

dry fermentation of hay demonstrates the highest CO_2 abatement costs. The utilisation of grass silage for biogas electricity production has lower, but still high reduction costs equivalent to about 250 €/t CO_2 (Fig. 5). However, if the heat produced can actually be used, the CO_2 reduction costs decline to the equivalent of 175 €/t CO_2.

The costs for avoiding greenhouse gas emissions are much lower if hay from low-input grassland is used to produce thermal energy. They range from the equivalent of 70–80 €/t CO_2 for hay bales or hay pellets. But even the use of hay as solid biofuel is at present not competitive compared with the average price for EU certificates for CO_2 emissions, which in 2006 cost from around the equivalent of 18 €/t CO_2 on average. Meanwhile the prices for CO_2 emissions at the European Energy Exchange (EEX) have dropped to around 1 €/t CO_2. This decline in prices within the first phase of emission trading (2005–2007) is a result of allocating too many emission certificates and the existence of too many loopholes. For the second phase (2008–2012) the basic conditions have been adjusted, and the certificates should be more highly priced. Anyhow, these market prices do not reflect the externalities of the climate change. Compared with the loss expenses of climate change, which according to literature [10] are between 15 and 280 €/t CO_2 with an average of 70 €/t CO_2, the substitution of fossil energy through hay is of the same magnitude as the average external diseconomies. Yet, short-rotation poplars grown on converted high-productive grassland can today already achieve negative costs for the avoidance of CO_2 emissions (Fig. 5).

3.3. *Emissions leading to acidification, eutrophication and risks to human health*

With regard to the influence on acidification and eutrophication, all the process chains analysed, and the biogas process chains in particular, are bound up with higher emissions than the reference value. Only combustion of short-rotation poplar chips shows relatively good results. With regard to the emissions of substances detrimental to human health, such as NO_x and CO, the evaluation shows that most of the process chains analysed have equal or worse results than the reference values. However, the dry fermentation of hay, the combustion of round hay bales and the low-emission combustion of short-rotation poplar chips show better results than the reference values. For dry fermentation, this result is based on the credit for substituting mineral fertiliser (see Table 2). With respect to round hay bales and polar chips, the favourable result is based on the features of the combustion units.

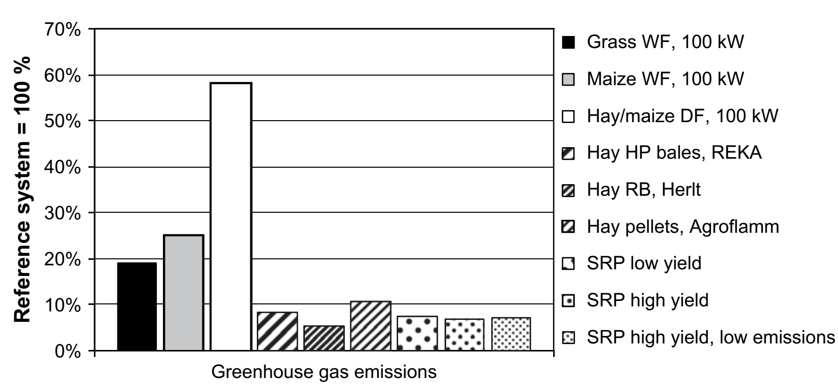

Fig. 4 – Reduction in greenhouse gas emission compared with the reference value (mulching and fossil fuels) (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

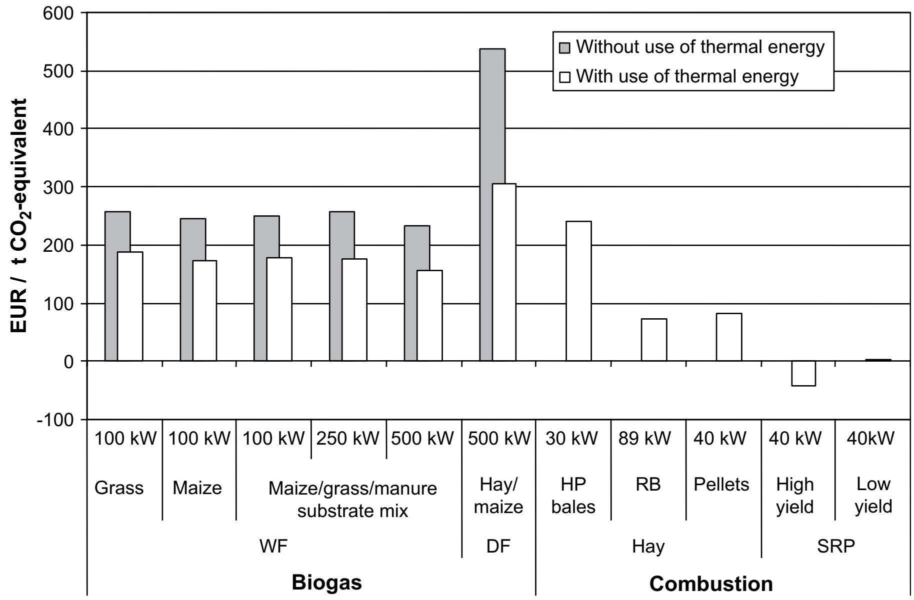

Fig. 5 – Greenhouse gas abatement costs of energy production from grassland biomass and energy plants grown on converted grassland (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

An increase in the emissions of particulate matter is found in all process chains that combust hay or short-rotation poplar chips (Fig. 6). Using retention techniques during the combustion of high-pressed hay bales in REKA devices, the emissions of particulate matter can be reduced significantly. The dry fermentation of hay and maize silage have almost zero emissions of particulate matter as this process leads to a reduced demand for mineral fertiliser (see Chapter 3.1) which decreases the emissions of particulate matter associated with the supply of mineral fertiliser caused by loading and unloading the fertiliser, respectively.

Among the emissions from combustion devices, the release of particulate matter is of great interest due to the great political emphasis on the relevance of aerosols and particulate matter originating from biomass combustion devices. There are indications that, out of the total amount of particulate matter <10 μm (PM_{10}) emissions in Europe in 2000 (2502 kton), small-scale biomass combustion devices contributed some 499 kton [11]. In countries such as Austria and Switzerland, about 50% of the ambient concentration of aerosols is attributed to the combustion of biomass. This is largely due to relatively inefficient and small-scale combustion devices, while more efficient, high-quality stoves emit far fewer aerosols and these also have a lower adverse impact on health, due to the absence of carbon. However, the amount of fine dust emitted can be reduced significantly with retention techniques. Both primary and secondary measures for emission reduction exist, for instance electrostatic precipitators.

Compared with the reference values, the process chains analysed lead to increased generation of summer smog. The process chains involving the combustion of hay cause the highest increase in summer smog. The lowest increase in summer smog is related to the short-rotation forestry and the wet fermentation process chains.

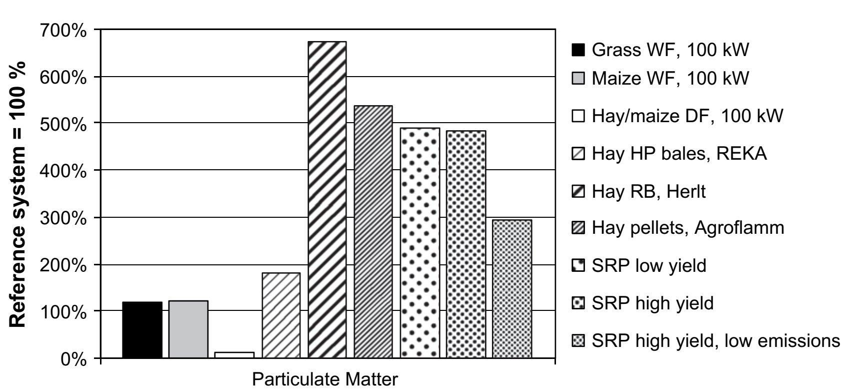

Fig. 6 – Emissions of particulate matter of the energy production from grassland biomass and energy plants grown on converted grassland (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

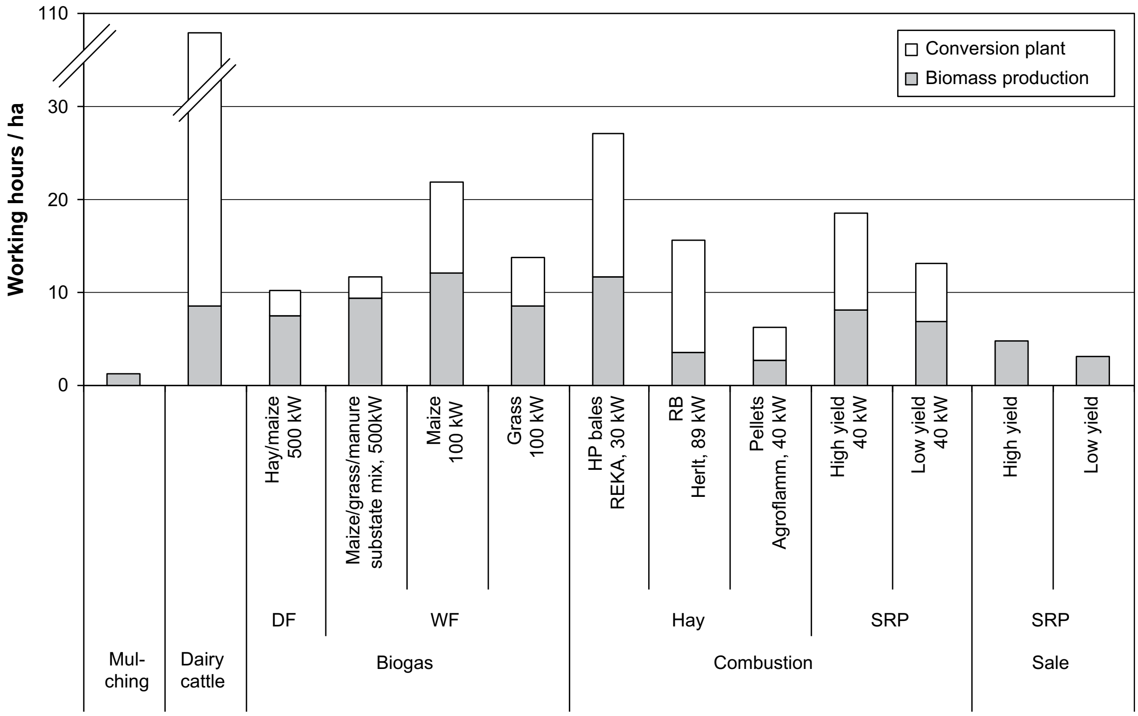

Fig. 7 – Working hours needed for energy production from grassland biomass and energy plants grown on converted grassland (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

Among the process chains analysed, it is mainly short-rotation forestry and dry fermentation which can lead to emissions of fungal spores that are relevant to human health. The moulds on wood chips contain representatives of the species Aspergillus, Penicillium und Cladsporium, which are pathogenic, toxic and allergenic. During the storage and handling of poplar chips, the concentration of fungal spores can reach a critical level from the perspective of work hygiene [12].

3.4. *Protection of soil and groundwater*

With regard to protecting soil from erosion and compaction, the process chains using grassland biomass as an energy resource show much better results than those converting grassland into arable land for the production of maize as feedstock for biogas plants. Furthermore, grassland plays a major role in groundwater protection, because the discharge of substances emanating from the use of fertilisers and pesticides towards groundwater is much lower with grassland than with arable land. In grassland, there is on average a low level of nitrate and pesticides, leaching similar amounts to those found under forest. By contrast, the conversion of grassland into maize fields can lead to negative impacts on groundwater quality. The plantation of short-rotation poplars brings a concomitant risk of soil erosion and nitrate leaching towards the groundwater directly after the partial conversion of grassland. However, over the years short-rotation poplars can attain a similar protection function for the quality of soil and groundwater as grassland and forests.

3.5. *Effects on biodiversity*

Grassland provides an important habitat for a variety of plants and animal species. In terms of biodiversity, low-input grassland is of great importance because it harbours most of the endangered species. From the same perspective, the use of hay as solid biofuel can be deemed superior to the reference value of mulching which is used to conserve grassland rich in species. The reason for this is that mulching leads to an accumulation of nutrients which can in turn lead to a loss of biodiversity [13]. However, the degree to which biodiversity shifts in comparison to the use of grassland biomass as energy resource strongly depends on the habitat and the time of cutting.

On the other hand, the use of grassland biomass as energy resource can also lead to a reduction in biodiversity. This is the case if the grassland management is intensified in order to produce high quantities of good-quality grass silage for biogas plants. The conversion of grassland into maize fields or short-rotation poplar plantations causes a significant change in the diversity of species compared to the reference value. The cultivation of maize significantly reduces the diversity of species, but the influence of short-rotation poplars is – depending on the habitat – less unfavourable. On some sites, new types of biodiversity can be built up within short-rotation poplars, including even endangered species [14]. Colonisation with plants and animals is related to the spectrum of species in the surrounding landscape and their potential for spreading [15].

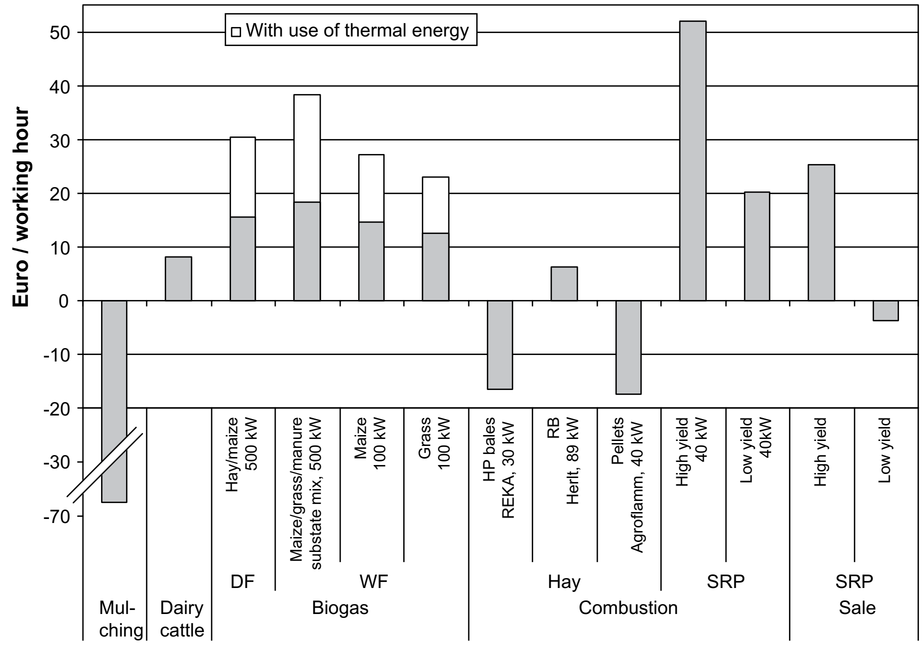

Fig. 8 – Wage compensation for energy production from grassland biomass and energy plants grown on converted grassland (WF, wet fermentation; DF, dry fermentation; HP, high-pressed bales; RB, round bales; SRP, short-rotation poplars).

3.6. *Effects on the cultural landscape*

In some regions of Germany, grassland shapes the cultural landscape and contributes considerably to the specific characteristics and attraction as well as to the quality of life and recreation in these areas. These cultural functions of grassland are disturbed if grassland is converted into maize fields. The plantation of short-rotation poplars on converted grassland leads to a similar result, which is, however, augmented by the loss of open or semiopen, cultivated landscape. In areas which already have a high percentage of forest, this will have mainly negative consequences on the quality of life and recreation as well as for tourism in the region [16,17]. In such cases, it can be assumed that short-rotation plantations will be rejected by the population. It is feasible, however, to achieve positive impacts with short-rotation plantations in areas that are used intensively for agricultural production and possess only a small percentage of trees and groves [18].

3.7. *Effects on employment and wage compensation*

Trying to rank the process chains analysed according to socioeconomic aspects of sustainable development is a quite difficult task for two reasons: First, there is no concept or consensus on the selection of targets or indicators to be used for evaluating the socioeconomic aspects of sustainable development of agriculture. Second, background information on the impacts of bioenergy production on socioeconomic aspects is somewhat lacking. Therefore, the analyses conducted in this study concentrate on effects on working time and wage compensation at the farm level. Taking these two indicators, it can be concluded that – with the exception of producing short-rotation poplar chips for the market – the labour time requirement is much higher than for the reference value of mulching grassland (Fig. 7). However, compared with the traditional use of grassland for roughage and milk production (data from [19]) significantly fewer working hours are required for producing energy from grassland biomass or energy plants grown on converted grassland.

In terms of wages, some techniques for producing energy from grassland biomass lead to wage compensation of between 6 and over 50 € per working hour (Fig. 8). However, the production of high-pressed hay bales, hay pellets and short-rotation poplar chips from sites with low yield for the market can lead to negative wage compensation.

Despite the relatively high wage compensation involved, producing thermal energy by the combustion of poplar chips or hay at the farm level only leads to a limited contribution to farmers' income. This is due to the fact that only a small area of land is needed to cover the average heat demand of a farm. Using short-rotation poplar chips, for example, only between 2 and 6 ha of short-rotation coppice are required. Despite relatively high energy prices and the financial support for the energetic use of biomass, the effects on wage compensation and employment in agriculture are modest, regardless of whether the biomass is used to satisfy the energy demand of the farm or sold on the market as feedstock for bioenergy plants. Regarding any contribution to the farmers' income, the biogas process chains are more interesting than the combustion chains if the available heat is used. However, without utilisation of the heat, producing short-rotation poplars on converted high-input grassland and selling the poplar chips on the market leads to a higher contribution to farmers' income.

Table 3 – Sustainability assessment of the grassland energy production chains analysed.

	Low-input grassland					High-input grassland			
	Utilisation for the production				Conversion	Utilisation	Conversion		
	Hay HP[a]	Hay RB[b]	Hay Pellets	Hay DF[c]	SRP ext.	Grass silage	Maize silage	SRP int.	SRP[d]
Sustainable use of non-renewable resources[e]									
Primary energy yield	+ + (7)	+ + (6)	+ + (5)	+ + (8)	+ + (3)	+ + (4)	+ + (2)	+ + (1)	+ + (1)
Sustainable use of the environment as a sink									
Greenhouse gas emissions	+ + (6)	+ + (5)	+ + (4)	+ (8)	+ + (2)	+ + (7)	+ + (3)	+ + (1)	+ + (1)
Cost of avoiding greenhouse gas emissions	– (5)	– (3)	– (3)	– – (6)	+ (2)	– – (4)	– – (4)	+ + (1)	+ + (1)
Emissions leading to eutrophication	– (5)	0 (3)	– (6)	– – (9)	0 (2)	– – (8)	– – (7)	0 (3)	0 (1)
Emissions leading to acidification	– (5)	0 (4)	– (6)	– – (9)	+ (3)	– – (8)	– – (7)	+ (2)	+ (1)
Protection of human health									
Emissions of particulate matter	0 (4)	– (7)	– (5)	+ (1)	– (8)	0 (2)	0 (3)	– – (9)	– (6)
NO_x emissions	– – (7)	– – (6)	– – (8)	+ (1)	– (4)	– (3)	– (5)	– – (6)	– (2)
CO emissions	– – (9)	+ (2)	0 (3)	0 (4)	– (6)	– (5)	– – (7)	– – (8	+ (1)
Summer smog	– – (8)	– (7)	– – (9)	+ (1)	– (4)	– (3)	– (5)	– (6)	0 (2)
Fungal spores	0	0	0	–	–	0	0	–	–
Sustainable use of renewable resources									
Biodiversity	+ (1)	+ (1)	+ (1)	+ (1)	– (4)	0/– (2)	– – (5)	0 (3)	0 (3)
Soil	0 (1)	0 (1)	0 (1)	0 (1)	– (2)	0 (1)	– – (3)	– (2)	– (2)
Groundwater	0 (1)	0 (1)	0 (1)	0 (1)	– (2)	0 (1)	– – (3)	– (2)	– (2)
Conservation of the cultural function of nature									
Landscape	+ (1)	+ (1)	+ (1)	+ (1)	–/+ (2)	+ (1)	– (3)	–/+ (2)	–/+ (2)
Securing an autonomous existence									
Employment	+ (1)	+ (4)	+ (8)	+ (7)[f]	+ (6)	+ (5)	+ (2)	+ (3)	+ (3)
Wage compensation	– (7)	+ (5)	– (8)	+ (6)[f]	+ + (2)	+ (4)	+ (3)	+ + (1)	+ + (1)

a High-pressed bales.
b Round bales.
c Dry fermentation of hay together with maize silage.
d Combustion of short-rotation poplars (SRP) in devices with low emissions.
e Indication, if the production chains have positive or negative impacts compared to the reference (mulching and fossil energy). A score of '1' indicates the best process chain, and as the numbers increase, the level of excellence of the process chain declines.
f These data are valid for the co-fermentation of hay from low-input grassland and maize silage.

3.8. *Comparison of the sustainability results*

The sustainability investigations for the bioenergy process chains analysed indicate both positive and negative impacts on different indicators. A further aggregation of impacts on different sustainability indicators on the basis of scientific concepts, e.g. the monetary valuation of environmental burdens, is delicate because the weighting method chosen has some influence on the results, and assumptions have to be made. Furthermore, great difficulties are encountered with regard to the availability of data for calculating, e.g. avoidance costs or loss expenses. Ranking sustainability objectives or indicators is an alternative way of summarising the results of the sustainability analysis. However, such a rating cannot be carried out by scientists alone, but needs broad consensus in society and politics.

For this reason as well as to retain a high degree of transparency in presenting the outcomes of the study, the findings of the integrated impact analysis are presented in single results (Table 3). Plus (+) and minus (–) indicate whether the energy production from grassland biomass and energy plants grown on converted grassland has positive or negative impacts compared with the reference value (mulching and energy production with fossil fuels). Additionally, the results of the different energy process chains for each indicator were numbered 1–9 to indicate their position among the process chains analysed. A score of '1' indicates the best process chain, and, as the numbers increase, the level of excellence of the process chain declines. The results in Table 3 reveal that the main ecological benefits of energy production from grassland biomass and energy plants grown on converted grassland are the savings in non-renewable energy resources and the reduction in greenhouse gas emissions. However, with regard to the costs of avoiding greenhouse gas emissions, only short-rotation poplars can be evaluated positively.

4. Conclusions

Evaluating different process chains to produce energy from 'surplus' grassland biomass and energy plants grown on converted 'surplus' grassland under German conditions from the perspective of sustainable development reveals that the techniques analysed have both advantages and disadvantages. The use of grassland biomass for the production of biogas – which is already practised in Germany – as well as the combustion of hay can attain economic viability at the farm level if the guaranteed agricultural premiums are included in the calculation. However, not every site and not all cases are amenable to economic use of the relevant technology. In addition, all the techniques have an impact on employment, which is high compared with mulching, but quite low compared with dairy cattle production.

All process chains can reduce greenhouse gas emissions, but only short-rotation poplars in good locations can reduce costs to a level that is competitive with current costs for EU emission certificates for CO_2. The other technologies result in relatively high greenhouse gas reduction costs. These costs would be even higher if retention techniques to avoid emissions of particulate matter and other environmental harmful substances were applied. Thus, research is needed to improve the existing small-scale combustion techniques and the know-how for producing bioenergy from different types of grassland if the benefits are to be increased (e.g. through a more efficient use of grassland biomass as feedstock) and the accompanying disadvantages for the environment and human health decreased. Where grass silage is used for biogas plants, one way of achieving these goals is to create financial incentives for using biogas at locations with a high demand for thermal energy or distribute the produced biogas over biogas grids or the natural gas distribution grid to customers with a high and constant heat demand all year round. If in the long run new and innovative techniques to convert biomass rich in lignocellulose into biofuels (e.g. biomass ethanol or biomass synfuel) are demonstrated to be successful, this would open up new vistas for grassland biomass. According to [20], biofuels derived from low-input, high-diversity mixtures of native grassland perennials can provide more usable energy, greater greenhouse gas reductions, and less agrochemical pollution per hectare than corn grain ethanol or soybean biodiesel.

The production of short-rotation poplars on converted grassland performs surprisingly well with regard to sustainability, if the emphasis is put on saving non-renewable energy and reducing greenhouse gas emissions. However, if the emphasis is on conserving grassland in favour of biodiversity and cultural landscape, on low-input grassland the combustion of hay – preferably with particulate matter retention measures – would be the preferred choice from the sustainability perspective. Since the conversion of grassland is still possible to a certain extent, a development plan for grassland is needed to identify areas where grassland should be preserved and where it could be modified or even converted for the production of energy plants with high yields. In order to define these regions and to assure acceptability, this process should be conducted together with stakeholders.

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