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Greenhouse gas emissions and mitigation costs of selected bioenergy production chains

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TABLE OF CONTENTS

1 Introduction

In former chapters (deliverable report D7b) the most relevant provision chains at the present time for bioenergy in the field of European agriculture (and forestry) have been described. Out of these possible paths, some have shown to be of major importance due to their technical maturity, amount of usage, technical potential and their potential of future development. Four major provision paths have been selected:

- Production of Fatty Acid Methyl Esters (FAME) through esterification of vegetable oils (rape seed, sunflower)
- Production of ethanol or Ethyl Tertiary Butyl Ether (ETBE) from starch or sugar crops (sugar beet, cereals, maize)
- Combustion of woody biomass to produce electricity and/or heat (Short Rotation Coppice (SRC), miscanthus, straw)
- Production of biogas from excrements, residues or energy crops in order to produce electricity (excrements, cereals, maize or grass silage) respectively.

Figure 1 presents an overview of possible production and provision chains; the selected provision chains for calculation have been highlighted in red.

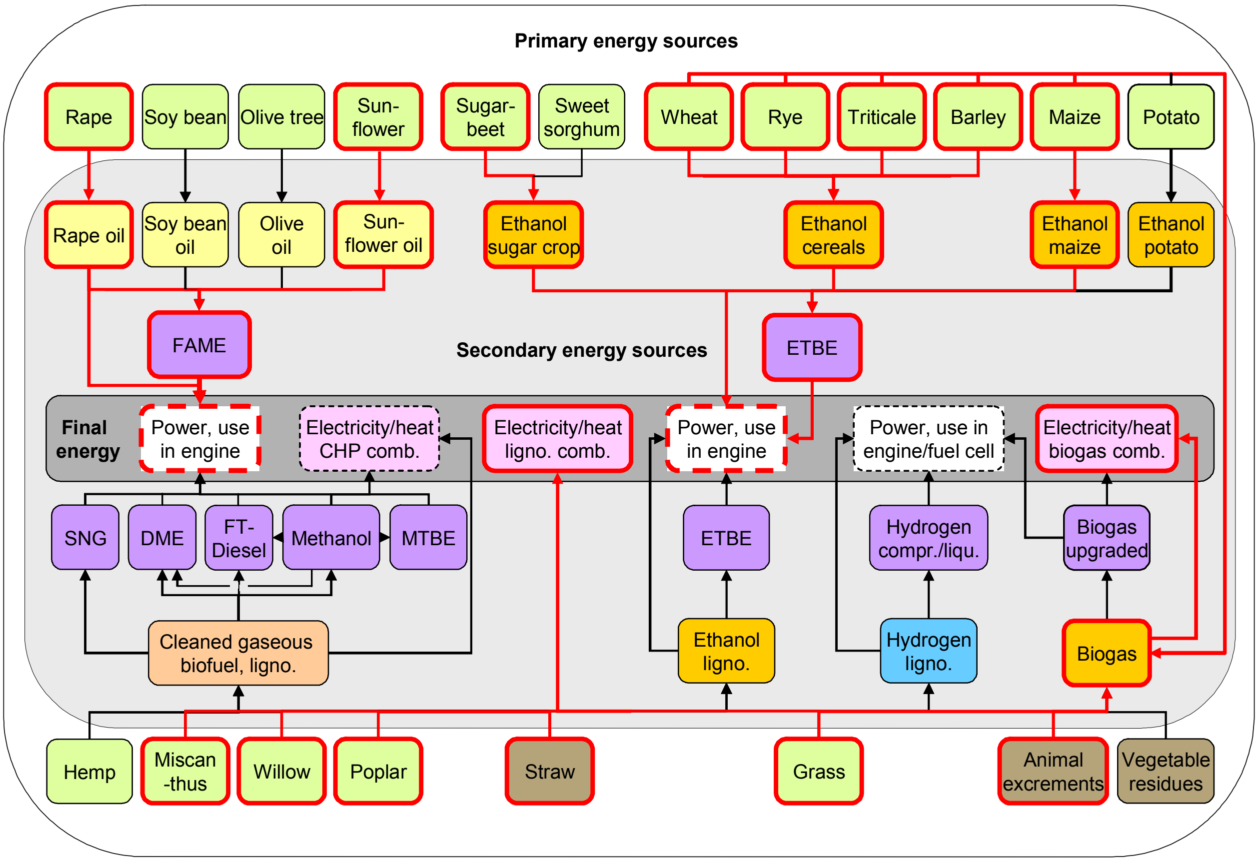


Figure 1: Bioenergy production and provision chains

The highlighted provision chains were described and analysed in deliverable report D10b in further detail. Important figures on input and output flows of the processes involved were given related to mass and energy. Besides short technical descriptions and relevant assumptions the economic performance of the four paths was calculated and reported.

Other possible production paths, especially paths for the provision of other biofuels, were not investigated in further detail, even if the investigation period of this report extends until 2015, because those paths do not have the required degree of maturity, yet. These biofuels of the so called 2nd generation of biofuels like Dimethyl Ether (DME), Substitute Natural Gas (SNG) or Fischer-Tropsch (FT) diesel are in the process of realisation, but figures of economic performance or environmental aspects mostly rely on estimations or simulation strategies, so far. Moreover, as the modelling in WP6 is focused on the period until 2015 these further provision paths are neglected within this analysis.

Based on the detailed technical and economic analysis in report D10b, the environmental effects of the use of bioenergy in the form of greenhouse gas (GHG) emissions via the four major paths are investigated and described in deliverable report D15b. In addition, general assumptions, boundaries and remarks of the environmental analysis are described and explained. Results on GHG emissions of the four paths, providing different types of final energy are presented and related to conventional final fossil energy sources. In a final step, the GHG mitigation costs associated with these individual processes in € t^{-1} CO_2-equivalent are calculated.

As in the summary of deliverable report D10b, the results of the different paths are presented in figures related to the appropriate conventional final energy sources. The GHG mitigation costs of the investigated paths are presented in tables thereafter.

Together with reports D7b and D10b the results of this report (D15b) make the classification of the investigated paths comparable to other sources of energy provision, since all relevant parameters for the provision of energy are known. Relevant results of D10b are summarised in Annex I of this report.

2 Greenhouse gas analysis

The use of energy is related to GHG emissions with various impacts on the natural surrounding or global system. This, for instance, accounts for the combustion of fossil fuels where huge amounts of greenhouse gases are emitted, but vice versa for the use of bioenergy as well. The provision of different types of bioenergy is related to GHG emissions due to necessary steps along the provision chain that implicate a relevant fossil energy demand and, hence, directly and indirectly, cause GHG emissions. It is the aim of the environmental analysis to investigate these steps and to calculate the share of GHG emissions on the total impact of the already described bioenergy production chains. To ensure a fair comparison, the whole provision chains have to be analysed and compared with appropriate types of conventional final energy.

Therefore, investigation of the provision of bioenergy starts with the production of the various selected crops as energy source of the whole production chain. The crops derive their energy from nutrients, sunlight, water and air (CO_2) in chemical processes like photosynthesis. At the time energy crops are used in any form of combustion process, they release the amount of CO_2 they have absorbed during their growth. Therefore, these CO_2 emissions of the bioenergy source are not included in the balance. But all efforts due to agricultural production as well as the conversion steps that follow harvest or the necessary steps in nutrient production (e.g. of mineral fertilisers) beforehand are taken into consideration. Comparable units of final energy like GHG emissions per unit of electricity, heat or one kilometre of passenger car transportation distance are used. The figures of the related reference energy systems are provided from the Ecoinvent database (Frischknecht et al., 2004).

3 Provision of (automotive) fuels

Short description. Two relevant paths for the provision of (automotive) fuels from energy crops have been established throughout the world so far. On the one hand, esters like FAME, mostly produced from rape seed oil can directly be used in conventional diesel engines. On the other hand, alcohols like bioethanol, produced from crops containing starch or sugar, are used. Pure alcohol can be used in adapted gasoline engines or can be mixed with petrol up to 5 % (according to DIN EN 228) to be used in conventional engines directly, without any modifications of the engines. Bioethanol can be processed further to ETBE, which is used as an additive in gasoline up to 15 % (Schmitz, 2003). Although it cannot be used as a pure fuel, the GHG emissions related to this share in the fuel are calculated comparably. For a suitable comparison the emissions of ETBE are compared to MTBE, which represents the so far established additive, to be replaced (Schmitz, 2003).

3.1 Boundaries, Assumptions, Remarks

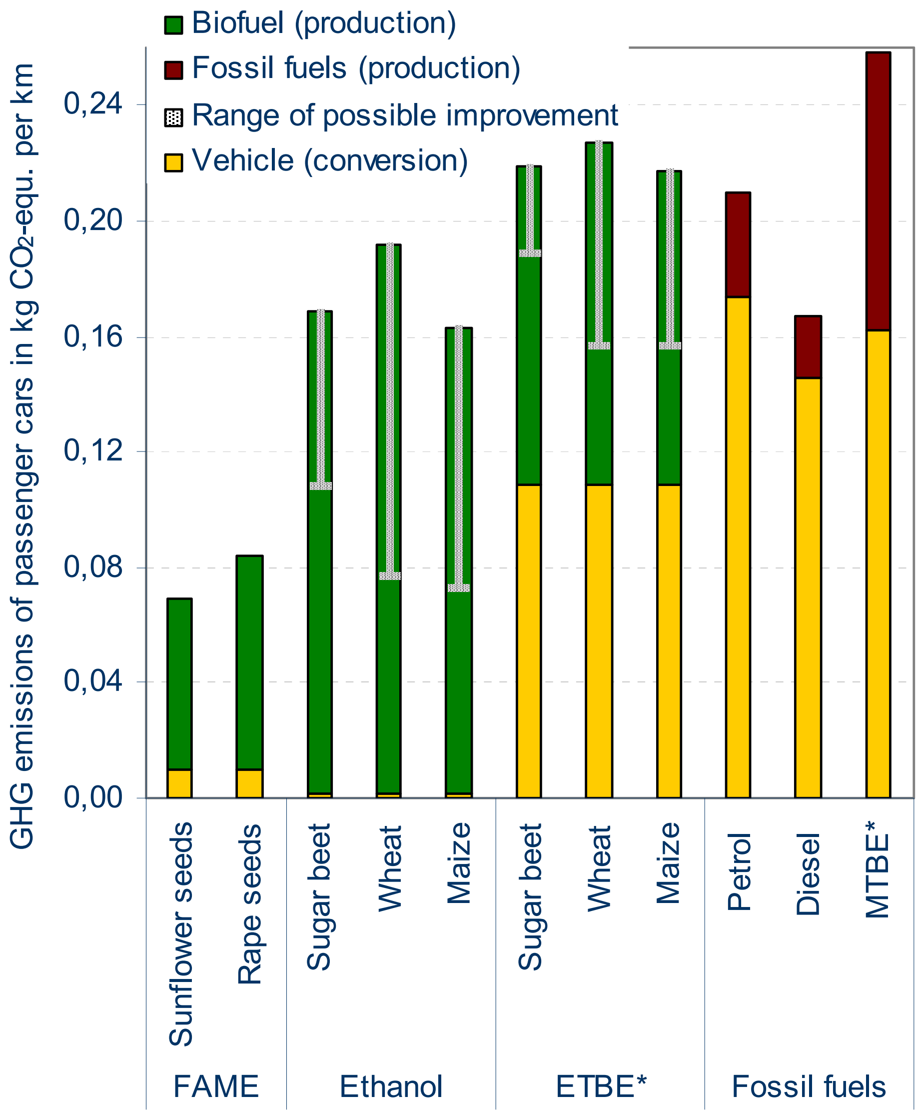
The calculation and evaluation of the provision of (automotive) fuels in existing studies does not necessarily always include the combustion of the fuel in the vehicle (‘well to tank’). Here, especially when fossil fuels are used, the main share of greenhouse gases is emitted. In general, motor engines like diesel or gasoline engines have different factors of efficiency. Thus, to compare different fuels, the final conversion from fuel to transportation distance (the performance of middle class passenger car engines of recent years was considered) has to be taken into account, since, for instance, 1 MJ of bioethanol results in a lower transportation distance compared to 1 MJ of FAME.

3.2 Results

The results of this comparison, related to 1 km of transportation distance (passenger car), are presented in Figure 2.

In general, 'tank to wheel' GHG emissions from biofuels are usually very low while 'well to tank' emissions from fossil fuels are lower than those from biofuel provision. This is due to a very efficient supply chain for fossil fuels with extensive experiences and knowledge. The use of fossil fuels in the vehicles ('tank to wheel'), however, produces very high emissions of greenhouse gases (Frischknecht et al., 2004).

In total, biofuels reduce GHG emissions per kilometre transportation distance when used in vehicles. FAME shows the highest reductions of greenhouse gases compared to diesel, whereas the reduction in emissions from ethanol (derived from conventional conversion processes) per kilometre is less than FAME (especially ethanol from wheat, which reduces emissions only slightly). These results do not apply to ethanol from sugar cane, which represents a crop of less importance in Europe. However, in contrast to the already established conversion to FAME, improved processes for the conversion of crops to ethanol have been developed in recent years and have partly been established in Europe (Schmitz, 2005). Especially the conversion of starch crops shows a high potential of improvement by the combination of ethanol production with other conversion processes such as the biogas production of the by-products from the fermentation and distillation and the heat use from biogas combustion for ethanol production (Schmitz, 2005). The possible improvement of these processes is estimated by the length of the bars of range, which have been added to the figures. ETBE, which is a mixture of bioethanol and isobutene from fossil origin, has a smaller production impact, but the share of fossil CO_2 from the combustion of isobutene accounts for direct vehicle emissions that enlarge the total compared to bioethanol or even petrol. In contrast, the use of ETBE as additive reduces GHG emissions compared to MTBE. If ethanol from improved conversion processes is used - to be mixed with isobutene - this produced ETBE results in higher GHG emission reductions compared to MTBE and petrol. Input and output figures as well as economic data of investigated production and conversion processes are documented in report D10b and summarised in Table 4-6 of Annex I.



* not a standalone fuel, only used as additive to petrol, GHG emissions are calculated following the assumption of pure use for the purpose of comparison.

Figure 2: Environmental performance of automotive fuel provision and use ("Biofuel (production)": share of energy crop production and following conversion steps on total GHG emissions in kg CO_2-equivalent per km; "Range of possible improvement": Ethanol conversion has high potential of improvement: therefore bars of range have been included to show the possible range of improvement, this improvement affects the ETBE provision, see bars of range; "Fossil fuels (production)": share of diesel/petrol/MTBE provision on total GHG emissions; "Vehicle (conversion)": share of final conversion process in vehicle (combustion) on total GHG emissions in kg CO_2-equivalent per km).

4 Production of electricity

Short description. Two major paths for the provision of electricity from energy crops have been established throughout Europe so far.
The first path builds upon the use of woody biomass like SRC, miscanthus or straw, which are usually pre-treated at the place of plantation or at the heat/power plant to generate fuel chips or bales of straw, etc. before their use. After transportation to the combustion plant, the chips or bales are burned in a solid biofuel boiler, where water is vaporised to produce steam (for generating electricity in a turbine, etc.).
The bases for the second established path are different energy crops or residues from agriculture, which are digested under anaerobic conditions to produce biogas (methane). Usually, this biogas is combusted in CHP units (gas engine motors) after extensive pre-treatment near the digestion plant producing electricity (and heat).

4.1 Boundaries, Assumptions, Remarks

The provision of electricity includes all conversion steps that are relevant to the GHG emission impact. Therefore, 1 MWh of produced electricity serves as unit for the comparison of different provision chains. The two paths, namely solid biomass combustion coupled to a steam turbine, and biogas combustion in CHP units are compared to 1) the mix of power supply in Germany and Europe, and 2) to the provision of electricity by a natural gas-steam power plant as a typical state of the art electricity production system. With solid biomass combustion, cogeneration of heat and power is taken into account, whereas heat as by-product to the production of electricity from biogas near the digestion plant is assumed to be used only partly as heat supply to the fermentation process and not sold to other parties. The use of manure in digestion processes has to be related to credits that originate from avoiding emissions within typical manure handling (Weiske et al., 2006). These credits are higher than the impact of biogas production and conversion and therefore result in a negative total (IE assumptions and calculations). The more manure used, the higher the credit. Therefore, providing electricity from fermented manure alone has the highest negative impact with respect to GHG emissions. Besides the credit related to the avoidance of manure handling, credits for fertilising effects of the fermented substrates are taken into account (IE assumption).

4.2 Results

The results of the comparison of bioenergy production chains with conventional reference systems (Fischknecht et al., 2004; Nill, 2004), related to 1 MWh of produced electricity, are presented in Figure 3.

The use of solid biomass (SRC, miscanthus, straw) relates to GHG emissions that are about one third of the power mix (electricity) of Germany, 40 % of the European electricity mix or about half of the emissions of a gas-steam power plant. The differences among them are very little whereas straw has the smallest impact. If co-generation of heat and power is realised, the emissions of greenhouse gases are further reduced by about one third compared to exclusive electricity production. This is caused by the fact that the total GHG emissions are subdivided into the final energy sources electricity and heat (the subdivision of the impacts is performed by a simplified allocation procedure).

Due to credits, as explained above, the provision of electricity from digested manure mixed with energy crops results in negative GHG emissions. Since manure can be used with very little effort (only transportation, no production) compared to the plantation of maize silage, this path has, for instance, the highest negative impact on GHG emissions. Input and output figures as well as economic data of investigated production and conversion processes are documented in report D10b and in Table 7 and 8 of Annex I.

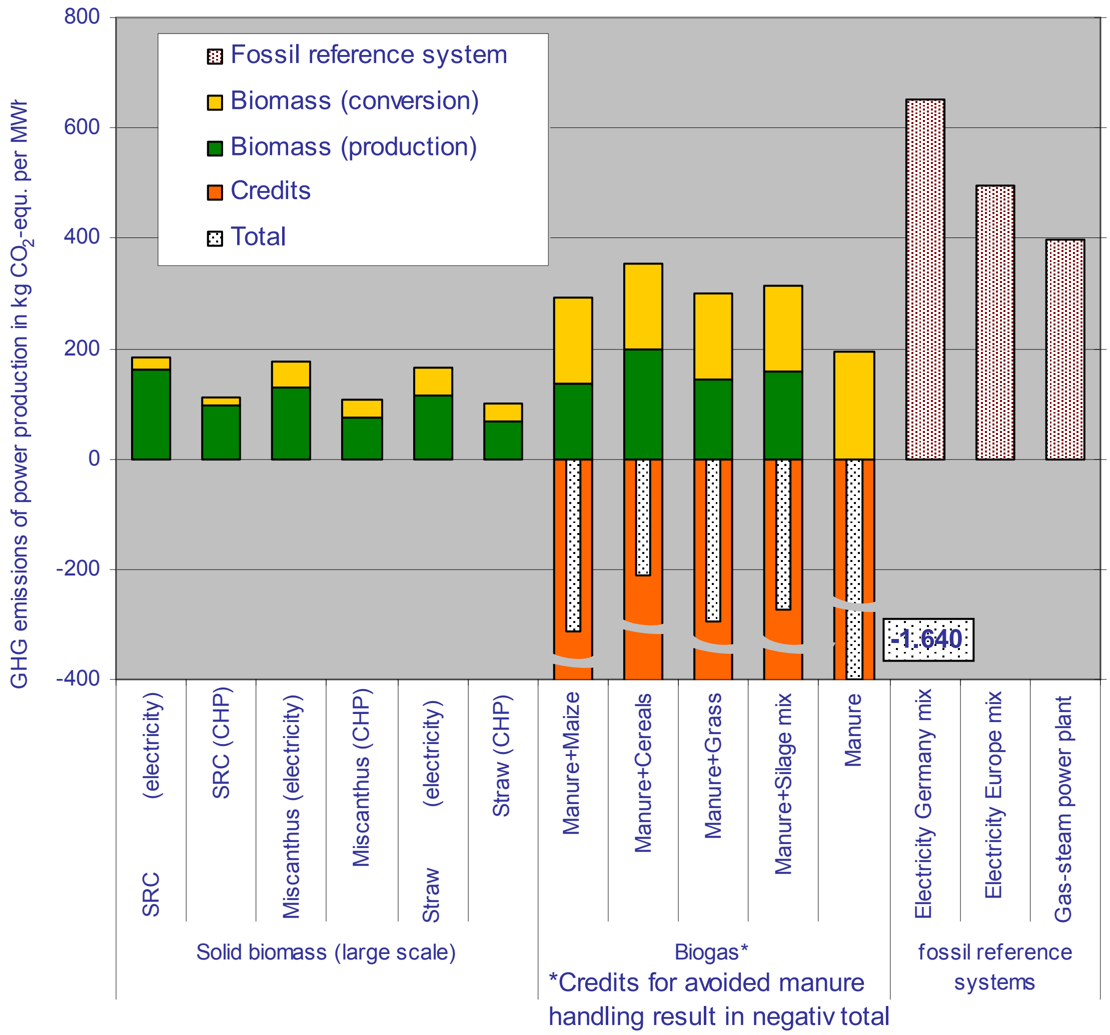


Figure 3: Environmental performance of electricity provision ("Biomass (production)": share of energy crop production on total GHG emissions in kg CO_2-equivalent per MWh; "Biomass (conversion)": share of conversion processes on total GHG emissions in kg CO_2-equivalent per MWh; "Credits": negative impact, due to avoided manure handling and fertilisation effects of the fermented substrates in kg CO_2-equivalent per MWh).

5 Combustion of woody biomass to produce heat

Short description. One path for the provision of heat from energy crops has been established so far. Wood, miscanthus or straw are usually pre-treated at the place of plantation or at the heat plant to generate fuel chips, split logs or bales of straw, etc. before their use. After transportation to the plant, the chips, logs or bales are burned in a solid biofuel boiler. Here, water is heated to provide necessary heat to a local heat system.

Smaller wood-fired systems (< 10 kW_{th}) for heat production mostly work without water circulation, heating the desired location directly.

5.1 Boundaries, Assumptions, Remarks

The environmental analysis of the provision of heat includes all conversion steps that are relevant to the GHG emission impact. Therefore, 1 GJ of heat serves as a unit for the comparison of different provision chains. For the provision of heat, small and large scale systems are analysed. Because of scaling effects and synchronisation factors, large systems usually have lower impacts on GHG emissions. In contrast, large heat production systems usually supply heat with back-up through fossil systems, since the biomass boiler is dimensioned for the base load only. The use of wood chips or split logs in small heating systems requires a higher amount of manual operation needs of the user compared to fossil reference systems.

5.2 Results

The results of the heat production comparison, related to 1 GJ of heat, are presented in Figure 4.

Small systems of heat provision using bioenergy have about one fourth of the GHG emission of a comparable fossil fuel fired system (mix of light oil and natural gas) (Frischknecht et al., 2004). Due to the necessary fossil back-up systems the emissions of large bioenergy systems are higher and at about one third to 40 % of the comparable fossil fuel fired system. Input and output figures as well as economic data of investigated production and conversion processes are documented report D10b and Table 9 of Annex I.

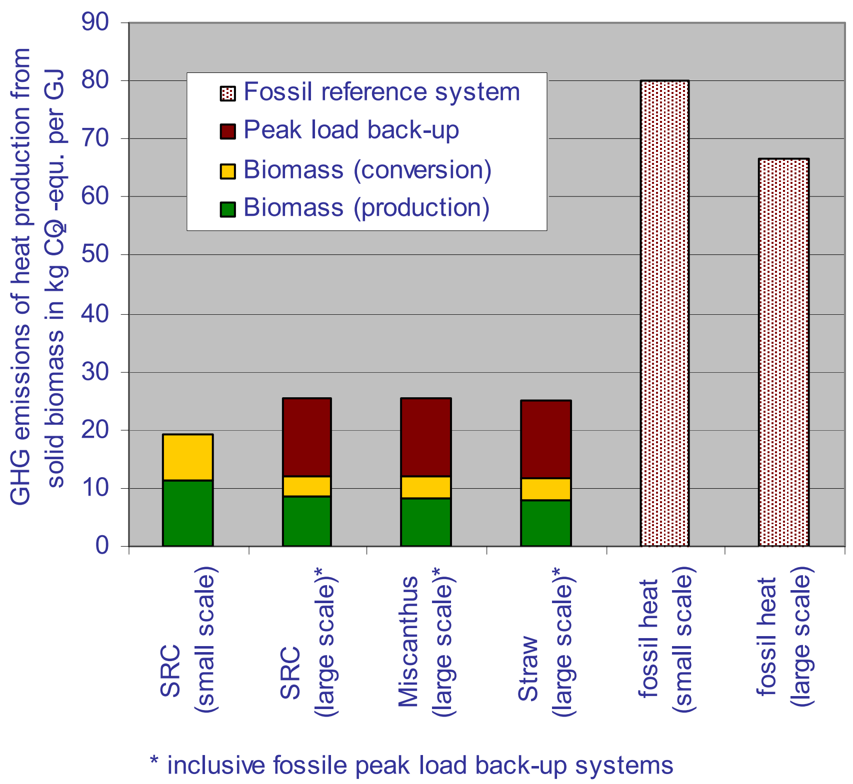


Figure 4: Environmental performance of heat provision ("Biomass (production)": share of energy crop production on total GHG emissions in kg CO_2-equivalent per GJ; "Biomass (conversion)": share of conversion processes on total GHG emissions in kg CO_2-equivalent per GJ; "Peak load back-up": large systems of heat supply provide heat with bivalent sources, the biomass system is dimensioned for base load, peak load is provided from fossil fuel burners).

6 GHG mitigation costs

In chapters 3 to 5, four major provision paths of different final energy sources from agricultural bioenergy production were analysed. The impact of the use of bioenergy concerning GHG emissions was presented in the sub chapters.
For the calculation of the GHG mitigation costs these results have to be combined with the results of the economic analysis, which are presented in Annex I and deliverable report D10b. Thus, the aim is to calculate the cost of reducing GHG emissions through the use of bioenergy. The results are summed up in the following tables, to make the comparison of different paths - reducing GHG emissions - possible.
In general, the paths provide three forms of final energy. Besides heat and electricity, fuels for combustion in engines are produced. The specific costs of GHG mitigation are given in Euro per tonne reduced CO_2-equivalent.

6.1 GHG mitigation costs for the use of (automotive) fuels

The analysed bioenergy provision chains are compared to two fossil fuels, since two motor concepts (diesel and gas-Otto engine) of these fuels are relevant. Biodiesel can substitute diesel and ethanol can substitute petrol. The mitigation costs of GHG emissions related to these substitutes range from 160 to more than one thousand Euro per tonne CO_2 emissions. ETBE reduces GHG emissions at about 85 to 310 € t^{-1} when compared to MTBE. It has to be taken into account that neither ETBE nor MTBE are standalone fuels and can only be used as additive to petrol. But the share of the resulting GHG emissions and mitigation costs are calculated comparably to a pure use (see chapter 3).

Table 1: GHG mitigation costs for the use of biofuels in passenger vehicles.

Path (large scale)	Fossil comparison*	GHG reduction costs in € t^{-1} CO_2-equ.
FAME from sunflower seeds	Diesel	176
RME from rape seeds	Diesel	165
Ethanol from sugar beet	Petrol	291 - 715
Ethanol from wheat	Petrol	239 - 1,767
Ethanol from maize	Petrol	214 - 624
ETBE from sugar beet ethanol	MTBE	127 - 224
ETBE from wheat ethanol	MTBE	95 - 311
ETBE from maize ethanol	MTBE	86 - 213

* assumption crude oil at 50 $ $barrel^{-1}$, resulting in approx. 11.9 € GJ^{-1} producer prices for diesel, petrol or MTBE

6.2 GHG mitigation costs for the provision of electricity

The provision of electricity from energy crops is compared to two types of fossil electricity supply. Firstly, the general electricity mix of Germany and Europe and secondly, a gas-steam power plant is considered as a reference system. The results are presented in Table 2.

Due to the credits concerning manure treatment (see chapter 4), the paths using biogas to provide electricity have very low GHG emissions (in total negative) and therefore have lower GHG mitigation costs. The costs of reducing one tonne of CO_2-equivalent compared to the German electricity mix range from 45 (biogas manure) to 115 € (miscanthus combustion to produce electricity). Compared to a gas-steam power plant or the European electricity mix the costs are higher, because this type of power plant or the electricity mix supplies electricity with lower GHG emissions at (very) moderate costs (see Table 2).

Table 2: GHG reduction costs for the provision of electricity.

Path (large scale)	**Fossil comparison***	**GHG reduction costs in € t^{-1} CO_2-equ.**
Combustion of short rotation coppice	German Electricity mix	136 [a] / 96 [b]
Combustion of miscanthus	German Electricity mix	159 [a] / 115 [b]
Combustion of straw	German Electricity mix	110 [a] / 78 [b]
Combustion of biogas from manure	German Electricity mix	45 [a]
Combustion of biogas from manure + maize silage	German Electricity mix	52 [a]
Combustion of biogas from manure + cereal silage	German Electricity mix	76 [a]
Combustion of biogas from manure + grass silage	German Electricity mix	74 [a]
Combustion of biogas from manure + silage mix	German Electricity mix	62 [a]
Combustion of short rotation coppice	European Electricity mix	223 [a] / 145 [b]
Combustion of miscanthus	European Electricity mix	259 [a] / 173 [b]
Combustion of straw	European Electricity mix	176 [a] / 116 [b]
Combustion of biogas from manure	European Electricity mix	48 [a]
Combustion of biogas from manure + maize silage	European Electricity mix	64 [a]
Combustion of biogas from manure + cereal silage	European Electricity mix	96 [a]
Combustion of biogas from manure + grass silage	European Electricity mix	91 [a]
Combustion of biogas from manure + silage mix	European Electricity mix	77 [a]
Combustion of short rotation coppice	Gas-steam power plant	319 [a] / 198 [b]
Combustion of miscanthus	Gas-steam power plant	363 [a] / 232 [b]
Combustion of straw	Gas-steam power plant	250 [a] / 160 [b]
Combustion of biogas from manure	Gas-steam power plant	52 [a]
Combustion of biogas from manure + maize silage	Gas-steam power plant	77 [a]
Combustion of biogas from manure + cereal silage	Gas-steam power plant	115 [a]
Combustion of biogas from manure + grass silage	Gas-steam power plant	107 [a]
Combustion of biogas from manure + silage mix	Gas-steam power plant	93 [a]

* assumption: electricity mix, industry use at 50 € MWh^{-1}, electricity from gas-steam power plant at 45 € MWh^{-1} [a)] use of power [b)] use of power and heat by CHP

6.3 GHG mitigation costs for the provision of heat

The provision of heat from energy crops is compared to a mix of fossil heat supply. The results are presented in Table 3.
Small systems using SRC (wood chips or split logs) may provide heat at lower prices than fossil reference systems if less comfort in terms of a higher amount of manual labour from the user is taken into account. Therefore GHG reduction costs are negative.
Using straw as a source to supply heat in large scale systems, results in low GHG mitigation costs of about 5 € per tonne CO_2-equivalent. The GHG emissions are comparable to other energy crops but the costs of heat supply using straw are almost as low as in conventional fossil reference systems. The other paths provide heat at GHG mitigation costs of about 60 to 70 € t^{-1} CO_2-equivalent (see Table 3).

Table 3: GHG mitigation costs for the provision of heat.

Path	Fossil comparison*	GHG reduction costs in € t^{-1} CO_2-equ.
Combustion of SRC (small scale)	Gas / oil mix	- 26
Combustion of SRC (large scale)	Fossil heat mix	63
Combustion of miscanthus (large scale)	Fossil heat mix	68
Combustion of straw (large scale)	Fossil heat mix	5

* assumption crude oil at 50 $ $barrel^{-1}$, resulting in approx. 10 € GJ^{-1} heat from natural gas, 12.2 € GJ^{-1} from light fuel oil and 6.1 € GJ^{-1} from heavy fuel oil for industrial use (average 11 € GJ^{-1}), assumption of average heat from natural gas and light fuel oil of 27,6 € GJ^{-1} for small scale use

7 Summary

For the calculation of GHG emissions and mitigation costs of bioenergy produced from agriculture, four major provision chains (FAME from rape seed and sunflower; ethanol or ETBE from sugar beet, cereals and maize; combustion of SRC, miscanthus and straw; biogas production from manure, cereals and maize or grass silage) were analysed for the supply of the three final energy sources; fuel, electricity and heat.

The use of biodiesel from vegetable oil (rape seed, sunflower) reduces GHG emissions per driven km by about 50 % compared to fossil diesel, whereas the use of ethanol from starch and sugar crops (sugar beet, cereals, maize) reduces GHG emissions by 8 % (wheat) to 24 % (maize) per driven km compared to conventional petrol use. Only if improved conversion processes for the provision of ethanol are used, these reductions might be higher (around 50 %). For the different ETBE types as a mixture of produced ethanol and isobutene from fossil origin, comparable results can be observed. The use of conventionally produced bioethanol results in low reductions of about 15 %. Ethanol from improved conversion processes leads to ETBE which has lower GHG emissions. Up to 38 % of the total GHG emissions can be saved compared to MTBE.

The production of electricity by the combustion of woody biomass or by biogas production from manure and/or energy crops (cereals and maize or grass silage) decreases GHG emissions considerably related to the German and European electricity production mix as well as compared to a new gas-steam power plant. The GHG emissions by the combustion of solid biomass is reduced by approximately two thirds per MWh compared to the German power mix, or about 60 % compared to the European electricity mix and by about 50 % compared to

a new gas-steam power plant. Due to high GHG credits, the provision of electricity from biogas digestion results in a negative emission balance.
With respect to different sources of bioenergy heat production, all production chains show a significant reduction in GHG emissions of 60-75 % compared to conventional small and large scale heat production.

The comparison of the mitigation costs, based on the economic calculations in deliverable report D10b and the GHG emission amounts of the different types of final energy sources, shows that for fuel production the biodiesel from rape seed causes the lowest mitigation costs. It is followed by biodiesel from sunflower, ETBE from conventional bioethanol production and finally bioethanol from conventional processes. Better results for bioethanol and ETBE occur, if improved conversion processes are implicated.

For electricity production from the combustion of woody biomass in CHP units and from biogas production, the mitigation costs are lower than for biodiesel if compared to the European power mix. The mitigation costs of the same production chains in comparison to a new gas-steam power plant are only lower for the biogas production chains whereas the mitigation costs for solid biomass combustion are at a similar level to those for biodiesel production.

In addition, the production of woody biomass for heat provision in large scale systems results in low GHG mitigation costs that are comparable with the costs per reduced tonne CO_2-equivalent of the electricity production from biogas compared to the German power mix. In total, these mitigation costs are on average approximately half if compared to biodiesel. The use of straw for heat production results in very low GHG mitigation costs (5 € t^{-1} CO_2-equivalent) but the use of SRC in small scale systems show negative GHG mitigation costs due to cheaper heat supply compared to fossil reference (but taking into account less comfort by a higher share of manual operations needs of the user).

Figure 5 gives an overview of the results of most provision chains by presenting the reduced CO_2-equivalent emission versus the calculated CO_2 reduction costs in € per t CO_2-equivalent. Results out of range are not presented.

The use of bioenergy sources for the production of automotive fuels results in comparably low reductions at comparatively high costs. This is true for the 1st generation of biofuels only and one reason why the 2nd generation of biofuels (like FT-Diesel, DME or SNG, see chapter 1) is promoted strongly. First analysis of these provision chains based on assumptions and simulated processes of pilot plants show that the potential for cost-efficient GHG mitigation is very promising. The provision of heat from solid biofuels shows low reductions at low to very low costs. The provisions of power from solid biofuels compared to the European electricity mix can result in higher reductions but tends to have reduction costs that are in between the costs of heat and automotive fuels. The highest emission reduction to low reduction costs shows the provision of power from biogas production (due to high credits).

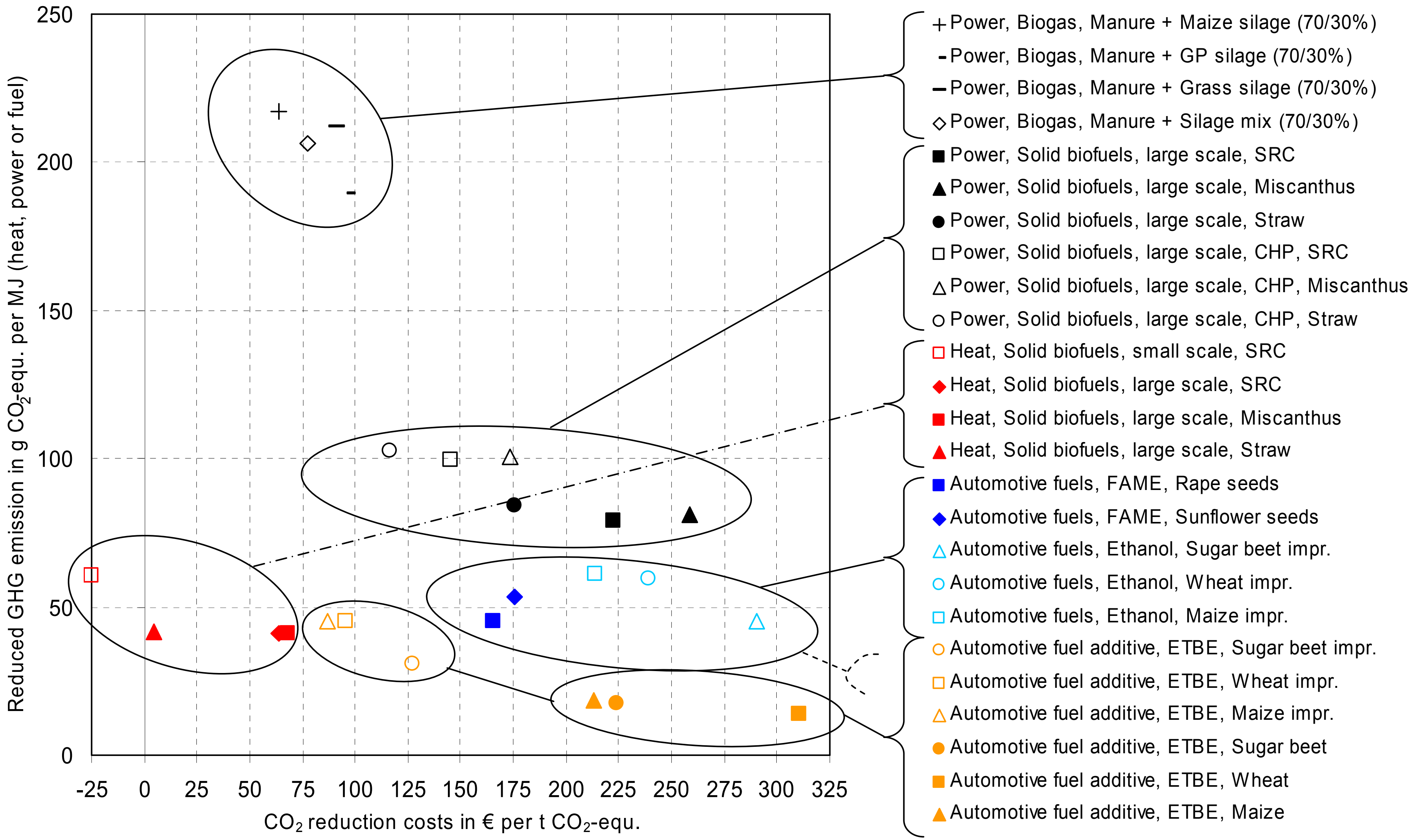


Figure 5: Reduced GHG emissions of final energy provision versus CO_2 reduction costs.

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Annex I

The following tables are excerpts of data provided in deliverable report D10b.

Table 4: Production of biodiesel

Production				**Rape seed**	**Sunflower**
Input	Seeds		kg/ha	3.3	6
	Fertilisers:	Nitrogen	kg/ha	129	93
		Phosphorus	kg/ha	54	36
		Potassium	kg/ha	30	54
		Lime	kg/ha	300	300
	Weed control		l AI/ha*	2.5	2.5
	Other services		$MJ/t_{dm,output}$	305	250
	Fuel		l/ha	84	74.5
Output	Biomass/crop		t_{dm}/ha	3.5	2.1
	By-products		t_{dm}/ha	10-12	6-8
Costs			€/ha	702	656
			€/t_{dm}	203	313
Conversion 1					
Input	Seeds		kg	1,000	1,000
	Electricity		GJ	0.24	0.24
	Natural gas		GJ	0.45	0.45
Output	Oil		kg	379.8	460
	By-product		kg	570	520
Conversion 2					
Input	Oil		kg	379.8	460
	Methanol		kg	41.4	48.6
	Acids		kg	0.4	0.5
	NaOH		kg	2.4	2.5
	Electricity		GJ	0.069	0.070
	Natural gas		GJ	0.625	0.650
	Light fuel oil		GJ	0.050	0.050
Output	Biodiesel		kg	376	441.6
	Glycerol		kg	37.6	44.2
Costs			€/$t_{Biofuel}$	722.1	797.4
			€/$GJ_{Biofuel}$	19.4	21.4

Table 5: Production of ethanol

Production				**Wheat**	**Maize**	**Sugar beet**
Input	Seeds		kg/ha	180	2.2*	0.91*
	Fertilisers:	Nitrogen	kg/ha	165	165	151
		Phosphorus	kg/ha	60	72	55
		Potassium	kg/ha	45	45	138
		Lime	kg/ha	300	300	300
	Weed control		l AI/ha*	2.5	2.5	3.5
	Fuel		l/ha	83.4	84	102
Output	Biomass/crop		t_{dm}/ha	7.5	9.0	12.7
	By-products		t_{dm}/ha	6.7	5	40
Costs			€/ha	752	1,172	1,034
			€/t_{dm}	100.5	130.1	81.7
Conversion						
Input	Biomass/crop		kg	1,000	1,000	1,000
	Water		kg	10,000	10,000	2,400
	NaOH		kg	2.98	3.37	1.42
	Acids		kg	5.78	6.5	2.8
	Chemicals		kg	2.3	2.59	1.1
	Electricity		MJ	506.6	439.5	68.4
	Natural gas		MJ	3,600	4,191	850
	LPG		MJ	10		
Output	Ethanol		kg	286.0	329	80.6
	DDGS		kg	326	375	55 / 38**
	Waste water		kg	9,900	9,900	2,300
Costs			€/$t_{Biofuel}$	699	669	670
			€/$GJ_{Biofuel}$	26.1	25	25
*units/ha		**dried cossettes / vinasse				

Table 6: Production of ETBE

Conversion		**Ethanol**	**From**	**Wheat**	**Maize**	**Sugar beet**
Input	Ethanol		kg	1,000	1,000	1,000
	Isobutene		kg	1,217	1,217	1,217
	Electricity		MJ	28.2	28.2	28.2
	Natural gas		MJ	997	997	997
Output	ETBE		kg	2,217	2,217	2,217
Costs			€/$t_{Biofuel}$	590	576	577
			€/$GJ_{Biofuel}$	16.2	15.8	15.8

Table 7: Production of electricity from solid biomass

Production				**SRC (large)**	**Miscanthus (large)**	**Straw (large)**
Input	Seeds		kg/ha	650*	1,000*	0*
	Fertilisers:	Nitrogen	kg/ha	34	52	25
		Phosphorus	kg/ha	9	7	15
		Potassium	kg/ha	25	104	70
		Lime	kg/ha	50	50	0
	Weed control		l AI/ha*	0.2	0.2	0
	Fuel		l/ha	18	35	10
Output	Biomass/crop		t_{dm}/ha	9	12	5
Costs			€/ha	717	1,021	253
			€/t_{dm}	79.6	85.2	49.6
Conversion						
Input	Biomass/crop		kg	1,000	1,000	1,000
	Electricity		MJ	0.2	0.6	0.6
Output	Electricity		GJ	3.89	4.67	4.7
	Ashes		kg	13	32	47
Costs			€/t_{Input}	123	162	135
			€/$GJ_{electricity}$	31.6	34.8	28.7

*units/ha

Table 8: Production of electricity from biogas

Production				**Manure 100 %**	**Cereal silage 30 %+ Manure**	**Maize silage 30 %+ Manure**	**Gras silage 30 %+ Manure**	**silage mix 30 %+ Manure**
Input	Seeds		kg/ha		200	28	0	
	Fertilisers:	Nitrogen	kg/ha		168	220	90	
		Phosphorus	kg/ha		83	80	120	
		Potassium	kg/ha		145	225	200	10 %
		Lime	kg/ha		300	300	300	of
	Weed control		l AI/ha*		2.5	3.5	0	each
	Fuel		l/ha		89	106	50.1	silage
Output	Biomass/crop		t_{dm}/ha		8.8	15	10	
Costs			€/ha		862	1,115	837	
			€/t_{dm}		98.5	74.3	83.7	
Conversion 1								
Input	Manure		kg	1,000	3,300	3,300	3,300	3,300
	Biomass		kg	-	1,000	1,000	1,000	1,000
	Electricity		MJ	8	92	89	89	92
Output	Biogas		m^3	25	278	268	268	278
	By-products		kg	1,000	4,000	4,000	4,000	4,000
Conversion 2								
Input	Biogas		kg	1,000	1,000	1,000	1,000	1,000
Output	Electricity		GJ	6.3	6.1	5.96	6.1	6.1
Costs			€/t_{Input}	266	196	165	202	182
			€/$GJ_{Electricity}$	42.2	32.1	27.7	33.2	29.8

Table 9: Production of heat from solid biomass

Production				**SRC (small)**	**SRC (large)**	**Miscanthus (large)**	**Straw (large)**
Input	Seeds		kg/ha	650*	650*	1,000*	0*
	Fertilisers:	Nitrogen	kg/ha	34	34	52	25
		Phosphorus	kg/ha	9	9	7	15
		Potassium	kg/ha	25	25	104	70
		Lime	kg/ha	50	50	50	0
	Weed control		l AI/ha*	0.2	0.2	0.2	0
	Fuel		l/ha	18	18	35	10
Output	Biomass/crop		t_{dm}/ha	9	9	12	5
Costs			€/ha	717	717	1,021	253
			€/t_{dm}	79.6	79.6	85.2	49.6
Conversion							
Input	Biomass/crop		kg	1,000	1,000	1,000	1,000
	Electricity		MJ	0.2	0.2	0.6	0.6
Output	Heat		GJ	9.48	9.48	11.8	12
	Ashes		kg	14	13	32	47
Costs			€/t_{Input}	246	129	162	135
			€/GJ_{heat}	26	13.6	13.8	11.2

*units/ha