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Life Cycle Assessment of Biogas Production from Different Substrates

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Abstract

In order to improve the yield of biogas plants, operators often purchase or cultivate substrates with high energy content. With a life cycle assessment (LCA), the environmental impacts due to the digestions of these substrates can be analysed.

In this report life cycle inventory datasets of biogas production from the following substrates are investigated: maize silage, sugar beets, fodder beets, beet residues, molasses, and glycerine. Furthermore, biogas from a grass refinery is analysed. The life cycle inventory data required for such an LCA are collected according to the ecoinvent v2.0 quality guidelines. The life cycle inventories are based on literature data and a current survey of 16 biogas plant operators, which was conducted within another project of the BFE "Biomass Research Programme".

In addition to the new inventories of the biogas production, life cycle inventories of the provision of electricity and heat from burning biogas from the examined substrates in a biogas engine (cogeneration unit) are set up. Part of this electricity and heat is then used for the operation of the biogas plants. In the survey the biogas plant operators declare that 62 % of the electricity consumption is met with electricity from a cogeneration unit that is operated with biogas. About 38 % of the electricity consumption is covered with electricity from the grid. The heat consumption is completely covered by the cogeneration unit.

Life cycle inventory datasets are also prepared for three technologies of biogas purification with the purpose of supplying biomethane to the natural gas grid. The considered technologies are amino washing, glycol washing, and pressure swing adsorption

The setup of life cycle inventory datasets allows for a detailed assessment and comparison of the environmental impacts of using biogas from different substrates and products of biogas operated cogeneration units.

The total greenhouse gas (GHG) emissions of a transport service with biogas fuel from the new established inventories and an average load of 1.6 passenger amounts to between 95 gCO_2-eq./pkm (biogas from grass refinery) and 163 gCO_2-eq./pkm (beet residues). Even though these values are lower than the greenhouse gas emissions of using conventional fuels, most biogas types analysed in this study do not comply with the thresholds for a tax reduction (40 % less GHG emissions compared to using conventional fuels). Important for the GHG result are the methane emissions from the biogas production and purification, and the dinitrogen monoxide emissions from the plant cultivation. Those emissions can vary significantly between individual biogas plants and different energy crops.

If considering the total environmental impacts assessed with the ecological scarcity method (2006), driving with biogas from non-waste substrates has higher environmental impacts compared to driving with conventional natural gas.

Electricity produced from biogas generated from energy crops has considerably higher environmental compared to the average electricity from the Swiss grid, whereas electricity produced from biogas generated from waste substrates has lower environmental impacts and can be considered as green electricity.

At present, biogas in Switzerland is mainly produced from sewage sludge, slurry, and biowaste. If the co-digestion with higher shares of substrates made from energy crops increases significantly in future, the produced biogas cannot comply with the thresholds for a fuel tax reduction anymore.

Kurzfassung

Um den Ertrag von Biogasanlagen zu verbessern, setzen die Anlagenbetreiber oftmals Substrate mit einem hohen Energiegehalt ein, die gekauft oder extra angebaut werden. Im Rahmen dieses Projekts wurde eine Ökobilanz der Vergärung von Maissilage, Zuckerrüben, Futterrüben, Rübenreste, Melasse und Glycerin in Biogasanlagen durchgeführt. Zudem wurde Biogas aus einer Grasraffinerie beurteilt. Die Sachbilanzinventare wurden basierend auf aktuellen Literaturdaten und einer Umfrage bei 16 Betreibern von Biogasanlagen in der Schweiz erstellt.

Zusätzlich zu der Biogasproduktion, wurde auch die Verbrennung des produzierten Biogases in einem Blockheizkraftwerk berücksichtigt, wobei ein Teil der produzierten Wärme und des Stroms wiederum in der Biogasanlage verbraucht wird. Des Weiteren wurde die Aufbereitung des Biogases mittels Druckwechseladsorption, Amin-Wäsche und Glykol-Wäsche zu Biomethan für das Erdgasnetz und die Verbrennung in Fahrzeugmotoren untersucht.

Die Treibhausgasemissionen (THG), wenn ein Personenfahrzeug mit einer Auslastung von 1.6 Personen mit Biogas aus diesen ausgewählten Substraten fährt, betragen zwischen 95 gCO2-eq./pkm (Biogas aus der Grasraffinerie) und 163 gCO2-eq./pkm (Rübenreste). Zwar liegen diese Resultate unten den Treibhausgasemissionen des Transports mit konventionellen Treibstoffen wie Benzin, Diesel oder Erdgas, doch erreichen die meisten Substrate nicht den Grenzwert für eine Reduktion der Mineralölsteuer (40 % weniger THG als konventionelle Treibstoffe) (Siehe Bild 1). Wichtig für das Resultat sind vor allem die Methanemissionen bei der Vergärung und der Gasaufbereitung, sowie die Lachgasemissionen beim Pflanzenanbau.

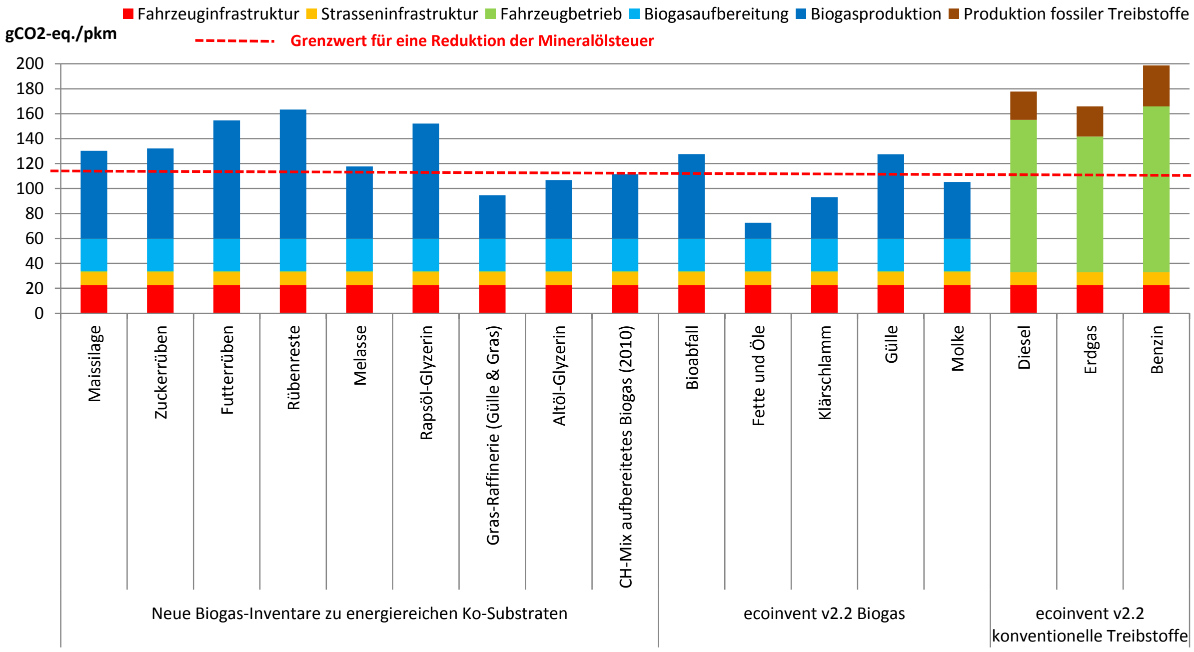

Bild 1 **Treibhausgasemissionen mit einem Zeithorizont von 100 Jahren (IPCC 2007) des Transports mit einem Personenfahrzeug unter Verwendung von Biogas aus verschiedenen Substraten und konventionellen Treibstoffen im Vergleich. Die Fahrzeugauslastung beträgt 1.6 Personen.**

Bei einer Betrachtung der gesamten Umweltbelastung gemäss der Methode der Ökologischen Knappheit (2006) zeigt sich, dass die Verwendung von Biogas aus sämtlichen untersuchten Substraten mit Ausnahme von Glyzerin aus Altöl höhere Belastung vorweist als der analoge Transport mit konventionellem Erdgas (siehe Bild 2).

Strom aus einem mit Biogas betriebenem Blockheizkraftwerk hat deutlich höhere Gesamtumweltbelastungen als der Schweizer Strommix, wenn das Biogas aus Maissilage, Rüben, oder Raps-Glyzerin produziert wird. Elektrizität aus vergärten Energiepflanzen kann deshalb nicht als ökologische Alternative betrachtet werden. Wenn jedoch das Biogas aus Abfallprodukten wie Klärschlamm, Gülle, Altöl-Glyzerin oder Bioabfall produziert wird, liegen die Gesamtumweltbelastungen tiefer als beim Schweizer Strommix.

Zurzeit wird Biogas in der Schweiz hauptsächlich durch Vergärung solcher Abfallprodukte hergestellt. Falls in Zukunft die Vergärung von pflanzlichen Produkten wie z.B. Maissilage, Futter- und Zuckerrüben, Rübenreste, Melasse und Raps-Glyzerin deutlich zunimmt, kann das produzierte Biomethan die Grenzwerte für eine Reduktion der Mineralölsteuer nicht mehr in allen Fällen einhalten.

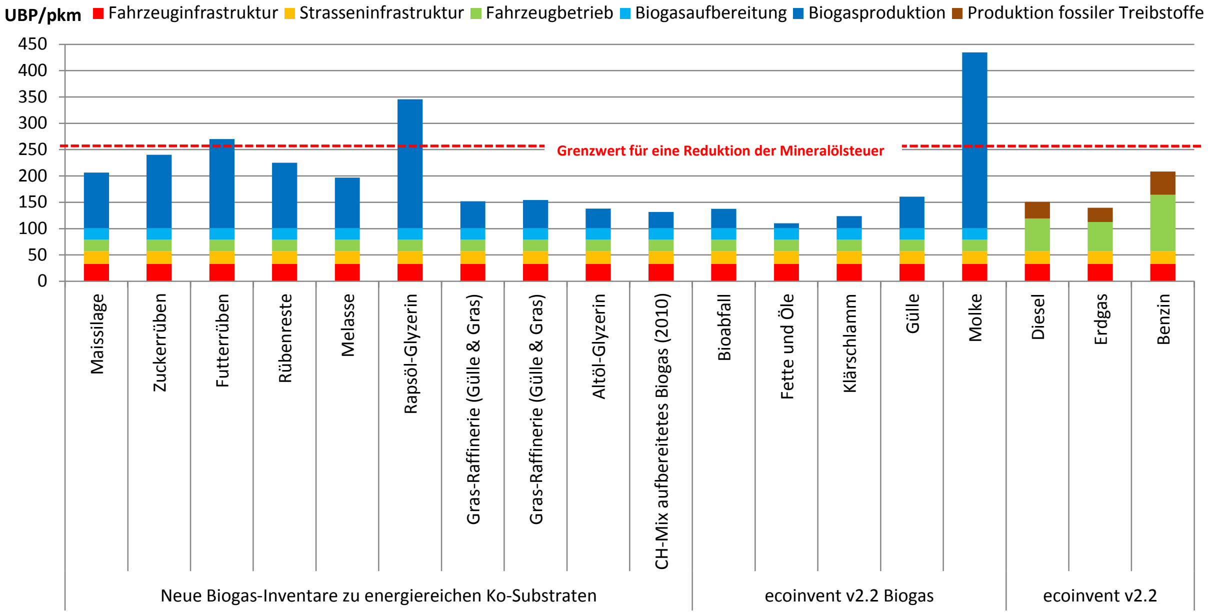

Bild 2 **Umweltbelastungspunkte (UBP) gemäss der Methode der Ökologischen Knappheit des Transports mit einem Personenfahrzeug unter Verwendung von Biogas aus verschiedenen Substraten und konventionellen Treibstoffen im Vergleich. Die Fahrzeugauslastung beträgt 1.6 Personen.**

1 Introduction

1.1 Background

Biogas from anaerobic digestion either can be burned directly in cogeneration power and heat plants or can be used as substitute for or additive to natural gas. In contrast to fossil fuel systems, the carbon dioxide released from biogas production and combustion, was just recently assimilated in photosynthesis. This emission does not result in a net production of carbon dioxide and is therefore neutral to climate change, as long as plants continue taking up carbon dioxide.

As a consequence, the overall environmental performance of biogas production is strongly dependent on the environmental impacts of the substrate provision, the biogas yield, the energy input and source for the digestion process and direct emissions from the process and the use of digestates (Börjesson & Berglund 2005). Actual biomass substrates used in anaerobic digestion have different biogas yields due to their different energy content. Substrates with high energy contents are often purchased or grown by farmers in order to enhance the biogas yield. The digestion of low-energy substrates is often treated as a disposal service and generates an additional income. This study focuses on substrates, which are added to the usual substrates in order to enhance the biogas yield of the digestion process. Furthermore, it includes life cycle inventories of a grass refinery providing the products insulation materials, organic fertilisers, biopolymers, and biogas from grass silage.

1.2 Goal and scope

This study aims to assess the environmental impact of the current situation of biogas production and potential substrates for future co-digestion in Switzerland. The goals of this study can be summarized as follows:

- Assessment of the environmental impact of purchased substrates in biogas plants
- Update of the emissions from cogeneration units
- Assessment of the environmental impacts of the various products of a grass refinery
- Modelling of the different technologies for biogas purification in Switzerland
- Evaluation of the actual production mix of purified biomethane for the natural gas supply grid and the use as fuel in vehicles in Switzerland

In a first step, this study gives an overview of different substrates that can be used in co-digestion, and six substrates are selected for an in-depth analysis in this project. For the assessment of the environmental performance of different biomass substrate, the supply of the substrate has to be taken into account. If the purpose of the substrate production is the production of biogas, the full production process has to be allocated to the environmental impact of biogas production. However, the substrates often are by- or co-products of other production processes and have to be dealt as multi-output process. The environmental impact of the production process is allocated using the price of the different products as allocation factor.

Secondly, the emissions from the biogas production and combustion in cogeneration units have to be considered. The two main gases produced in an anaerobic digestion plant are carbon dioxide and methane. Methane is a highly potential greenhouse gas. The release of methane during biogas production is of major interest considering the environmental performance of biogas production. The combustion of biogas in cogeneration units leads to specific emissions, which are dependent on the applied technology and composition of the biogas.

In Fig. 1.1 a flow chart of the production of biogas and biomethane as well as the co-generation of heat and electricity from the biogas is presented. Operators of biogas plants have the option to send some of the produced biogas for purification to biomethane which can be used as a fuel in road transportation. Alternatively, they can burn all biogas in a cogeneration unit in order to produce electricity and heat. A minimum amount of biogas needs to be burned in cogeneration unit, in order to cover the heat (and optionally also the electricity) requirement of the anaerobic digestion plant.

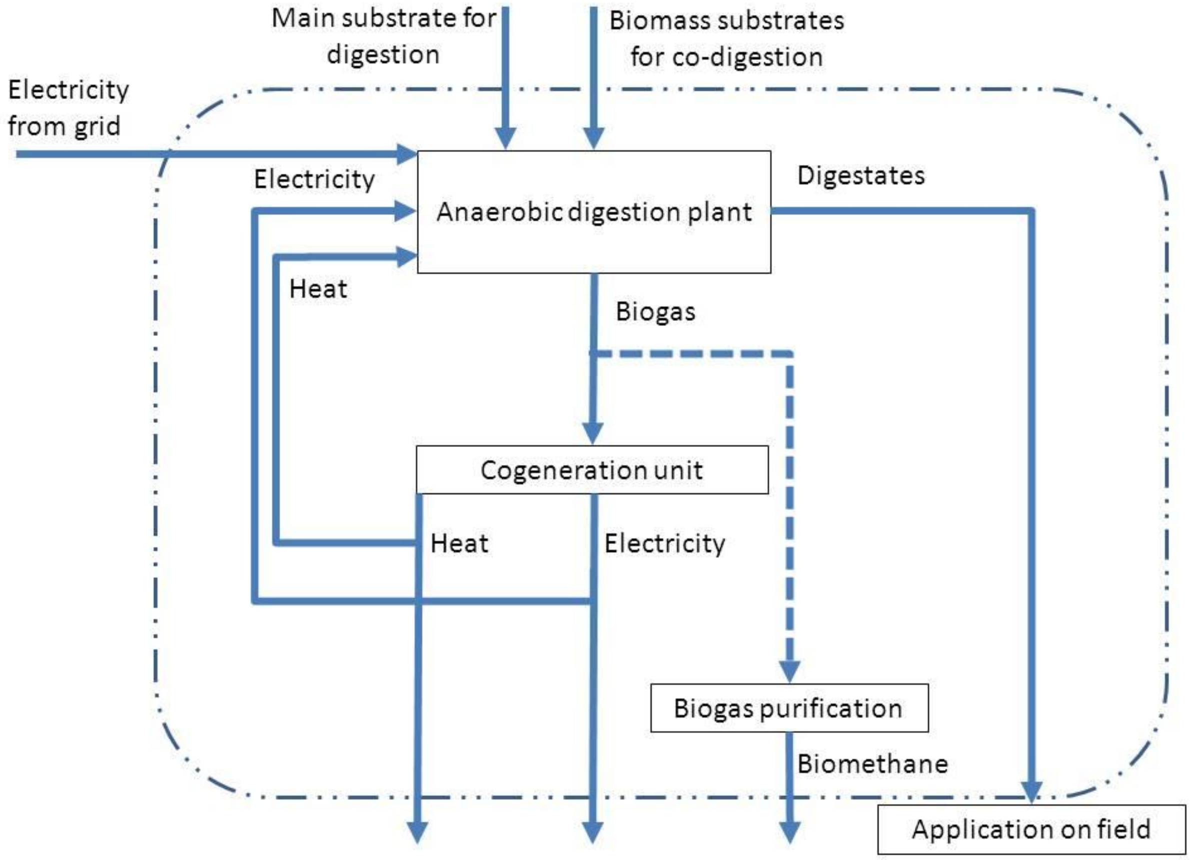

Fig. 1.1 **Flow chart of the biogas production from substrates of the purification to biomethane and of the generation of heat and electricity in a biogas co-generation unit**

In addition to the life cycle inventories of biogas from different substrates, new datasets of the various products from a grass refinery are established. These are insulation materials, organic fertilisers, biopolymers, and biogas. The substrates of the biogas plant in the grass refinery are cow slurry and grass slurry. In Fig. 1.2 a flow chart of the grass refinery is presented. The data of the grass refinery are based on a study prepared by Leuenberger & Jungbluth (2010).

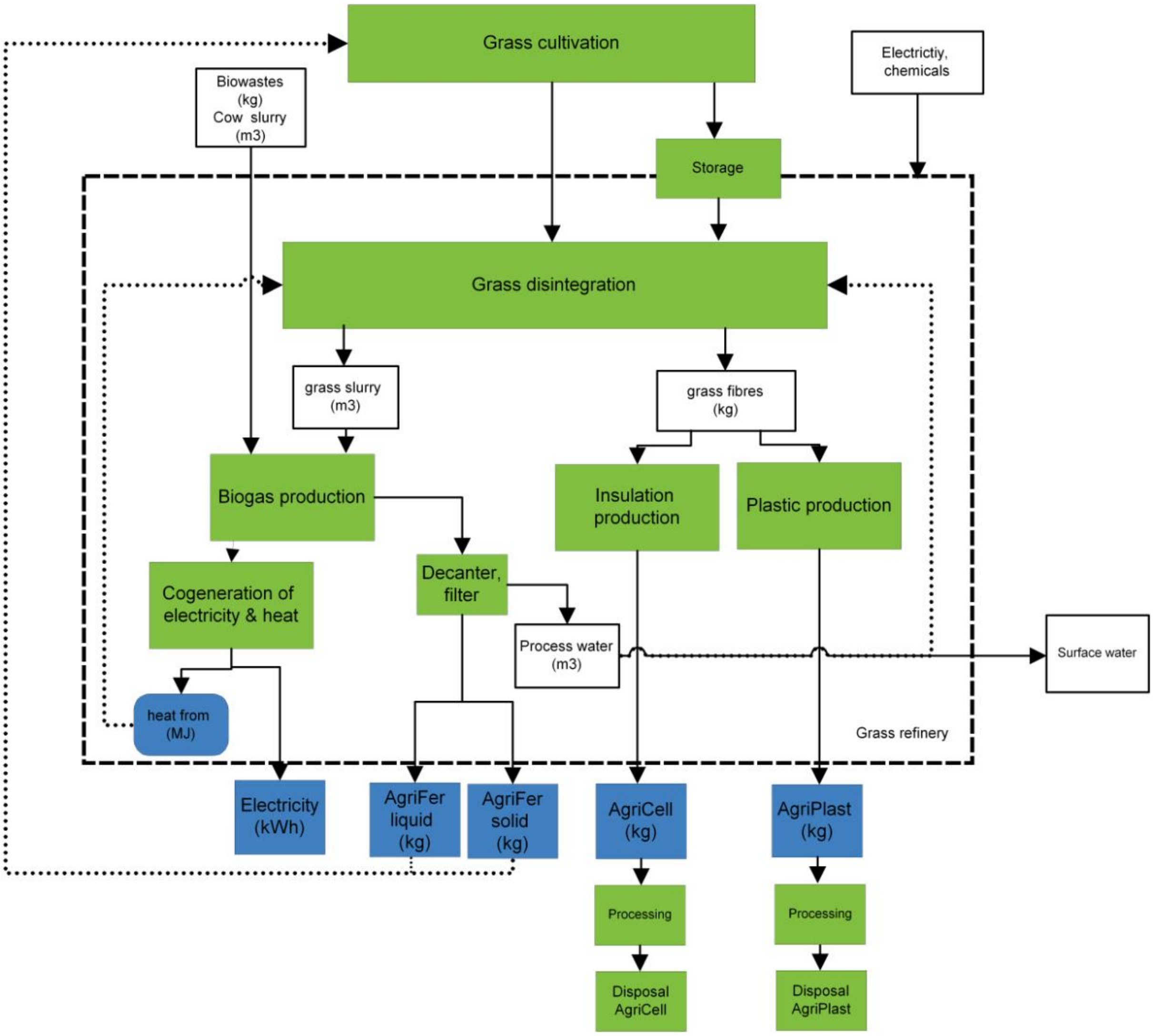

Fig. 1.2 Flow chart of the grass refinery

The following chapters firstly give an overview on substrates used for anaerobic co-digestions (Chapter 2). Secondly they present a summary of the life cycle inventories of biogas from six selected substrates, as well as models of burning the biogas from these substrates in a cogeneration unit, purifying biogas with different technologies, and producing various products in a grass refinery (Chapter 3). Finally, the life cycle impact assessment results of using biogas for transportation are shown (Chapter 4). The detailed life cycle inventory data are presented in the Appendix.

1.3 Allocation

With regard to the LCA of biogas production, allocation questions come up concerning the production of the biogas substrates and the fate of the biogas digestates.

Fig. 1.3 shows how the production of the substrate and the fate of the digestate are allocated in the datasets of biogas from sewage sludge and manure prepared by Jungbluth et al. (2007) and in this study.

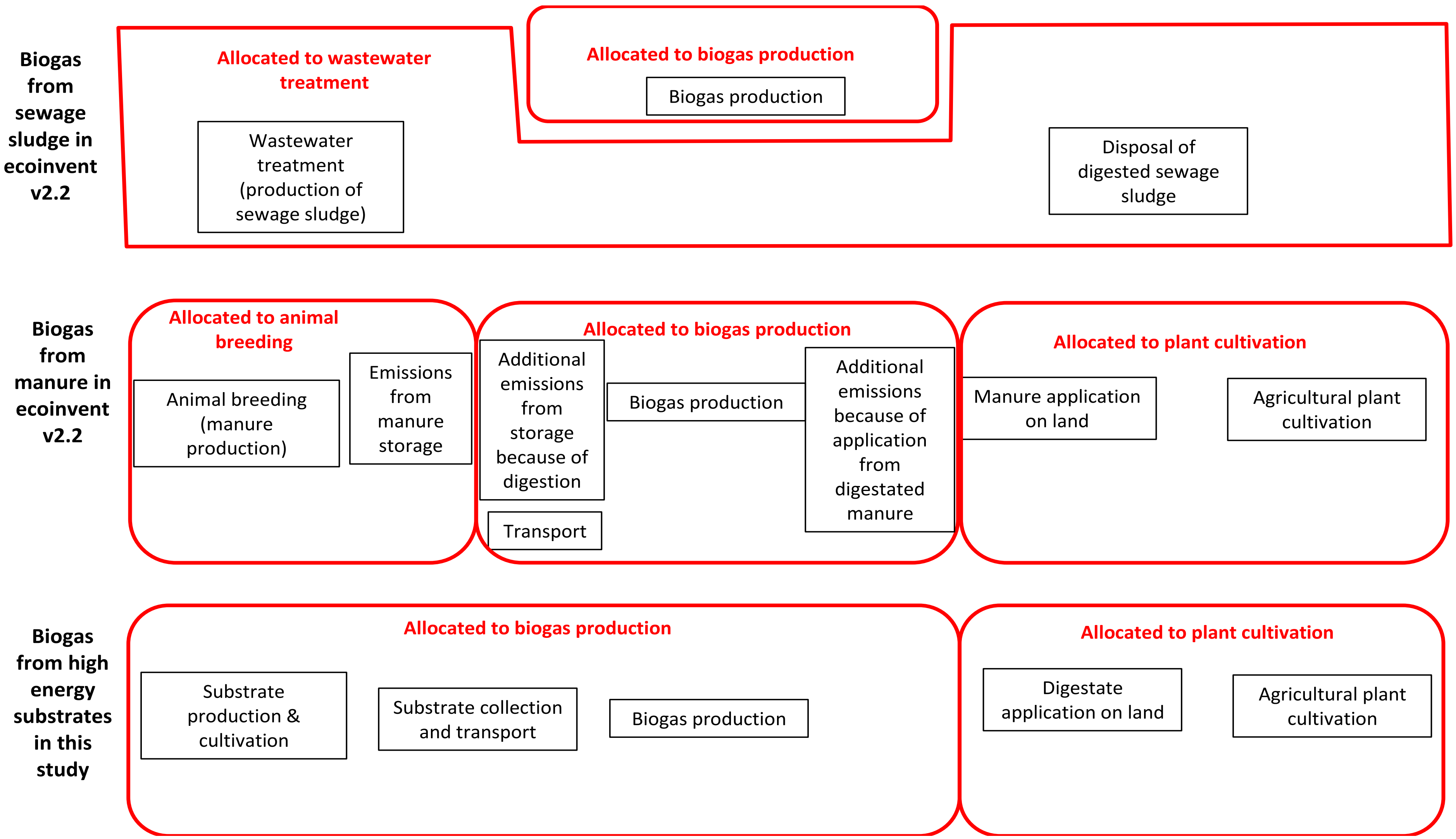

Fig. 1.3 **Allocation in datasets of biogas from sewage sludge and manure prepared by Jungbluth et al. (2007) and in datasets of biogas from energy substrates in this study**

In the case of biogas from sewage sludge only the resource consumption and emissions directly related to the biogas production are considered in the biogas dataset. The production of sewage sludge is part of the wastewater treatment service in a sewage plant and is therefore not considered in the biogas inventory. The disposal of sewage sludge is also part of wastewater treatment in sewage plants without biogas production. Consequently, the environmental impacts of the disposal of the digested sludge are not considered in the biogas inventory.

In the case of biogas from manure, the substrate (manure) is considered as a waste product from animal breeding. Consequently, the environmental impacts from animal breeding are allocated to the animal products such as meat, milk etc. and not to the manure. Emissions from manure also occur, if manure is not digested in biogas plants. Therefore, those emissions are allocated to the animal breeding. However, if manure is used as biogas substrate, there are higher emissions compared to conventional manure digestion. These additional emissions are considered in the inventory of the biogas production. Manure is an important fertilizer in agricultural plant production. Thus, the environmental impacts from application of digested or undigested manure on agricultural land is allocated to the agriculture and not to the biogas production.

Finally, in the case of biogas from energy substrates in this study, operators of biogas plants purchase those substrates or grow them on their own field in order to increase the biogas production. Hence, these products are not wastes and the environmental impacts of their production are considered in the life cycle inventory of the produced biogas. With regard to the application of digestates on agricultural land, the situation is similar to the application of manure. The digestates have a fertilizing effect on the soil and therefor the environmental impacts of their application in agriculture are attributed to the life cycle of the cultivated plants.

The allocation of the digestate fate as described above is a common approach in LCA. However, a common agreement on how to allocate the environmental impacts (e.g. transport, spreading, heavy metal emissions into soil) from the digestate application on agricultural fields is not achieved yet. In order to increase the fertility of their soil, some farmers purchase these digestates from biogas plants by paying a price. However, in other cases farmers who accept the digestates from biogas plants receive a payment for this disposal service of the residues. This would justify an allocation of the digestate application to the biogas produced. Very common is the situation where the biogas plant is the part of the same entity as the agricultural fields where the digestates are applied. Obviously, there is no money transferred with regard to the digestate application and an economic allocation is not feasible. In order to incorporate the different expert opinions on how to allocate the environmental impacts from digestate application, we include a scenario in this study where the digestate application is allocated to the biogas production.

The economic allocation between sugar beets and beet residues as well as between plant oil methyl ester and glycerine is described in Appendix 8.

2 Overview of biomass substrates for co-digestion

Traditionally, mainly sewage sludge was used to generate biogas, but with growing interest other substrates are fed into anaerobic digestion.

According to the list by VKS (Verein Kompost und Vergärung Schweiz), the following categories of substrates can be used for anaerobic digestion (Inspektorat der Kompostier- und Vergärbranche der Schweiz 2006):

- Crops + grass
- Harvest residues and by-products
- Manure
- Industrial organic waste by-products and waste
- By-products and waste from horticulture and landscape management
- Municipal organic waste

For most of these substrates categories, life cycle inventories have been established and are published in the ecoinvent database v2.2 (Jungbluth et al. 2007).

An overview of potential biomass substrates for biogas production is given in Tab. 2.1. The overview bases on a literature study of different biomass substrates. The variety of biomass substrate suitable for anaerobic digestion is large. Leuenberger & Jungbluth (2009) evaluated the different substrate with regard to an update of the ecoinvent database and they recommend to establish datasets for the co-digestion of the following selected substrates:

- Maize silage
- Sugar beet
- Fodder beet
- Beet residues
- Molasses
- Glycerine

Within this project, life cycle inventory datasets of biogas from these substrates are established. Furthermore, the cogeneration of heat and electricity with biogas from these substrates is modelled and datasets of the various products from a grass refinery are set up.

Tab. 2.1 Overview of potential biomass substrates for anaerobic digestion

Type	Substrate
Crops	Grains, maize, beans, beets etc. Ley crops
Harvest residues	Tops and leaves of sugar beet Straw
Manure	Liquid manure pig Liquid manure cattle Agricultural co-digestion
Industrial organic waste	Slaughterhouse waste Brewing industry pomace Vinification residues Whey (dairy) Vinasse/distillery residues Mixed waste from food industry Sugar beet meal Molasses residues Apple pulp Pulp from coffee production Coffee grounds and tea residues Waste from mushroom production Spoilt foods Cooking oil Plant residues from grease separator Sludge from vegetable oil production Residues from spice production Palm oil cake Jatropha oil cake Rape oil cake Sunflower oil cake Waste (water) from cellulose production Waste from textile production Waste water food industry Waste water from sugar production from sugar beet
Horticulture and landscape management	Foliage/greenery Potted plant residues Greenery
Municipal organic waste	Average data municipal organic waste Organic waste Residues from lawn mowing Average data food waste Kitchen waste Debris
Other	Glycerine Sewage sludge

3 Life cycle inventories: summary

In this Chapter, a summary of the modelled life cycle inventories is given. Subchapter 3.1 describes the production of biogas, Subchapter 3.2 describes the application of digested matter on agricultural land, Subchapter 3.3 explains the model for the cogeneration of heat and electricity from biogas, Subchapter 3.4 presents the detailed model of a grass refinery, and Subchapter 3.5 describes the life cycle inventories of biogas purification. The full description of the life cycle inventories is presented in the Appendix.

3.1 Biogas conversion in agricultural biogas plants

In this Subchapter, we describe specific substrates that are used in biogas plants for co-digestion. These are maize silage, sugar beets, fodder beets, beet residues, molasses, and glycerine.

In Tab. 3.1 the properties of the average Swiss biogas mix are shown. Since the methane content of biogas is the key property, the biogas yields of different biogas substrates are corrected according to the methane content of the produced biogas (see Tab. 3.2). Furthermore, Tab. 3.2 shows the biogas conversion efficiency calculated as the ratio of the energy content of the produced biogas to the energy content of the used substrate.

Tab. 3.1 Summary of main properties of the Swiss biogas mix according to Jungbluth et al. (2007:244)

		Biogas-Mix
Methane	Vol. %	63.3
Carbon dioxide	Vol. %	33.4
Methane	Kg/Nm^3	0.45
Carbon Dioxide	Kg/Nm^3	0.66
Total Carbon Content	Kg/Nm^3	0.52
Nitrogen	Vol. %	3.17
Density	Kg/Nm^3	1.15
Lower heating value	MJ/Nm^3	22.7

Tab. 3.2 Actual and methane corrected biogas yield of different substrates (Institut für Energetik und Umwelt 2006) and biogas conversion efficiency

Substrate	Unit	Maize silage	Sugar beet	Fodder beet	Beet residues	Molasses	Glycerine
Biogas yield	Nm3 per t fm	188.4	175.0	109.4	59.5	287.3	976.5
Methane content	Vol. %	53%	54%	54%	55%	73%	50%
Methane corrected biogas yield	**Nm3 per t fm**	**156.1**	**147.8**	**92.4**	**51.2**	**328.9**	**770.6**
Energy content of substrate	MJ/kg	5.3	3.8	3.0	3.5	n/a	18.0
Biogas conversion efficiency	**MJ_{biogas}/MJ_{in}**	**67%**	**89%**	**70%**	**34%**	**n/a**	**97%**

3.1.1 Biogas from maize

Maize is one of the most commonly used energy crop in agricultural or industrial biogas production plants and therefore plays an important role for the evaluation of different substrates in anaerobic digestion. Compared to other energy crops, the properties of maize silage are favourable for biogas production. The cultivation has no special requirements, the maize yield per hectare is comparably high, and the silage can easily be stored in bunker silos (Institut für Energetik und Umwelt gGmbH 2006). The biogas yield per ton maize silage depends on the variety. Varieties with late ripening produce more biogas than early ripening varieties (Amon et al. 2007a; Institut für Energetik und Umwelt gGmbH 2006). A drawback of maize silage used in anaerobic digestion is its competitive use as animal feed.

Experiences with maize in anaerobic digestion are available from biogas production in Germany, where maize is often added as a co-substrate. The agricultural production of maize has to be fully attributed to the environmental impact of the biogas production. LCI data on maize cultivation is available in the ecoinvent database (Nemecek et al. 2007).

The specifications of maize silage that are used in this study are declared in Tab. 3.3.

Tab. 3.3 Specification of maize silage and of the production of biogas from this substrate (Institut für Energetik und Umwelt gGmbH 2006)

		Maize silage
Dry matter content	**%**	**27.5%**
organic substance	**% DM**	**90.0%**
N	**% DM**	**1.6%**
P	**% DM**	**0.3%**
Biogas yield	**m3 per t DM**	**672.7**
CH_4 content	**%**	**52.5%**

3.1.2 Biogas from sugar beet, fodder beet and beet residues

Apart from maize, beet cultivation in Switzerland provides large amounts of biomass, which could be potentially used in biogas production. Currently, beets are used for sugar production or as animal feed. If the beet silage is directly added to anaerobic digestion, the environmental impact of beet production has to be taken into account for the LCA of biogas production.

Similar to maize silage, the cultivation of beets has a high yield and the methane production is comparably high. Cultivation requirements and the storage of the silage on the other hand are more complicated. The dependence of biogas yield from fodder beet digestion on microbiologic conditions has been investigated by Scherer et al. (2009).

As sugar and fodder beets are primarily used for sugar production or animal feed respectively, the use of the entire beet as substrate still is uncommon. More often the residues from sugar and fodder beet, leafs and tops, are fermented in closed silos and later used as substrates (Börjesson & Berglund 2005).

Residues from sugar and fodder beet processing, mainly tops and leaves, are organic by-products with high dry matter contents. This makes them attractive for the use as substrate in anaerobic digestion. Depending on the market price paid for the sugar and fodder beet residues, a part of the environmental impact arising from beet production has to be allocated to the beet residues.

The use as substrates with solid potato waste showed, that the biogas yield can be enhanced, when fodder beet leafs are digested together with other substrates (Parawira et al. 2008).

The specifications of sugar beets, fodder beets and beet residues that are used in this study are declared in Tab. 3.4.

Tab. 3.4 Specification of sugar beet, fodder beet, and beet residues, as well as of the production of biogas from these substrates

		Sugar Beet	**Fodder Beet**	Beet leaves	Beet leaves	**Beet residues**
		Institut für Energetik und Umwelt (2006)	**Institut für Energetik und Umwelt (2006)**	Institut für Energetik und Umwelt (2006)	Baserga (2000)	**This study**
Dry matter content	**%**	**23.0%**	**12.0%**	16.0%	16.5%	**16.3%**
Organic substance	**% DM**	**92.5%**	**80.0%**	82.5%	79.0%	**80.8%**
N-content	**% DM**	**2.6%**	**1.9%**	0.3%	-	**0.3%**
NH_4-content	**% DM**	**0.2%**	**0.4%**	-	-	**0.04%**
P-content	**% DM**	**0.4%**	**0.3%**	0.8%	-	**0.8%**
Biogas yield	**Nm^3 per t DM**	**760.8**	**729.1**	437.5	355.5	**396.5**
CH_4 content	**%**	**53.5%**	**53.5%**	54.5%	-	**54.5%**

3.1.3 Biogas from molasses

Molasses are a by-product of sugar production. They have high dry matter and sugar contents and therefore are suitable to increase the biogas yield of liquid biogas substrates. Like the other sugar beet residues, molasses are used as animal feed or in distilleries, which makes it rather rare for the use as substrate for anaerobic digestion (Institut für Energetik und Umwelt gGmbH 2006).

The specifications of molasses that are used in this study are declared in Tab. 3.5.

Tab. 3.5 Specification of molasses and of the production of biogas from this substrate

		Molasses	Molasses	**Molasses**
		Institut für Energetik und Umwelt (2006)	Baserga (2000)	**This study**
Dry matter content	**%**	85.0%	80.0%	**82.5%**
organic substance	**% DM**	87.5%	79.0%	**91.3%**
N	**% DM**	1.5%	-	**1.5%**
P	**% DM**	0.3%	-	**0.3%**
Biogas yield	**m3 per t DM**	370.6	427.5	**399.0**
CH_4 content	**%**	72.5%	-	**72.5%**

3.1.4 Biogas from glycerine

Glycerine for biogas production is mainly extracted in vegetable oil esterification plants, but it can also be produced by many other industries (petrochemical, soap by-product etc.). Glycerine is used with increasing popularity as a substrate and increases the biogas yield considerably. The use of glycerine as a mono-substrate in biogas fermentation has been investigated by Erb et al. (2008). In the questionnaires filled in by operators of agricultural biogas plants, three operators declare that they pay a price of between 200 and 220 CHF per ton of glycerine in 2008 and 2009 (Dauriat et al. 2011). In this study we investigate the use of glycerine made from rape oil and glycerine made from waste oil in the biogas production.

The specifications of glycerine that are used in this study are declared in Tab. 3.6.

Tab. 3.6 Specification of glycerine and of the production of biogas from this substrate (Erb et al. 2008; Institut für Energetik und Umwelt gGmbH 2006])

		Glycerine
Dry matter content	**%**	**97.2%**
organic substance	**% DM**	**93.6%**
N	**% DM**	**0.03%**
P	**% DM**	**0.003%**
Biogas yield	**m3 per t DM**	**1004.3**
CH_4 content	**%**	**50.0%**

3.1.5 Energy consumption

In order to evaluate typical conditions of the operation of agricultural biogas plants in Switzerland, a questionnaire was sent to biogas operators. Sixteen operators filled in the questionnaire.

About 61.7 % of the biogas from these biogas plants is produced with self-produced electricity and 38.3 % with purchased electricity. The heat used in the biogas plants is commonly generated onsite from burning biogas.

From the 16 filled in questionnaires we obtained the information that the electricity consumption of biogas production in an agricultural co-digestion plant e.g. for stirring the substrates amounts between 0.5 and 36.4 kWh per ton substrate with an average of 12.9 kWh/ton. The heat consumption of the biogas plants amounts between 16.7 and 356.4 MJ per ton substrate with an average of 187.7 MJ/ton. The average energy consumption per ton of substrates is applied in the inventories.

With regard to the energy consumption per m^3 of biogas, the average amounts to 0.158 kWh of electricity and 3.470 MJ heat per m^3 biogas.[1] (Dauriat et al. 2011)

3.1.6 Infrastructure

According to the questionnaires, 62.9 % of the biogas is produced in plants with digestate cover and 37.1 % in plants without digestate cover. We apply two different inventories for biogas plants with and without cover, respectively. The calculation of the infrastructure use per ton of handled substrate is shown in Tab. 3.7.

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[1] All information from this Section: Personal communication with Arnaud Dauriat from ENERS on 22.11. 2010

Tab. 3.7 Calculation of infrastructure use per ton of handled substrate in biogas plants (based on data from Jungbluth et al. (2007))

Uncovered biogas plant		
Capacity	m^3	300
Life time	years	20
Annual biogas production Co-substrate and manure mix	m^3/a	104000
Potential Biogas Production	m^3/t substrate	53.08
Annual substrate handling	tons/a	1959
Infrastructure requirement	m^3/t substrate	2.55E-05
Covered biogas plant		
Capacity	m^3	500
Life time	years	20
Annual biogas production	m^3/a	300000
Potential Biogas Production	m^3/t substrate	53.08
Annual substrate handling	tons/a	5652
Infrastructure requirement	m^3/t substrate	8.85E-06

3.1.7 Ammonia, dinitrogen monoxide, and methane emissions

From the filled in questionnaires we obtained the information that 62.9 % of the biogas is produced in plants with digestate cover and 37.1 % in plants without digestate cover. The LCI datasets described in this chapter refer to biogas production in a mix of biogas plants with and without digestate cover.

Ammonia emissions arise from the storage of digestates. According to Edelmann et al. (2001) because of the conventional storage and application of liquid manure, 50 % of the ammonium content is released as ammonia emissions. 1/6th of these emissions stem from the storage and 5/6th from the application resulting in emission factors of 8.3 % during storage and 41.7 % during and after application on fields.

Furthermore, Edelmann et al. (2001) explain that the conversion in a biogas plant leads to increased ammonia emissions due to an increased degradation of organically bound nitrogen in the fermenter and an increase of the pH value. Ammonia emissions are therefore increased by 40 % during storage and by 10 % during application. This leads total ammonia emission factors of 11.7 % of the ammonia content in the substrates during digestate storage and 45.8 % during digestate application on fields. With appropriate measures these emissions can be reduced. The emissions during storage are reduced by 80 % when digestates are covered.[2]

Dinitrogen monoxide emissions from digesting substrates amount to 0.1 kg /t according to Jungbluth et al. (2010). When digestates are covered, these emissions are reduced by 75 %.

According to Jungbluth et al. (2007) the methane emission factor amounts to 1 % in biogas plant with covered stock and to 5 % in biogas plants with uncovered stock. The emission factor of an average biogas plant is considered by applying the shares of biogas plants with and without digestate cover as described above and by considering the methane share of 63.3 % in the volume of the produced biogas.

3.2 Application of digested matter on agricultural land

After the production of biogas, the digested matter is usually spread as fertiliser on agricultural land. This requires vehicles and machinery for transport and spreading and it leads to ammonia emissions

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[2] www.nw.ch/dl.php/de/20060502101744/Ammoniak_NH3_Faktenblatt.pdf (access on 11.10.2011)

into air and heavy metal emissions into soil. In the standard case, the environmental impacts from the digestate application are allocated to the agricultural cultivation and not to the biogas production (see Subchapter 1.3). However, in a scenario we analyse the environmental impacts if the digestate application is allocated to the biogas production.

The filled in questionnaires show that solid digested matter is delivered over a distance between 1.5 km and 5 km with a weighted average distance of 3.0 km. Liquid digested matter is delivered over a distance between 0.5 km and 20 km with a weighted average distance of 10.5 km.

As described in Section 3.1.7, 45.8 % of the ammonia content in the substrate is released into air when applying the digestates on agricultural fields. New biogas plants in Switzerland often use trail hoses for spreading liquid digested matter, which reduces the ammonia emissions about 40 % according to Edelmann (2006). We assume in the application datasets that such trail hoses are used. Hence, the ammonia emissions per kg digested matter are calculated with the following procedure: First, the share of NH_4 available nitrogen in the dry matter content is multiplied with the dry matter content of the substrate input per m^3 biogas and the amount of nitrogen is converted into ammonia with the molecular weight of the two substances. This amount of ammonia is multiplied with the emission factor of 45.8 %. The resulting figure is divided by the amount of digested matter per m^3 biogas and the 40 % emission reduction due to the use of trail hoses is applied. The nitrogen and ammonium content of the substrates is presented in Tab. 3.8.

Tab. 3.8 Nitrogen and ammonium content in substrates

	Nitrogen content according to the Institut für Energetik und Umwelt (2006)	NH_4-content according to according to the Institut für Energetik und Umwelt (2006) and own estimations
	% TS	% TS
Maize silage	1.1-2	0.15-0.3
Sugar beets	2.6	0.2
Beet residues	0.2-0.4	0.04
Molasses	1.5	0.17

No dinitrogen monoxide emissions arise from the application of digestates, when using trail hoses (Jungbluth et al. 2010).

When digested matter is applied as fertiliser on agricultural land, the heavy metal content of the biogas substrates is emitted into the soil. In general, the heavy metal emissions from the digestates are calculated from the elemental composition of the substrates reported by the Institut für Energetik und Umwelt (2006). Missing data are completed with information from Freiermuth-Knuchel (2006).

3.3 Cogeneration of electricity and heat in agricultural biogas plants

In most agricultural biogas plants, biogas is burned in order to co-generate electricity and heat. The heat consumption in the biogas plants is usually met with the own heat generation whereas the electricity consumption is only partly met with own produced electricity and additional electricity from grid needs to be bought.

3.3.1 Emissions from combustion of biogas in agricultural co-generation units

Some older cogeneration units use pilot fuel, which leads to higher emission values. Newer types however use lean-burn engines with a SCR catalyst, which reduces the emissions considerably. Emission data for cogeneration unit of these newer technologies were updated and documented in

Jungbluth et al. (2010). For the update of the ecoinvent data on biogas combustion, these values are applied.

In previous inventories, the emission of biogas is mainly estimated based on data of natural gas furnaces. However, newer publications show that in biogas plants partly much higher emissions occur (Bayer. Landesamt für Umwelt (Hrsg.) 2006:62ff, Nielsen & Illerup 2003:33ff, Kath 2009:3). Therefore, these emission factors are applied in this study.

The Swiss Clean Air Act[3] regulates the exhaust emissions of biogas cogeneration units with limits of 50 mg particulate matter per Nm^3, 400 mg/Nm^3 of NO_x and 650 mg/Nm^3 of CO (related to 5 % residual oxygen). The amount of nitrous oxides fluctuates considerably depending on the biogas quality (methane content). A typical 100 kW_{el} cogeneration unit with ignition engine emits about 1’100 mg/Nm^3 NO_x and 800 mg/Nm^3 CO (Ruch 2005).

In a research project a catalyst with SCR basis was developed which balances all fluctuations in the exhaust emissions from cogeneration units in biogas plants. This catalyst enables operators of cogeneration units to smoothly comply with the limits of the Clean Air Act (Ruch 2005).

In contrast to cogeneration units with very high emission factors, there are also cogeneration units available with much lower emissions which even fall below the limits in the canton Zurich of 50 mg NOx/Nm^3 and 150 mg CO/Nm^3.

Currently, no cogeneration units with catalysts are known in Switzerland. Normally, lean burn engines are used, which comply with the Clean Air Act limit of 400 mg/Nm^3. Considerably higher can be the emissions from ignition gas engines which are typically used in Germany and in which 5 to 10 % of diesel is co-burnt. With these engines it is difficult to comply with the Swiss limits (median of measurements at 450 mg/Nm^3). Therefore such ignition gas engines are a phased-out model. As far as it is known to the authors, since the last few years only lean burn engines were installed in Switzerland. Gas motors like all type of furnaces have to be checked regularly with regard to compliance with the exhaust emission limits in the Clean Air Act. (Jungbluth et al. 2010)

Within the survey about Swiss operators of biogas plants that was conducted in this project, 87.5 % of the operators declared that they installed biogas engines in their biogas plants. Only two operators use ignition engines, one with diesel and one with biodiesel. The operators declare their nitrous oxide emissions as between 300 and 900 mg/Nm3 with an average at 470 mg/Nm3 which is considerably higher than the 15 mg/Nm3 estimated by Jungbluth et al. (2007) based on natural gas furnaces. The average nitrous oxide emissions from the survey are used for the dataset of the combustion of biogas in a biogas engine.

3.3.2 Cogeneration of electricity and heat

The range of capacities and the efficiency of the cogeneration units with biogas engines considered in the survey within this project is displayed and compared to the data used in Jungbluth et al. (2007) in Tab. 3.9. The average electric and thermal efficiency from the survey is considered in order to establish datasets of the cogeneration of electricity and heat with biogas from specific substrates.

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[3] Luftreinhalteverordnung (LRV)

Tab. 3.9 Selected results of the survey of 16 Swiss operators compared to the data implemented by Jungbluth et al. (2007)

		Survey of 16 Swiss biogas operators (2010)			
		minimum	maximum	This study (average)	Jungbluth et al. (2007)
capacity	**kW**	15	250	118.6	160
electric efficiency	**%**	25%	39%	35.4%	32%
thermal efficiency	**%**	45%	64%	51.0%	55%
nitrous oxide emissions	**mg/Nm^3**	300	900	470.0	15

The inventory of the cogeneration of heat and electricity encompasses the infrastructure, the operation of the engine (including auxiliary materials and emissions into air), and the specific type of used biogas. The allocation of the emissions and the shared infrastructure elements to the two products heat and electricity is based on exergy content. The exergy value of electricity is 1 and the exergy value of heat is 0.17. The multiplication of the exergy value with the heat and electricity outputs per MJ biogas input leads to an allocation of 80 % to the electricity generation and 20 % to the heat generation.

3.4 Grass refinery

The grass refinery of the Biowert Industrie GmbH. produces insulation material (AgriCell), organic fertiliser (AgriFer) and biopolymers (AgriPlast) from grass silage as raw material. The grass silage is stored in a silo and later fed in a disintegration process. After the disintegration process, the grass fibres are used for AgriCell and AgriPlast production. Grass slurry is a by-product of the grass disintegration. Together with cow slurry it is used as a substrate in the biogas production. All parts of the biogas plant are covered. This leads to considerably lower emission values compared to uncovered biogas plants. In a proxy, the allocation factor is set to 90% for biogas and 10% for the digestate.

The biogas is burned in a cogeneration unit, which generates heat and electricity used for the different production processes or could be sold as grid electricity. The allocation of the environmental impact to heat and electricity is carried out according to the allocation factor used in the ecoinvent data set (exergy content).

In order to utilize digestate from the anaerobic digestion, the organic matter content is concentrated in a reversed osmosis. The products of this process can be used as organic fertilizers (AgriFer) on the grass fields. The nutrient content of the AgriFer products is shown in Tab. 3.10.

Tab. 3.10 Nutrient contents of AgriFer fertiliser products (Bundesgütegemeinschaft Kompost E.V. 2008)

AgriFer	Unit	Liquid	Solid
Density	g/l	1.039	0.757
Dry matter content	%	0.0402	0.28
N content	%DM	0.283	0.0391
P_2O_5 content	%DM	0.0118	0.0313
K_2O content	%DM	0.1582	0.0089
MgO content	%DM	0.001	0.0146
N per m^3	kg/m^3	11.7	8.25
N per kg	kg/kg	0.0113	0.0109
P_2O_5 per m^3	kg/m^3	0.42	6.59
P_2O_5 per kg	kg/kg	0.0004	0.0087
K_2O per m^3	kg/m^3	6.55	1.82
K_2O per kg	kg/kg	0.0063	0.0024
Amount AgriFer	m^3	17	
Amount AgriFer	kg		3714.29
N input	kg	198.9	40.49
P_2O_5 input	kg	7.14	32.31
K_2O input	kg	111.35	8.91

The production process as described above creates two options for closed loop resource management. Firstly, the electricity produced in the cogeneration unit could be used meet the electricity demand of the production process. Secondly, the fertiliser AgriFer can be used in the grass cultivation. We investigate two scenarios; one scenario meeting the fertilizer and electricity requirement in the grass refinery system with electricity and AgriFer produced in the refinery, and one scenario meeting those requirements with purchased products (mineral fertiliser, electricity from grid).

This Chapter is based on an LCA study of the Biowert grass refinery prepared by Leuenberger & Jungbluth (2010).

Tab. 3.11 Parameters used for the biogas production from grass

Input		Value	Source
Input grass slurry	m^3/a	27500	Questionnaire Biowert
Input cow slurry	m^3/a	10000	Questionnaire Biowert
Input bio waste	t/a	15000	Questionnaire Biowert
Electricity from cogen grass refinery	kWh/a	4.20E+05	Questionnaire Biowert
Heat from cogen grass refinery	MJ/a	9.25E+06	Questionnaire Biowert
Life expectancy biogas plant	a	20	
Annual yield			
Digestate	m^3/a	42000	
AgriFer solid	t/a	1300	Estimation Biowert:
AgriFer liquid	m^3/a	10000	Estimation Biowert:22.5% of digestion residues
Process water at decanter	m^3/a	27500	
Biogas	m^3	4600000	Questionnaire Biowert
Emissions			
CO_2	kg/m^3	6.62E-03	Calculated; 1% of CO2 in biogas emitted from covered stock
NH_3	kg/m^3	4.06E-04	Calculated; 80% of emission reduction due to stock cover
N_2O	kg/m^3	2.85E-04	Calculated; 75% of emission reduction due to stock cover
Heat waste	MJ/m^3	3.29E-01	Calculated from electricity use
CH_4	kg/m^3	4.54E-03	Calculated; 1% of methane in biogas emitted from covered stock
H_2S	kg/m^3	1.55E-03	Calculated with 0.7g H2S/kg DM

3.5 Biogas purification, distribution and use as fuel

The inventories of biogas purification, distribution and combustion in passenger cars are modelled in order to enable a comparison of methane from different biogas substrates with liquid biofuels that are for example presented by Zah et al. (2007).

Due to the fact that operators of biogas plants burn biogas in cogeneration units in order to supply the anaerobic digestion unit with heat and electricity, only the amount of biogas that is not required for covering the digestion unit's heat demand can be purified to biomethane. In this calculation, the heat consumption of the digestion unit is the limiting factor, since the entire heat demand is met with the production of the cogeneration unit in contrast to electricity that is not only consumed from the cogeneration unit but also from grid. Tab. 3.12 shows the maximum share of biogas from different substrates available for purification.

Tab. 3.12: Maximum share of biogas available for purification after subtraction of the amount of biogas required for producing the heat required in the anaerobic digestion unit

	Maize silage	Sugar beet	Fodder beet	Beet residues	Molasses	Glycerine
Minimum share of biogas required in cogeneration unit	10.4%	11.0%	17.5%	31.6%	4.9%	2.1%
Maximum share of biogas available for purification	89.6%	89.0%	82.5%	68.4%	95.1%	97.9%

Fig. 3.1 shows an energy and mass flow chart for the example of biogas from maize silage with the assumption that only the biogas amount required for providing the heat consumption of the biogas plant is sent to a cogeneration unit and the remaining amount of biogas is purified to biomethane for the natural gas grid. Alternatively, operators of biogas plants could also generate all their consumed electricity by burning biogas in a cogeneration unit, they could burn all produced biogas in a cogeneration

unit and send no biogas for purification, or they could send all biogas to a purification plant and meet their energy demand with electricity from grid and heat from other sources. Depending on the decision of the biogas usage, different datasets have to be considered for the electricity and heat input in the biogas plant. Nevertheless, since the consumption of electricity and heat has a relatively small share in the total environmental impacts of biogas (less than 10 %), this decision is not very important for the LCA results.

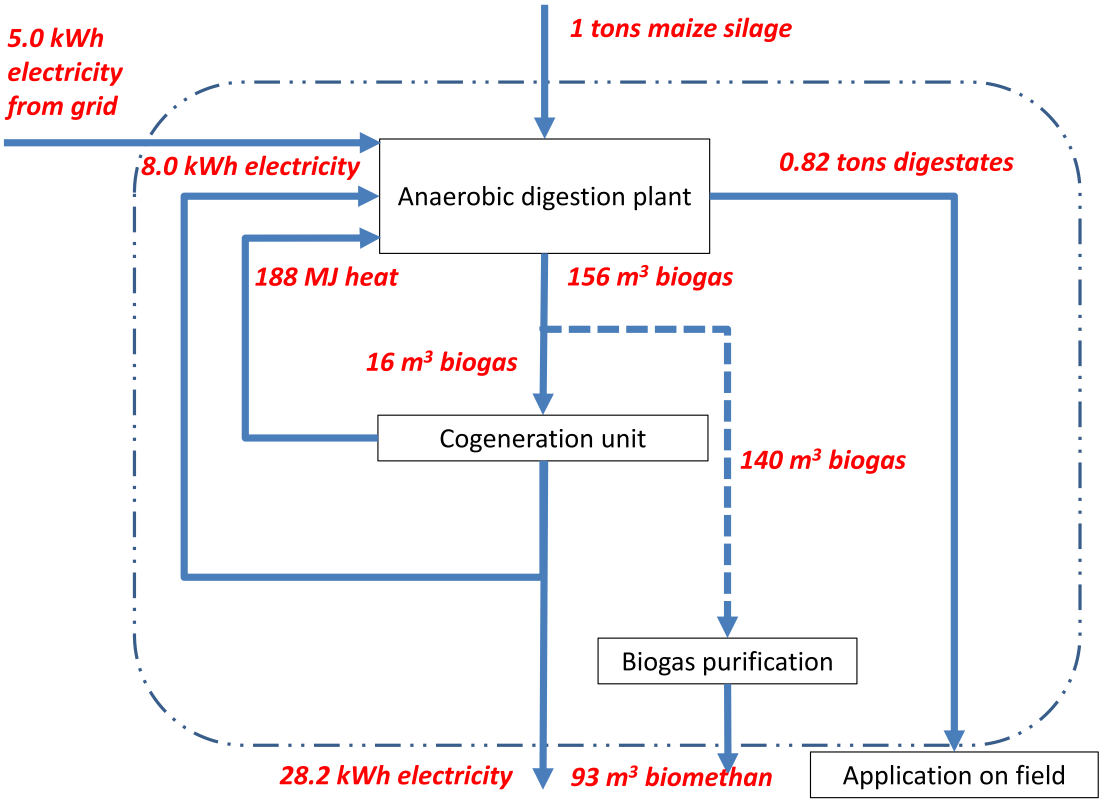

Fig. 3.1 **Energy and mass flow chart of the biogas production from maize silage, the purification to biomethane and the generation of heat and electricity in a biogas co-generation unit**

3.5.1 Biogas mix for purification

Most operators of biogas plants in Switzerland burn all produced biogas in a cogeneration unit in order to produce heat and electricity. In the year 2010, only 13 operators purified their biogas to biomethane that was fed into the natural gas grid or sold in a pumping station. Based on these operators, we created the biogas mix in Tab. 3.13 with information about their substrates and their production capacities (see Tab. 3.15 on page 29).

Tab. 3.13: Unit process raw data of the biogas mix for purification in Switzerland

	Name	Location	InfrastructurePr	Unit	biogas, production mix, at storage, Update	UncertaintyType	StandardDeviati on95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	biogas, production mix, at storage, Update	CH	0	Nm3	1			
shares	biogas, from biowaste, at storage	CH	0	Nm3	55%	1	1.24	(3,1,1,1,1,5,BU:1.05); 7 operators in Switzerland
	biogas, from sewage sludge, at storage	CH	0	Nm3	34%	1	1.24	(3,1,1,1,1,5,BU:1.05); 5 operators in Switzerland
	biogas, mix, at agricultural co-fermentation, covered	CH	0	Nm3	12%	1	1.24	(3,1,1,1,1,5,BU:1.05); 1 operator in Switzerland

3.5.2 Purification technologies

In Switzerland, biogas is purified with three different technologies: pressure swing adsorption (PSA), glycol washing, and amino washing. Fig. 1.1 shows the unit process raw data of these technologies excluding the biogas input.

Amino washing

Up to date information about a purification plant using amino washing and operating in Switzerland are available from EMPA (2009). The amount of electricity and heat consumed, as well as the amount of amine (monoethanolamine) and tap water used for the washing, and the amount of activated carbon (charcoal) and thermal oil (lubricating oil) for desulphurisation is taken from this publication. The amount of used tap water is treated as sewage in a wastewater treatment plant. The amine is considered to be disposed in a hazardous waste incineration after use. Several publications report that less than 0.1 % of the methane content in the raw biogas is emitted into air in the amino washing process (EMPA 2009; Urban et al. 2009).

Glycol washing

Glycol washing is used in biogas plants in Romanshorn, Bischofszell, and Pratteln (see Fig. 3.2). The average specific electricity consumption of two operators in Switzerland is 0.81 kWh per Nm^3 biomethane which is significantly higher than what can be derived from literature sources.

The washing agent used in the glycol washing process is a mixture of dimethyl ether and polyethylene glycol. The density of the washing agent varies between different formulations, but is around 1 kg/l (Clariant 2002). In the Biogas plant Pratteln, 110 litre of washing agent were refilled in 2010.[4] In relation to the biomethane production of 626'885 m^3 in the same year, this results in a washing agent consumption of 0.18 g/m^3. Since no specific information of the detailed composition of washing agent is available, it is assumed that the two components each have a share of 50 %. It is assumed that the washing agent is disposed in a hazardous waste incineration after its end of life. According to Urban et al. (2009), 1 % of the methane content in the raw gas is emitted into air. We apply an emission factor of 2.6 % of the methane content in the raw gas, calculated from up to date information from a Swiss operator.[5]

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[4] Biopower-Anlage Pratteln, Biogasaufbereitung, Betriebskennzahlen Jahr 2010, personal information from Mike Keller from the Biopower Nordwestschweiz AG, on 21.02.2011.

[5] ARA Region Romanshorn Biogasaufbereitung - Energieflussdiagramm 2010, personal information from Heinz Greuter from Erdgas Romanshorn, on 31.01.2011.

Fig. 3.2 **Installation for biogas purification using glycol washing at the biogas plant in Pratteln (Source: Keller, Biopower Nordwestschweiz AG)**

PSA

The most common technology of biogas purification in Switzerland is pressure swing adsorption (PSA). Urban et al. (2009) report an electricity consumption of the PSA process of 0.22 kWh per m^2 raw biogas. Schulte-Schulze (2006) mentions an electricity consumption of 0.25 kWh per m^2 raw biogas. We apply a value of 0.23 kWh per m^2 raw biogas, which results in 0.35 kWh per m^2 purified biomethane. A detailed study published by Baier et al. (2008) analysed the methane emissions of a PSA plant in Switzerland and revealed that 2.6 % of the methane content in the raw biogas are emitted into air during the purification process.

3.5.3 General assumptions

Since, the amino washing process and the PSA process also require a desulphurisation step, the same amount of activated carbon and lubricating oil is taken into account as in the amino washing process.

The generic value of infrastructure facilities is taken from Jungbluth et al. (2007).

The compositions of raw biogas, waste gas and biomethane from PSA is obtained from Jungbluth et al. (2007). The hydrogen sulphide content in the biomethane from PSA is adjusted to 0.0003 % as declared by Rütgers (general) cited in Jungbluth et al. (2007). And the composition of biomethane from amino and glycol washing is calculated from composition of biomethane from PSA and the higher methane share as reported by Urban et al. (2009).

The amount of waste heat is calculated from the energy consumption. The carbon dioxide emissions are calculated from the carbon dioxide input in the raw biogas (1.5 m^3 biogas/m^3 biomethane; 33.5 vol% carbon dioxide share) and the carbon dioxide output in the purified biomethane (0.5 vol% - 2 vol%). The methane emissions are calculated by applying the methane emission factors from literature on the methane input from the raw biogas. Hydrogen sulphide emissions are calculated from the H_2S content in the waste gas reported by in Jungbluth et al. (2007) and 0.5 m^3 waste gas per m^3 purified gas. We assume that the retained sulphur dioxide is oxidised to sulphur dioxide and emitted into air. The amount of sulphur dioxide is calculated from the difference between the hydrogen sulphide input from raw biogas and hydrogen sulphide output in the purified biomethane and the waste gas.

Tab. 3.14: Average composition of raw biogas, waste gas, and biomethane from different purification technologies

Component	Raw biogas	Waste gas	Biomethane		
			from amino washing	from glycol washing	from PSA
Methane	63.30%	6%	99%	97%	96%
Carbon dioxide	33.50%	91%	0.5%	1.5%	2%
Nitrogen	3.2%	3%	0.3%	0.8%	1%
Hydrogen sulphide	0.0005%	0.0004%	0.0001%	0.0002%	0.0003%

3.5.4 Purification technologies in Switzerland

The biogas purification facilities that were operating in Switzerland in 2009 are listed in Tab. 3.15. We estimated their production capacity based on data from the IEA Bioenergy Task 37[6] and information about the individual plants available on the internet. Two operators feed their biomethane in a filling station for vehicles whereas the other operators feed their biomethane into the natural gas grid. The purification plant in Bischofszell is not operating any more in the year 2011.

Tab. 3.15: Biogas purification facilities in Switzerland

	location	substrate	year of installation	plant capacity in 2010	methane use
				m3/h	
pressure swing adsorption	Rümlang	greenery, waste food, etc.	1998	30	Filling station
	Otelfingen	greenery, waste food, etc.	1998	50	Filling station
	Samstagern	greenery, waste food, etc.	1997	50	Natural gas grid
	Emmen	sewage sludge	2005	75	Natural gas grid
	Widnau	manure, vegetables, greenery, waste food etc.	2007	200	Natural gas grid
	Bern	sewage sludge	2008	300	Natural gas grid
	Utzenstorf	biowaste	2009	150	Natural gas grid
	Lavigny	biowaste	2008	120	Natural gas grid
amino washing	Obermeilen	sewage sludge	2008	60	Natural gas grid
	Volketswil	biowaste	2010	250	Natural gas grid
glycol washing	Pratteln	greenery, waste food, etc.	2006	300	Natural gas grid
	Bischofszell	*sewage sludge*	*2007*	*120*	*Natural gas grid*
	Romanshorn	sewage sludge	2007	30	Natural gas grid

Based on Tab. 3.15, we calculated the capacity weighted shares of 56 % biogas purified using pressure swing adsorption, 18 % using amino washing, and 26 % using glycol washing. According to Jungbluth et al. (2007), 1.5 m^3 of biogas is required in order to produce 1 m^3 of purified biomethane. In this study we calculate with a methane content of 63.3 % in the raw biogas and a minimum methane content of 96.0 % in the purified biomethane. Therefore, 1.52 m^3 biogas is required for 1 m^3 of purified biomethane.

3.5.5 Distribution and combustion in passenger car

The unit process data of the biomethane distribution and the passenger car transportation with a biogas-operated vehicle are considered with ecoinvent datasets described by Jungbluth et al. (2007) without any modifications.

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[6] Personal information from Arthur Wellinger from Nova Energie on 31.01.2011

3.6 Comparison between biogas modelled in this study and in ecoinvent v2.2

The major differences between the biogas modelling in this study and the biogas datasets in ecoinvent v2.2 are listed in Tab. 3.16. If one compares the new datasets from this study with the biogas datasets in ecoinvent, these differences should be considered.

Tab. 3.16 Comparison between biogas modelled in this study and in ecoinvent v2.2 (Jungbluth et al. 2007)

	This study	ecoinvent v2.2
Heat consumption	100% from biogas	Sewage: from natural gas Others: from biogas
Electricity consumption	62% from biogas 38% from grid	Agricultural: 50-60% from biogas, 0-50% from grid Biowaste/whey: 100% from biogas
Substrates	Production of substrates (energy crops) included	Production of substrates not included because of cut-off approach for wastes
Digested matter	Application on agricultural land not included (only included in a scenario)	Application on agricultural land not included
Methane emissions	62.9% (with digestate cover) * 1% + 37.1% (without cover) * 5%	With digestate cover: 1% Without cover: 5%
Ammonia emissions	See Section 3.1.7	Different calculation approach
Dinitrogen monoxide emissions	62.9% (with digestate cover) * 25 mg N_2O/kg substrate + 37.1% (without cover) * 100 mg N_2O/kg substrate	Proportional to ammonia emissions
Biogas combustion in cogeneration unit	166 mg NO_x/MJ_{in} 102 mg CH_4/MJ_{in}	15 mg NO_x/MJ_{in} 23 mg CH_4/MJ_{in}
Biogas purification	56 % pressure swing adsorption technology, 26 % glycol washing technology, and 18 % amino washing technology	100% Pressure swing adsorption technology

4 Life cycle impact assessment

Zah et al. (2007) and Jungbluth et al. (2008) compared the environmental impacts of several biofuels with using fossil fuels in conventional cars. The authors used two single score impact assessment methods for their evaluation, namely the Eco-indicator 99 (H,A)(Goedkoop & Spriensma 2000) and the Ecological Scarcity 2006 Method (Frischknecht et al. 2009) as well as the cumulative non-renewable energy use (Frischknecht et al. 2007) and the global warming potential (IPCC 2007). In order to make the results of this study comparable with those from Zah et al. (2007) and Jungbluth et al. (2008), the same life cycle impact assessment methods are applied.

The Swiss regulation on LCA of fuels describes the requirements for biofuels in order to get a tax reduction. The life cycle greenhouse gas emissions and the total environmental impacts of the use of such biofuels, shall be lower than 60 % and 125 % of that of the use of conventional fuels respectively (TrÖbiV 2009). We evaluate to what extend the use of energy crops in co-digestion influences the compliance with this regulation.

The transportation with biogas modelled in this study is compared to transportation datasets using biogas and conventional fuels from the ecoinvent v2.2 database (ecoinvent Centre 2010) combined with the updated inventories of biogas purification. When comparing the new datasets from this study with the biogas datasets in ecoinvent, the modelling differences in Tab. 3.16 on page 30 should be considered. In order to seek consistency, the purification of biogas is considered with the new datasets from this study for all types of biogas (ecoinvent v2.2 datasets and new biogas datasets).

For the biogas from the grass refinery, two scenarios are shown. The first scenario represents the model where mineral fertiliser is used for the grass cultivation and electricity from grid is purchased for the operation of the grass refinery. The second scenario, marked in the figures with a star (*), represents the model where the produced AgriFer fertilizer is used for the grass cultivation and the electricity generated from biogas is used for the operation of the grass refinery.

4.1 Car transportation using biogas

4.1.1 Cumulative energy demand

Fig. 4.1 shows the renewable and non-renewable energy consumption of passenger transportation with an average load of 1.6 passengers, fuelled with biogas and conventional fossil fuels. The transport service with one of the new inventoried biogas substrates results in a cumulative non-renewable energy demand per passenger kilometre between 1.5 MJ-eq. (grass in grass refinery) and 2.1 MJ-eq. (rape oil glycerine), the one of the compared biogas substrates from ecoinvent v2.2 amounts to between 1.4 MJ-eq. (fat and oil) and 1.9 MJ-eq. (sewage sludge) compared to the transportation with conventional fuels which requires an amount of between 3.0 MJ-eq. (diesel) and 3.3 MJ-eq. (petrol) of non-renewable energy per passenger kilometre.

Compared to conventional fuels, fuelling a vehicle with biogas requires more nuclear energy in all cases due to the electricity consumption in the biogas production process and the biogas purification process. About 0.3 MJ-eq./pkm is required for the operation and maintenance of the road infrastructure independent from the type of fuel used. The total consumption of non-renewable energy is considerably higher when using conventional fuels, since these fuels are based on fossil resources. Compared to driving a car with petrol, using biogas can reduce the consumption of non-renewable energy resources between 37% (rape oil glycerine) and 59 % (fat and oil).

If the total energy demand including renewable energy is considered, using biogas from energy crops leads to higher results than using conventional fuels, because of the solar energy uptake during the growth of the biomass substrate.

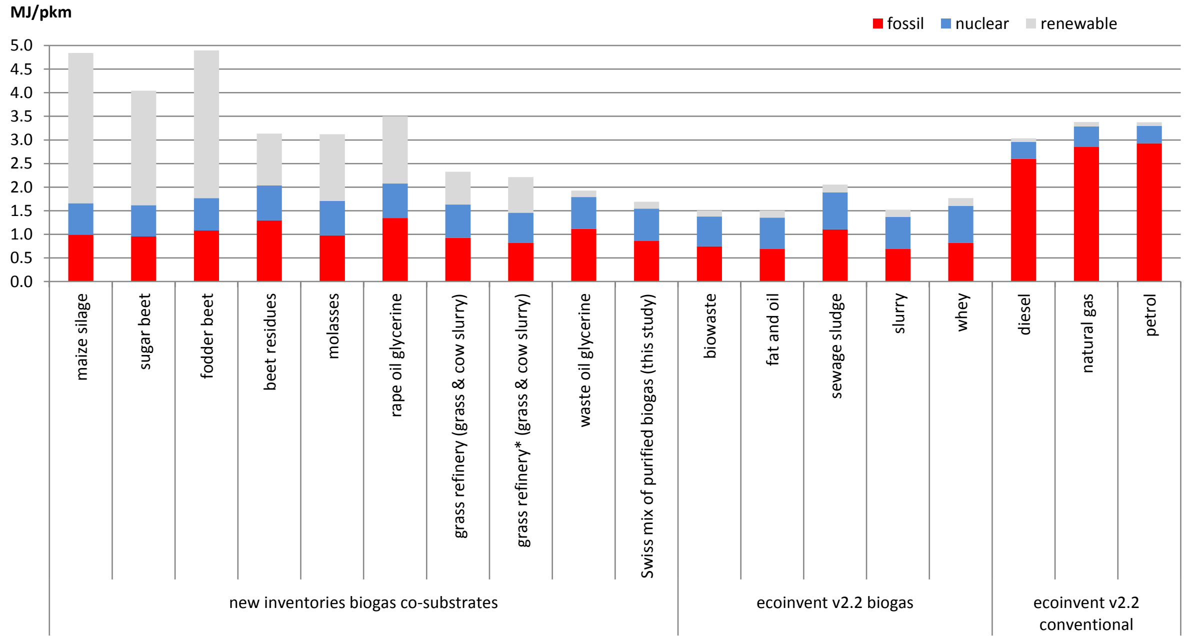

Fig. 4.1 **Renewable and non-renewable cumulative energy demand (Frischknecht et al. 2007) of the transport service (MJ-eq/pkm) with an average load of 1.6 passengers**

4.1.2 Greenhouse gases

In Fig. 4.2, the carbon footprint of passenger transport with biogas from different substrates and with conventional fuels is displayed. The carbon footprint of the transport service with biogas from the new established inventories amounts to between 95 gCO_2-eq./pkm (biogas from grass refinery) and 163 gCO_2-eq./pkm (beet residues). Biogas from substrates with the highest carbon footprint is comparable with natural gas fuels whereas those biogas types with the lowest carbon footprint enable a reduction of 54 % of greenhouse gas emissions compared to transportation with a petrol fuelled passenger car. Most biogas types analysed in this study do not comply with the thresholds for a tax reduction.

The carbon footprint of transportation with conventional fuels is strongly dominated by the carbon dioxide emissions during the car operation, whereas biogenic methane emissions during the biogas production and purification as well as the dinitrogen monoxide emissions during the substrate cultivation have major shares in the carbon footprint of a transport service with biogas fuels. However, it needs to be considered that methane leakage rates can differ significantly between individual biogas plants.

Using biogas from beet residues has the highest emissions within the different biogas types, which is because of the low methane yield of this substrate, which results in a larger volume of beet residues that is required to produce one m^3 of biogas. The production of this amount of substrate, but also its transportation and the electricity and heat consumption for its handling in the biogas plant, results in higher greenhouse gas emissions compared to biogas from other substrates.

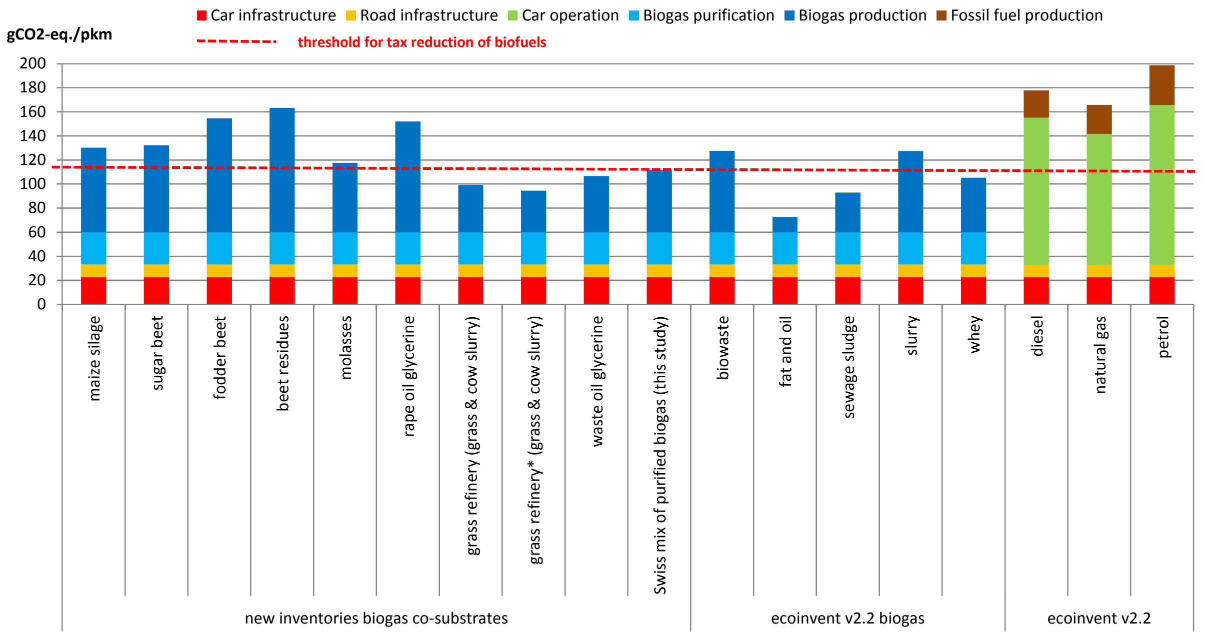

Fig. 4.2 **Global warming potential over a time horizon of 100 years (IPCC 2007) of transport services (g CO2-eq per pkm) with an average load of 1.6 passengers**

4.1.3 Ecological Scarcity 2006

The environmental impacts assessed with the Ecological Scarcity Method (2006) are presented in Fig. 4.3 und Fig. 4.4. The results show a similar result as the assessment with Eco-indicator 99 shown in Fig. 4.6.

The highest environmental impacts stem from biogas produced from whey, rape oil glycerine, and fodder beets. If those substrates are used in biogas plants, the total life cycle environmental impacts of the produced biogas are increased and a tax reduction might not be achieved.

All other substrates considered would comply with threshold for a tax reduction of biofuels in Switzerland. The use of molasses or energy crops such as sugar beets, beet residues, and maize silage can achieve the requirement for a tax reduction depending on the individual circumstances of the agricultural cultivation and the biogas plant. Using biogas from maize silage and molasses has about the same amount of environmental impacts as using conventional petrol.

Car driving with biogas from a grass refinery or from waste products such as vegetable waste oil (glycerine), biowaste, fat and oil, sewage sludge, and slurry can easily achieve the total environmental impact requirements for a tax reduction. Driving with the current Swiss mix of purified biomethane has lower environmental impacts than driving with a petrol fuelled car, since the current biomethane mix uses only waste substrates (biowaste, sewage sludge, and slurry) for the production of biogas. Nevertheless, the total environmental impacts of using biogas from these substrates are comparable to the total environmental impacts of using conventional diesel or natural gas. Consequently, the potential of reducing environmental impacts by driving with biogas is about the same as the one by driving with diesel or natural gas.

In the case of driving a car with biogas from maize silage, sugar beet, or molasses, the assessment results in an environmental credit due to the plant uptake of heavy metals during the agricultural cultivation of the substrates. However, the reader should keep in mind that producing biogas from agricultural substrates does usually not remove heavy metals from nature. The environmental impacts from returning the heavy metals to soil when applying digestates on agricultural land can just be allocated to another product (the plant grown on the fertilised field) and therefore be considered as outside of the system boundary.

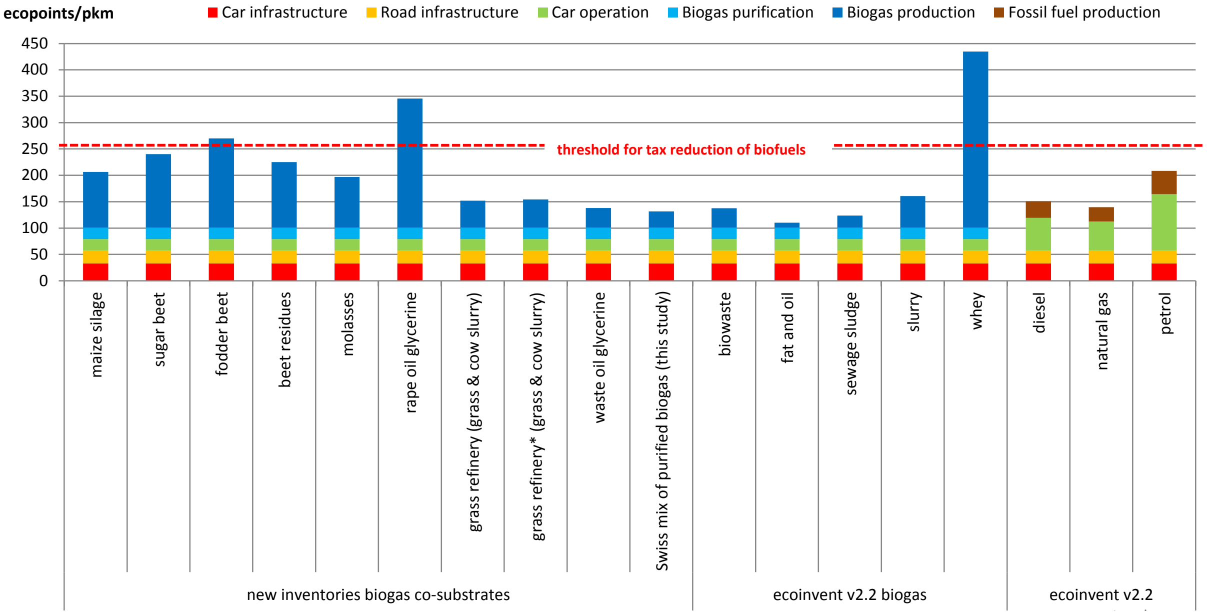

Fig. 4.3 **Ecological scarcity (2006) score of the transport service (points/pkm) excluding environmental impacts due to application of digestates on agricultural land.**

The total environmental impacts of driving with conventional fuels are dominated by emissions to air with effects on climate change and human health. Even though being smaller in the case of driving with biogas, the same two categories are also important for biogas. Furthermore, the total environmental impacts of using biogas from energy crops are determined by fresh water eutrophication caused by agricultural emissions from fertilizer application during the crop cultivation.

The high result of using biogas from whey digestion is driven by the phosphate, nitrate, and ammonium emissions from the treatment of the whey wastewater.

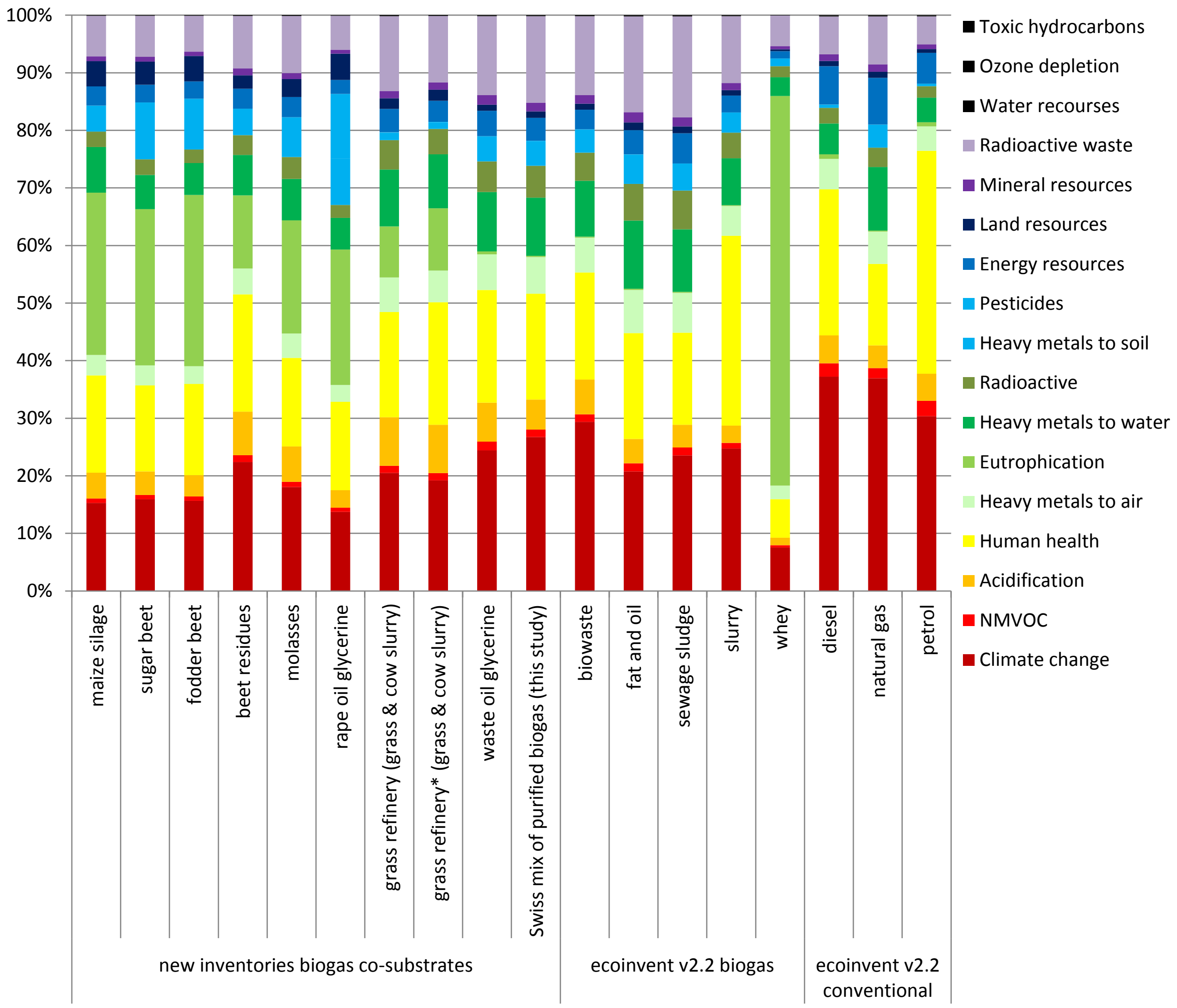

Fig. 4.4 **Contribution of different environmental impacts to the Ecological scarcity (2006) score of transport service with different fuels scaled to 100 %. The contribution of toxic hydrocarbons, ozone depletion, and water recourses is too small to be obvious from this figure.**

In a scenario we calculated the total environmental impacts if the application of the digested matter on agricultural land is allocated to the biogas production instead of the crop cultivation. Fig. 4.5 shows the environmental impacts assessed with the ecological scarcity method (2006) when including the environmental impacts from the digestate application. When allocating the digestates and their use in agriculture to the biogas production, the overall environmental impacts from transport services using biogas substrates are significantly increased (up to 45 % in case of fodder beets and beet residues). With this approach, beside biogas from rape oil glycerine, also biogas from sugar beets, fodder beets, and beet residues does not comply with the requirements for a tax reduction. The total environmental impacts of biogas from maize silage and molasses are close to the threshold for a tax reduction.

It has to be considered that if digested matter from biogas plants is used as fertilizer in the cultivation of energy crops (e.g. used as substrates for biogas production) the use of conventional fertilizers can be reduced.

As the two scenarios show quite different results it will be very important to consider the most appropriate modelling of fertilizer application for a final judgment. It has to be known if the energy crops used in the biogas plants are fertilized by the digestate from the plant and how much of conventional fertilizers can be saved by applying the digestates. So far the data in this study did not take into account such an integrated production.

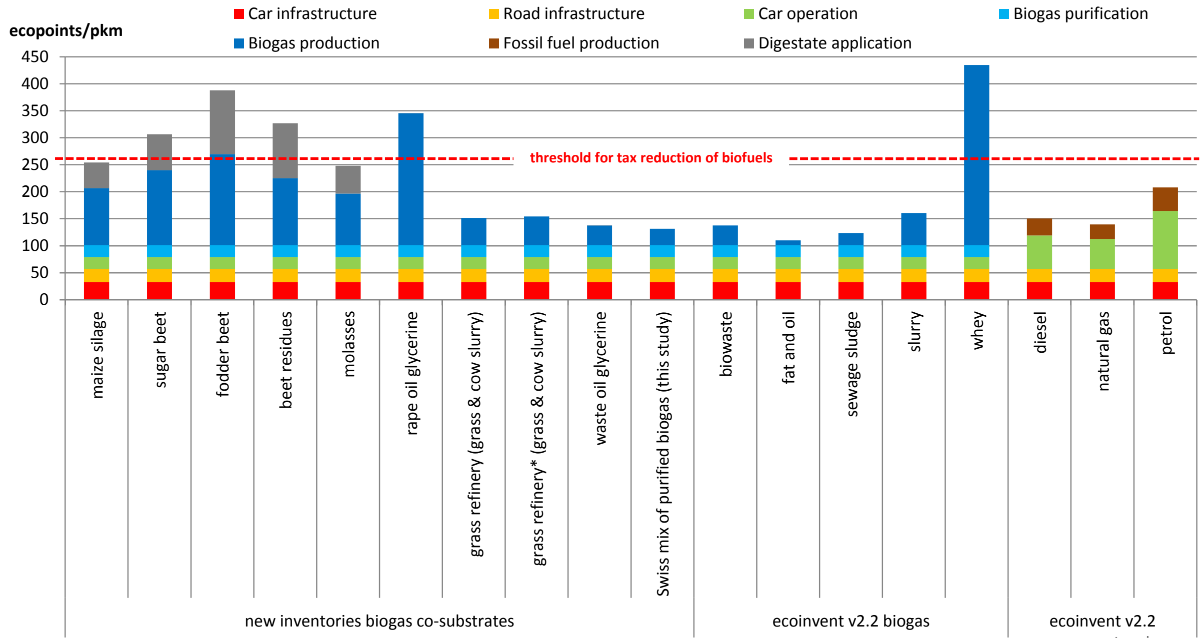

Fig. 4.5 **Ecological scarcity (2006) score of the transport service (points/pkm) with an average load of 1.6 passengers. This scenario includes environmental impacts due to application of digestates on agricultural land (see grey bar).**

4.1.4 Eco-indicator 99

Fig. 4.6 presents the overall environmental impacts of passenger transport assessed with the Eco-indicator 99 (H,A) method. In contrast to driving with biogas described by existing ecoinvent v2.2 datasets which all have a considerably lower environmental impact compared to driving with conventional fuels, driving with biogas from substrates evaluated in this study has considerably higher environmental impacts than conventional fuels. The reason for this difference is the fact that the analysed biogas inventories from ecoinvent are based on waste products whereas most of the substrates in the new established biogas inventories have an economic value and are not waste products. In contrast to waste substrates, non-waste substrates bear environmental burdens from their production which cover e.g. agricultural plant cultivation. The cultivation of silage maize, sugar beet, fodder beet, and rape seeds requires agricultural land and the use of agricultural appliances which has a strong influence on the environmental impacts of the transport service. If such energy crops are used in cogeneration, the environmental impacts are higher compared to using only waste products, and depending on the share of substrates from energy crops, the biogas might not comply with the requirement for a tax reduction.

The reason for the low environmental impacts of using biogas from waste oil glycerine is the fact that the basis for the glycerine is a waste product which does not bear any environmental burdens. The low environmental impacts of biogas from grass in a grass refinery can be explained with the fact that the environmental impacts from the grass cultivation and processing are allocated to the different products of the biogas refinery. In consequence, biogas from grass bears only a small share of the overall environmental impacts from the grass refinery.

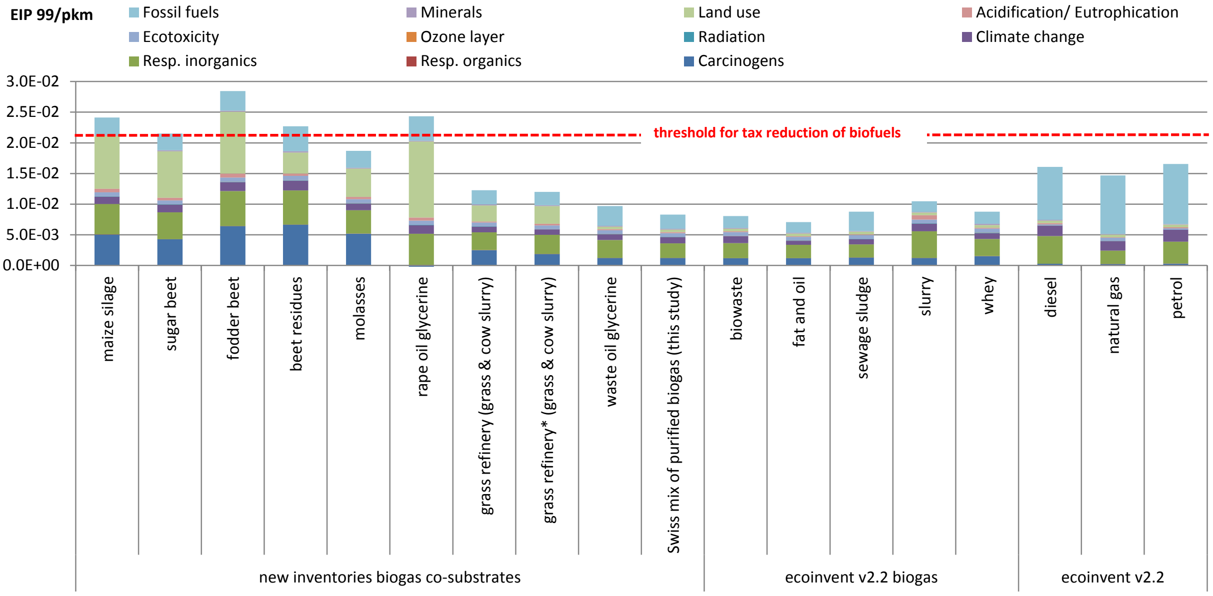

Fig. 4.6 **Eco-indicator 99 (H,A) score of the transport service with an average load of 1.6 passengers**

4.1.5 Yield and impacts per hectare

In addition to the environmental impacts per passenger kilometre, we also present two dimensional diagrams showing the kilometric performance and the greenhouse gas emissions and total environmental impact, respectively, per hectare of energy crop, cultivated. In these charts only the results of biogas from energy crops are displayed, since a presentation of agricultural land use and non-agricultural biogas substrates would not meaningful.

In Fig. 4.7, passenger car transportation using biogas produced from energy crops that are analysed in this study, is compared to passenger car transportation using plant methyl ester, ethanol or biomass-to-liquid fuels that were analysed by Jungbluth et al. (2008) and Zah et al. (2007). It is shown that the greenhouse gas emissions and the kilometric performance of car transportation using biogas are in the same order of magnitude as compared to using liquid biofuels. However, the kilometric performance using biogas is higher as compared to using liquid biofuels with exception of palm oil methyl ester and ethanol from sugar beets and also the greenhouse gas emissions of using biogas from one hectare is higher compared to using liquid biofuels from most energy crops cultivated on the same area. Overall, the higher kilometric performance does not outweigh the higher greenhouse gas emissions and therefore from a climate point of view, using energy crops for biogas cultivation is less favourable than using energy crops for the production of liquid biofuels. The reason for the higher greenhouse gas emissions of biogas fuels is mainly the leakage of methane in the biogas plant and during the purification of biogas.

A comparison of the biogas and bioethanol conversion route can be made, based on datasets of sugar beet usage in both routes (see the two red data points connected with a dashed line in Fig. 4.7). Driving with biogas from sugar beets requires 0.96 kg beets per km whereas driving with bioethanol from sugar beets requires 0.73 kg beets per km. It can be concluded from these results that in case of sugar beets the bioethanol conversion route is a more efficient way of producing biofuels than producing biogas from the same crop. Bioethanol not only has a higher kilometric performance per hectare, but also lower greenhouse gas emissions. Nevertheless, from this single example it cannot be generalized to other substrates and biofuel types.

The lower kilometric performance of the analysed biomass-to-liquid (BTL) fuels and of soy bean methyl ester is not because of an inefficient conversion route, but because of a low yield of soy bean, wood, and miscanthus per cultivated hectare.

The datasets of methyl ester from different crops consider an economic allocation with 2001 prices of methyl ester and glycerine. Since prices of glycerine have decreased significantly within the last few years, updating this allocation will result in a slightly lower yield and higher environmental impacts.

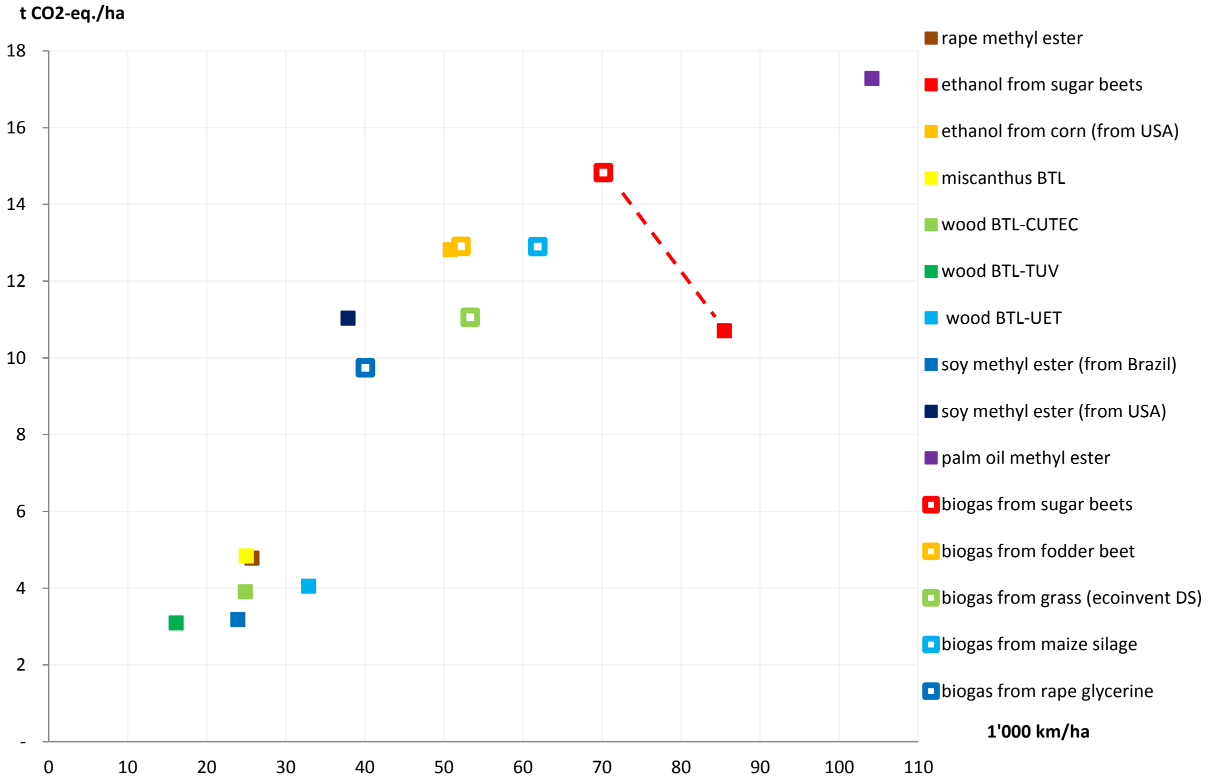

Fig. 4.7 Two dimensional presentation of kilometric performance per hectare and greenhouse gas emissions per hectare of different energy crops and biofuel conversion. Filled squares represent liquid biofuels and hollow squares represent biogas fuels.

As well as in Fig. 4.7, also in the two dimensional diagram in Fig. 4.8, where kilometric performance and total environmental impacts assessed with the method of Ecological Scarcity (2006) per hectare are displayed, it is shown that the results for using biogas in cars is in the same order of magnitude as compared to using liquid biofuels.

The example of using sugar beets shows that bioethanol is the more efficient conversion route than driving with biogas produced from the same crop (see the two red data points connected with a dashed line in Fig. 4.8). Both alternatives have about the same amount of total environmental impacts per hectare of cultivated sugar beet, but ethanol from sugar beets has a significantly higher kilometric performance compared to biogas from sugar beets. If looking at all examples, the liquid biofuels tend to have a lower kilometric performance, because of the crops with low yields such as wood, soy bean, and miscanthus

In contrast to the greenhouse gas emissions, the higher total environmental impacts of using biogas can be outweighed by the higher kilometric performance. Finally, this leads to similar amounts of total environmental impacts per passenger or vehicle kilometre when using biogas and liquid biofuels respectively.

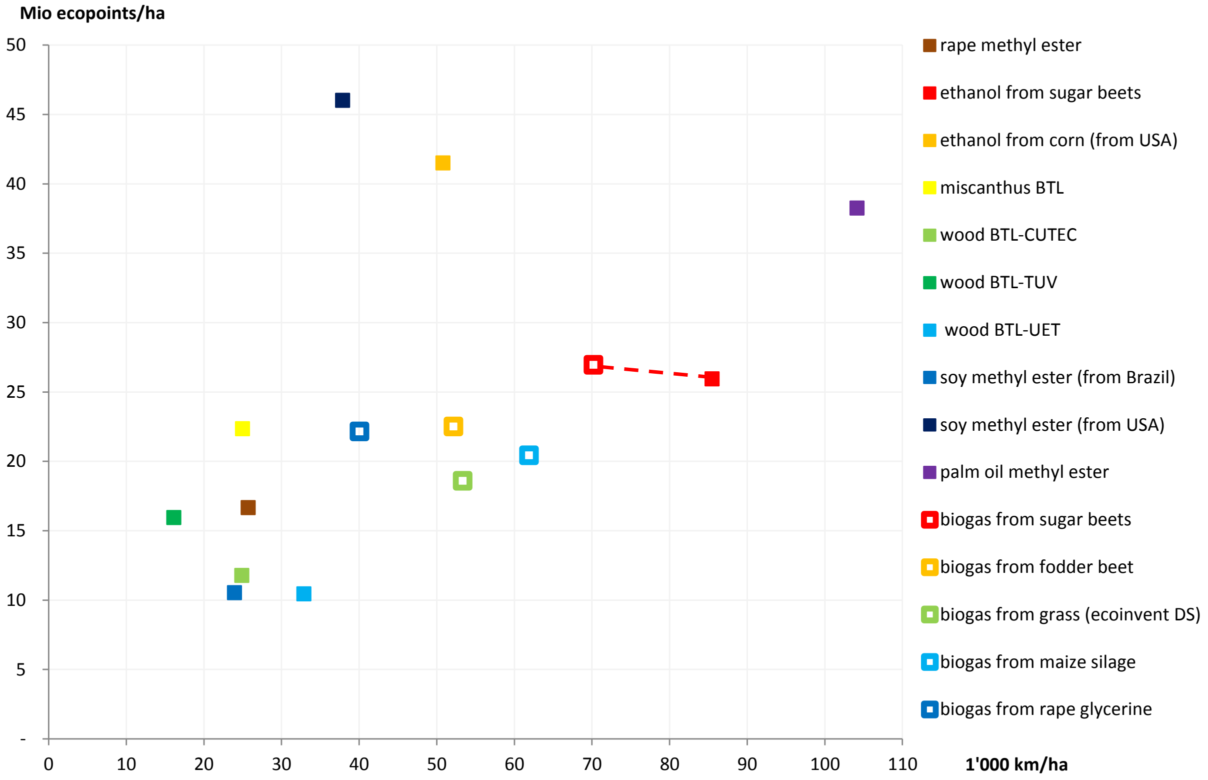

Fig. 4.8 **Two dimensional presentation of kilometric performance per hectare and total environmental impacts assessed with the method of Ecological scarcity (2006) per hectare of different energy crops and biofuel conversion. Filled squares represent liquid biofuels and hollow squares represent biogas fuels.**

4.2 Grass refinery products

The impact assessment of the various products from the grass refinery that are different than biogas is presented in a separate report published by Leuenberger & Jungbluth (2010). The key findings are:

- The total environmental impacts of all grass refinery products are lower compared to a total of comparable products with the same functional unit with regard to all applied impact assessment methods.
- On products level, the results differ depending on the selected impact assessment methods. Whereas AgriCell has higher environmental impacts compared to conventional insulation materials, AgriPlast has lower environmental impacts compared to similar products using high density polyethylene with regard to most indicators.
- Extensive grass cultivation leads to significantly lower environmental impacts compared to intensive grass cultivation.
- Since the grass cultivation has a high impact on the total environmental impacts of the refinery, the chosen allocation between the different products is important. Depending on the selected allocation factors, the environmental impacts of the individual products can be varied.
- Using electricity from burning biogas has lower environmental impacts compared to operating the grass refinery with electricity from the German grid.

4.3 Electricity from Cogeneration

At present, more common than purifying biogas for the use as fuel in transportation, is the burning of biogas in a cogeneration unit in order to produce electricity and heat. Fig. 4.9 shows the total environmental impacts assessed with the Ecological Scarcity Method (2006). Electricity produced from wastes such as biowaste, sewage sludge, or slurry, can reduce the environmental impacts compared to the average Swiss electricity mix significantly, because they avoid the generation of radioactive wastes from Swiss nuclear power plants.

On the other hand, electricity from biogas produced from energy crops has considerably higher total environmental impacts compared to the average electricity from grid. Hence, from an environmental point of view, it is not reasonable, if operators of biogas plants purchase energy crops in order to enhance their biogas production. This supports the criteria of the naturemade star label which defines that only the share of electricity that is produced from biogenic wastes can be certified as green electricity and electricity from other biogas substrates is not entitled for certification (naturemade 2011).

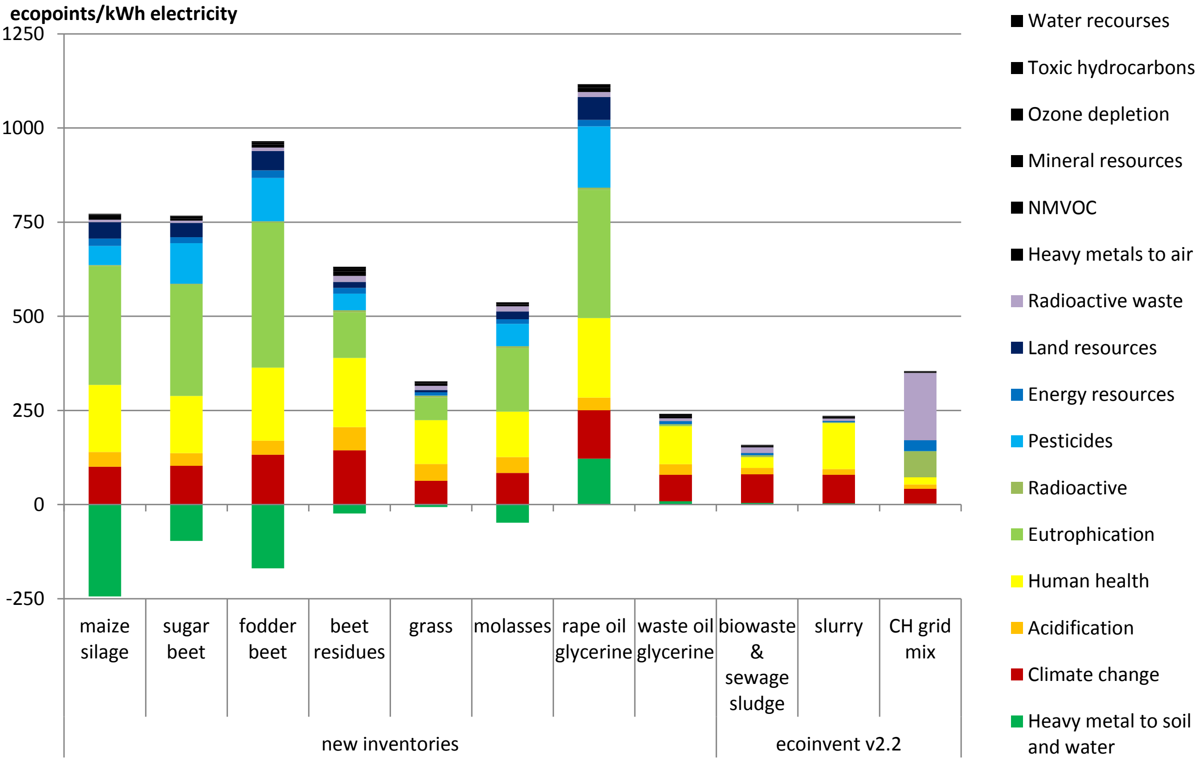

Fig. 4.9 Ecological Scarcity (2006) scores of electricity generated from biogas in cogeneration units and of average electricity from the Swiss grid. The contribution of toxic hydrocarbons, ozone depletion, water and mineral recourses, NMVOC, and heavy metals to air is too small to be obvious from this figure.

5 Conclusion

As shown in this study, using biogas from non-waste substrates as vehicle fuels instead of using conventional fuels has some benefits regarding the consumption of non-renewable energy resources and regarding carbon footprint. However, these benefits are lower than when using biogas from waste substrates.

The overall environmental impacts of transport services with biogas from non-waste substrates is considerably higher compared to those of transport services with biogas from waste substrates. In most cases it also exceeds the total environmental impacts of driving with conventional fuels. In particular important are the use of agricultural land, and emissions during the cultivation of plants used as biogas substrates or as feedstock for biogas substrates.

There is a large range of environmental impacts depending on which specific substrate is used in an agricultural biogas plant. Since several biogas substrates bear high environmental impacts, we suggest analysing these impacts in depth before making decisions that have an impact on the type and amount of biogas substrate produced.

The allocation of emissions from applying digestates influences the final performance of biogas produced from energy crops. In this study we assume in the standard case that these emissions are allocated to the crop produced with the digestates used as a fertilizer. If digestates are more seen as a waste and thus emissions are allocated to the biogas plant, this raises the environmental impacts considerably. A possibility not investigated in this study is the situation where energy crops used in the biogas plant are fertilized with digestates from the same biogas plant.

Out of the biogas substrates considered in this study, only the combination of cow and grass slurry in a grass refinery as well as glycerine made from waste oil comply with the Swiss requirements for a tax reduction on biofuels, which are a threshold of 60 % of the greenhouse gas emissions and a threshold of 125 % of the total environmental impacts, respectively, of transportation with conventional fuels. In particular the threshold for greenhouse gas emissions is not achieved by other types of substrates. Due to the additional environmental impacts from the crop cultivation, none of the biogas substrates from energy crops meets this requirement, if digested as a single substrate. The current trend towards using high energy substrates made from agricultural crops leads to more environmental impacts and a worse environmental performance of biogas.

At present, biogas in Switzerland is mainly produced from sewage sludge, slurry, and biowaste. If the co-digestion with higher shares of substrates made from energy crops increases significantly in future, the produced biogas cannot comply with the thresholds for a fuel tax reduction.

Electricity produced from biogas made from non-waste energy crops has significantly higher total environmental impacts than the average electricity form grid in Switzerland. Therefore, such electricity cannot be considered as green, in contrast to electricity made from biogas produced from waste substrates, which has significantly lower environmental impacts.

This study confirms in general the knowledge gained for other types of biofuels. There is not a single judgement for one type of fuel, since the environmental impacts are quite dependent on the biomass resource used as a starting point and the conversion efficiency in the process. A comparison for sugar beets used as an input for biogas or ethanol production also shows that in certain cases other conversion routes than biogas are more efficient from an environmental point of view.

6 Outlook

The life cycle inventories that are established in this project in EcoSpold format v1 are available from the public webpage www.lc-inventories.ch. They can be downloaded and imported into LCA software such as SimaPro.

In addition to the life cycle inventories presented in this report, new life cycle inventories of the biogas production from further substrates recommended by Leuenberger & Jungbluth (2009) could be considered in a next step. These are waste cooking oils, potato starch and potato starch residues, as well as rape meal and oil residues.

Also it would be interesting to analyse the environmental effects, if the energy crops for biogas production are cultivated using biogas digestates as fertilizer.

Within this project, the economic allocation of the esterification of rape oil and vegetable oil from waste cooking oil are updated. However, there are more datasets in ecoinvent using the same allocation factors, which should be updated as well.

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8 Appendix A: LCI of biogas conversion in agricultural biogas plants

8.1 Biogenic carbon balance methodology

In contrast to the life cycle inventory data presented by Jungbluth et al. (2007), in this project in most cases no specific corrections are made in order to maintain the biogenic carbon balance of multi-output processes. In consequence, assessing the global warming potential of products described in this project should not include a climate change characterization factor for biogenic carbon uptake nor for biogenic carbon dioxide emissions.

8.2 General assumptions

8.2.1 Yields

In Tab. 8.1 the properties of the average Swiss biogas mix are shown. Since the methane content of biogas is the key property, the biogas yields of different biogas substrates are corrected according to the methane content of the produced biogas (see Tab. 8.2).

Tab. 8.1 Summary of main properties of the Swiss biogas mix according to Jungbluth et al. (2007) p. 244

		Biogas-Mix
Methane	Vol. %	63.3
Carbon dioxide	Vol. %	33.4
Methane	Kg/Nm^3	0.45
Carbon Dioxide	Kg/Nm^3	0.66
Total Carbon Content	Kg/Nm^3	0.52
Nitrogen	Vol. %	3.17
Density	Kg/Nm^3	1.15
Lower heating value	MJ/Nm^3	22.7

Tab. 8.2 Actual and methane corrected biogas yield of different substrates (Institut für Energetik und Umwelt 2006) and biogas conversion efficiency

Substrate	Unit	Maize silage	Sugar beet	Fodder beet	Beet residues	Molasses	Glycerine
Biogas yield	Nm3 per t fm	188.4	175.0	109.4	59.5	287.3	976.5
Methane content	Vol. %	53%	54%	54%	55%	73%	50%
Methane corrected biogas yield	**Nm3 per t fm**	**156.1**	**147.8**	**92.4**	**51.2**	**328.9**	**770.6**
Energy content of substrate	MJ/kg	5.3	3.8	3.0	3.5	n/a	18.0
Biogas conversion efficiency	**MJ_{biogas}/MJ_{in}**	**67%**	**89%**	**70%**	**34%**	**n/a**	**97%**

8.2.2 Energy consumption

In order to evaluate typical conditions of the operation of agricultural biogas plants in Switzerland, a questionnaire was sent to biogas operators. Sixteen operators filled in the questionnaire.

About 61.7 % of the biogas from these biogas plants is produced with self-produced electricity and 38.3 % with purchased electricity. The heat used in the biogas plants is commonly generated onsite from burning biogas.

From the 16 filled in questionnaires we obtained the information that the electricity consumption of biogas production in an agricultural co-digestion plant e.g. for stirring the substrates amounts between 0.5 and 36.4 kWh per ton substrate with an average of 12.9 kWh/ton. The heat consumption of the biogas plants amounts between 16.7 and 356.4 MJ per ton substrate with an average of 187.7 MJ/ton. The average energy consumption per ton of substrates is applied in the inventories.

With regard to the energy consumption per m^3 of biogas, the average amounts to 0.158 kWh of electricity and 3.470 MJ heat per m^3 biogas.[7] (Dauriat et al. 2011)

8.2.3 Infrastructure

According to the questionnaires, 62.9 % of the biogas is produced in plants with digestate cover and 37.1 % in plants without digestate cover. We apply two different inventories for biogas plants with and without cover, respectively. The calculation of the infrastructure use per ton of handled substrate is shown in Tab. 8.3.

Tab. 8.3 Calculation of infrastructure use per ton of handled substrate in biogas plants (based on data from Jungbluth et al. (2007))

Uncovered biogas plant		
Capacity	m^3	300
Life time	years	20
Annual biogas production Co-substrate and manure mix	m^3/a	104000
Potential Biogas Production	m^3/t substrate	53.08
Annual substrate handling	tons/a	1959
Infrastrucuture requirement	m^3/t substrate	2.55E-05
Covered biogas plant		
Capacity	m^3	500
Life time	years	20
Annual biogas production	m^3/a	300000
Potential Biogas Production	m^3/t substrate	53.08
Annual substrate handling	tons/a	5652
Infrastrucuture requirement	m^3/t substrate	8.85E-06

8.2.4 Ammonia, dinitrogen monoxide, and methane emissions

From the filled in questionnaires we obtained the information that 62.9 % of the biogas is produced in plants with digestate cover and 37.1 % in plants without digestate cover. The LCI datasets described in this chapter refer to biogas production in a mix of biogas plants with and without digestate cover.

Ammonia emissions arise from the storage of digestates. According to Edelmann et al. (2001) because of the conventional storage and application of liquid manure, 50 % of the ammonium content is released as ammonia emissions. 1/6th of these emissions stem from the storage and 5/6th from the application resulting in emission factors of 8.3 % during storage and 41.7 % during and after application on fields.

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[7] All information from this Section: Personal communication with Arnaud Dauriat from ENERS on 22.11. 2010

Furthermore, Edelmann et al. (2001) explain that the conversion in a biogas plant leads to increased ammonia emissions due to an increased degradation of organically bound nitrogen in the fermenter and an increase of the pH value. Ammonia emissions are therefore increased by 40 % during storage and by 10 % during application. This leads a total ammonia emission factors of 11.7 % of the ammonia content in the substrates during digestate storage and 45.8 % during digestate application on fields. With appropriate measures these emissions can be reduced. The emissions during storage are reduced by 80 % when digestates are covered.[8]

Dinitrogen monoxide emissions from digesting substrates amount to 0.1 kg /t according to Jungbluth et al. (2010). When digestates are covered, these emissions are reduced by 75 %.

According to Jungbluth et al. (2007) the methane emission factor amounts to 1 % in biogas plant with covered stock and to 5 % in biogas plants with uncovered stock. The emission factor of an average biogas plant is considered by applying the shares of biogas plants with and without digestate cover as described above and by considering the methane share of 52.5 % in the volume of the produced biogas.

8.3 Biogas from maize

8.3.1 System characteristics

Maize is one of the most commonly used energy crop in agricultural or industrial biogas production plants and therefore plays an important role for the evaluation of different substrates in anaerobic digestion. Compared to other energy crops, the properties of maize silage are favourable for biogas production. Firstly, the cultivation has no special requirements, the maize yield per hectare is comparably high and the silage can easily be stored in bunker silos (Institut für Energetik und Umwelt gGmbH 2006). The biogas yield per ton maize silage depends on the variety. Varieties with late ripening produce more biogas than early ripening varieties (Amon et al. 2007a; Institut für Energetik und Umwelt gGmbH 2006). A drawback of maize silage used in anaerobic digestion is its competitive use as animal feed.

Experiences with maize in anaerobic digestion are mainly available from biogas production in Germany, where maize is often added as a co-substrate. The agricultural production of maize has to be fully attributed to the environmental impact of the biogas production. LCI data on maize cultivation is available in the ecoinvent database (Nemecek et al. 2007).

The specifications of maize silage that are used in this study are declared in Tab. 8.5.

Tab. 8.4 Specification of maize silage and of the production of biogas from this substrate (Institut für Energetik und Umwelt gGmbH 2006)

		Maize silage
Dry matter content	**%**	**27.5%**
organic substance	**% DM**	**90.0%**
N	**% DM**	**1.6%**
P	**% DM**	**0.3%**
Biogas yield	**m3 per t DM**	**672.7**
CH_4 content	**%**	**52.5%**

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[8] www.nw.ch/dl.php/de/20060502101744/Ammoniak_NH3_Faktenblatt.pdf (access on 11.10.2011)

8.3.2 Raw material input

The Institut für Energetik und Umwelt (2006) reports a biogas yield of 170 – 200 Nm^3 per ton fresh matter and 450 – 700 Nm^3 per ton of organic dry matter as well as a dry matter content of 27.5 %. Adjusting the mean value to the dry matter content of maize silage in ecoinvent (moisture content of 72%) results in 188.4 Nm^3 of biogas per ton of maize silage. Since biogas from maize silage has a methane content of 52.5 % which is lower than the average biogas content of 63.3 %, the methane corrected biogas yield is 156.1 Nm^3 of biogas per ton of maize silage. It is assumed that the maize silage is transported by lorry over a distance of 50 km.

8.3.3 Emissions to air

As described in section 8.2.4 the ammonia emissions from storage of the maize digestate are calculated from the emission factor of 11.7 % of the ammonium content and an 80 % emission reduction for the share of 62.9 % of biogas plants with a digestate cover. The ammonia content of the substrate is between 0.15 % and 0.30 % (mean: 0.23 %) of the maize silage dry matter mass (Institut für Energetik und Umwelt gGmbH 2006). Applying these factors, results in 0.28 g ammonia per m^3 biogas.

The biogenic carbon dioxide emissions are considered with the same emission factor as methane and the carbon dioxide share of 33.4 % in the biogas (see Tab. 8.1).

Gronauer et al. (1997) cited in Jungbluth et al. (2007: 188) claim a hydrogen sulphide emission factor of 700 g per ton input dry matter. From this factors follow H_2S emissions of 1.04 g per m^3 biogas.

8.4 Biogas from sugar beet, fodder beet and beet residues

8.4.1 System characteristics

Apart from maize, beet cultivation in Switzerland provides large amounts of biomass, which could be potentially used in biogas production. Currently, beets are used for sugar production or as animal feed. If the beet silage is directly added to anaerobic digestion, the environmental impact of beet production has to be taken into account for the LCA of biogas production.

Similar to maize silage, the cultivation of beets has a high yield and the methane production is comparably high. Cultivation requirements and the storage of the silage on the other hand are more complicated. The dependence of biogas yield from fodder beet digestion on microbiologic conditions has been investigated by Scherer et al. (2009).

As sugar and fodder beets are primarily used for sugar production or animal feed respectively, the use of the entire beet as substrate still is uncommon. More often the residues from sugar and fodder beet, leafs and tops, are fermented in closed silos and later used as substrates (Börjesson & Berglund 2005).

Wastes from sugar and fodder beet processing, mainly tops and leaves, are organic wastes with high dry matter contents. This makes them attractive for the use as substrate in anaerobic digestion. Depending on the market price paid for the sugar and fodder beet residues, a part of the environmental impact arising from beet production has to be allocated to the beet residues.

The use as substrates with solid potato waste showed, that the biogas yield can be enhanced, when fodder beet leafs are digested together with other substrates (Parawira et al. 2008).

The specifications of sugar beets, fodder beets and beet residues that are used in this study are declared in Tab. 8.5.

Tab. 8.5 Specification of sugar beet, fodder beet, and beet residues, as well as of the production of biogas from these substrates

		Sugar Beet	**Fodder Beet**	Beet leaves	Beet leaves	**Beet residues**
		Institut für Energetik und Umwelt (2006)	**Institut für Energetik und Umwelt (2006)**	Institut für Energetik und Umwelt (2006)	Baserga (2000)	**This study**
Dry matter content	**%**	**23.0%**	**12.0%**	16.0%	16.5%	**16.3%**
Organic substance	**% DM**	**92.5%**	**80.0%**	82.5%	79.0%	**80.8%**
N-content	**% DM**	**2.6%**	**1.9%**	0.3%	-	**0.3%**
NH_4-content	**% DM**	**0.2%**	**0.4 %**	-	-	**0.04%**
P-content	**% DM**	**0.4%**	**0.3%**	0.8%	-	**0.8%**
Biogas yield	**Nm^3 per t DM**	**760.8**	**729.1**	437.5	355.5	**396.5**
CH_4 content	**%**	**53.5%**	**53.5%**	54.5%	-	**54.5%**

8.4.2 Raw material input

Applying the biogas yield per ton of dry matter presented in Tab. 8.5 and the beet dry matter content in ecoinvent of 23 % (sugar beet) and 15 % (fodder beet) results in a biogas yield of 175.0 Nm^3 biogas per ton of sugar beets, 109.4 Nm^3 biogas per ton of fodder beets, and 59.5 Nm^3 biogas per ton of beet residues. Since the substrates lead to a methane content of 53.3 % (beets) and 54.5 % (beet residues, the methane corrected biogas yields are 147.8 Nm^3 (sugar beet), 92.4 Nm^3 (fodder beet), and 51.2 Nm^3 (fodder beet) ton of substrate. It is assumed that the substrates are transported by lorry over a distance of 50 km.

Since the heavy metal uptake in the ecoinvent v2.2 datasets of sugar beet and fodder beet cultivation was not modelled correctly (confusing dry matter and moisture content), new datasets prepared by Agroscope for the ecoinvent v3 database release were used. Agroscope also prepared a dataset of sugar beet cultivation with crown and leaf harvesting, to be implemented in the ecoinvent v3 database.[9] In this multi-output dataset, we conducted an economic allocation using contribution margins of the ÖLN.[10] These are shown in Tab. 8.6. The loading of the beet residues on a trailer is allocated fully to the sugar beet crowns and leaves.

Tab. 8.6 Allocation in the multi-output dataset of sugar beet cultivation with harvesting of crown and leaves

	sugar beet roots	**sugar beet crown and leaf**
Price, Deckungsbeiträge, ÖLN	5.3 CHF/t	0.75 CHF/t
Income	41149.2 CHF/ha	3882.0 CHF/ha
Economic Allocation	91%	9%
Allocation CO2 uptake	73%	27%

8.4.3 Emissions to air

As described in section 8.2.4 the ammonia emissions from storage of the beet digestates are calculated from the emission factor of 11.7 % of the ammonium content and an 80 % emission reduction for the

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[9] Dataset received from Julian Schnetzer on 19.09.2011 and 24.10.2011

[10] Personal communication with Julian Schnetzer from Agroscope on 03.10.2011

share of 62.9 % of biogas plants with a digestate cover. The ammonia content of the substrates is given in Tab. 8.5. The ammonia content of beet residues is calculated with the average ammonia-N share in the total nitrogen content of sugar and fodder beets, which is 13 %. Applying these factors, results in 0.22 g NH_3/m^3 biogas from sugar beets, 0.32 g NH_3/m^3 biogas from fodder beets, and 0.08 NH_3/m^3 biogas from beet residues.

The biogenic carbon dioxide emissions are considered with the same emission factor as methane and the carbon dioxide share of 33.4 % in the biogas (see Tab. 8.1).

Gronauer et al. (1997) cited in Jungbluth et al. (2007:188) claim a hydrogen sulphide emission factor of 700 g per ton input dry matter. From this factors follow H_2S emissions of 0.92 g per m^3 biogas from sugar beets, 0.96 g per m^3 biogas from fodder beets, and 1.77 g per m^3 biogas from beet residues.

8.5 Biogas from molasses

8.5.1 System characteristics

Molasses are a by-product of sugar production. They have high dry matter and sugar contents and therefore are suitable to increase the biogas yield of liquid biogas substrates. Like the other sugar beet residues, molasses are used as animal feed or in distilleries, which makes it rather rare for the use as substrate for anaerobic digestion (Institut für Energetik und Umwelt gGmbH 2006).

The specifications of molasses that are used in this study are declared in Tab. 8.7.

Tab. 8.7 Specification of molasses and of the production of biogas from this substrate

		Molasses	Molasses	**Molasses**
		Institut für Energetik und Umwelt (2006)	Baserga (2000)	**This study**
Dry matter content	**%**	85.0%	80.0%	**82.5%**
organic substance	**% DM**	87.5%	79.0%	**91.3%**
N	**% DM**	1.5%	-	**1.5%**
P	**% DM**	0.3%	-	**0.3%**
Biogas yield	**m3 per t DM**	370.6	427.5	**399.0**
CH_4 content	**%**	72.5%	-	**72.5%**

8.5.2 Raw material input

As molasses input, we include an ecoinvent inventory dataset of molasses from sugar beet in Switzerland, which considers a molasses price of 240 CHF/t as basis for the economic allocation between sugar, beet pulps, and molasses (Jungbluth et al. 2007).

Applying the biogas yield per ton of dry matter presented in Tab. 8.7 and the molasses dry matter content in ecoinvent of 72 % results in a biogas yield of 287.3 Nm^3 biogas per ton of molasses. Since biogas from molasses has a methane content of 72.5 %, the methane corrected biogas yield is 328.9 Nm^3 of biogas per ton of molasses. It is assumed that the molasses are transported by lorry over a distance of 50 km.

8.5.3 Emissions to air

As described in section 8.2.4 the ammonia emissions from storage of the beet digestates are calculated from the emission factor of 11.7 % of the ammonium content and an 80 % emission reduction for the share of 62.9 % of biogas plants with a digestate cover. In the data published by the Institut für Energetik und Umwelt (2006), the average share of NH4-N in the total nitrogen content of the agricultural processing industry is about 12 %, which means an ammonia content of 0.2 % of the molasses dry matter. Applying these factors, results in 0.31 g NH_3/m^3 biogas from molasses.

The biogenic carbon dioxide emissions are considered with the same emission factor as methane and the carbon dioxide share of 33.4 % in the biogas (see Tab. 8.1).

Gronauer et al. (1997) cited in Jungbluth et al. (2007:188) claim a hydrogen sulphide emission factor of 700 g per ton input dry matter. From this factors follow H_2S emissions of 1.75 g per m^3 biogas.

8.6 Biogas from glycerine

8.6.1 System characteristics

Glycerine for biogas production is mainly extracted in vegetable oil esterification plants, but it can also be produced by many other industries (petrochemical, soap by-product etc.). Glycerine is used with increasing popularity as a substrate and increases the biogas yield considerably. The use of glycerine as a mono-substrate in biogas fermentation has been investigated by Erb et al. (2008). In the questionnaires filled in by operators of agricultural biogas plants, three operators declare that they pay a price of between 200 and 220 CHF per ton of glycerine in 2008 and 2009 (Dauriat et al. 2011). In this study we investigate the use of glycerine made from rape oil and glycerine made from waste oil in the biogas production.

The specifications of glycerine that are used in this study are declared in Tab. 8.8.

Tab. 8.8 Specification of glycerine and of the production of biogas from this substrate (Erb et al. 2008; Institut für Energetik und Umwelt gGmbH 2006])

		Glycerine
Dry matter content	**%**	**97.2%**
organic substance	**% DM**	**93.6%**
N	**% DM**	**0.03%**
P	**% DM**	**0.003%**
Biogas yield	**m3 per t DM**	**1004.3**
CH_4 content	**%**	**50.0%**

8.6.2 Raw material input

Jungbluth et al. (2007) apply an economic allocation to the multi-output processes of plant oil esterification. They consider the product methyl ester with a price of 1’010 SFr./t and the product glycerine with a price of 1’380 SFr./t. However, in 2010 the glycerine is not sold in a highly pure quality anymore and is valorised in a biogas plant instead. Glycerine that is used in biogas power plants is of lower purity. In questionnaires, biogas plant operators report an average glycerine price of 208 SFr./t. Applying this glycerine price and a rape oil esterification yield of 864 kg methyl ester and 93 kg glycerine from one ton of rape oil results in an allocation factor of 97.8 % to methyl ester. In order to update the inventory datasets of rape oil and vegetable oil esterification, this new allocation factor is included.

This correction influences the LCA results of both types of biofuels, rape methyl ester (RME) and biogas from glycerine. With the updated allocation, RME shows higher environmental impacts whereas biogas from glycerine shows lower environmental impacts, compared to the analysis with the previous allocation.

Erb et al. (2008) report a biogas yield of 940 Nm^3 per ton organic substance, an organic substance content of 93.6 % in the total dry matter of glycerine and a dry matter content of 97.2 %. This results in a biogas yield of 976.2 Nm^3 biogas per ton of glycerine. Since biogas from glycerine has a methane content of 50.0 %, the methane corrected biogas yield is 770.6 Nm^3 of biogas per ton of glycerine.

In addition to the biogas from glycerine made from rape oil, a scenario is considered with glycerine from vegetable waste oil from France. The prices for obtaining and treating waste oil are very volatile.[11] Waste oil can be considered as a material for disposal and therefore, when calculating environmental life cycle impacts, waste oil does not carry any environmental burdens from the oil production.

In the filled in questionnaires, 5 operators of agricultural biogas plants report transport distances of glycerine between 6 and 50 km (average 39 km), which can be considered as the distance from the local reseller. However, since most glycerine is imported from abroad[12], it is assumed in this study that the glycerine is transported by lorry over a distance of 500 km.

8.6.3 Emissions to air

As described in section 8.2.4 the ammonia emissions from storage of the beet digestates are calculated from the emission factor of 11.7 % of the ammonium content and an 80 % emission reduction for the share of 62.9 % of biogas plants with a digestate cover. In the data published by the Institut für Energetik und Umwelt (2006), the share of NH_4-N in the total nitrogen content of fat is 46 %, which we consider also for glycerine. Applying these factors, results in 2.4 mg NH_3/m^3 biogas from glycerine.

The biogenic carbon dioxide emissions are considered with the same emission factor as methane and the carbon dioxide share of 33.4 % in the biogas (see Tab. 8.1).

Gronauer et al. (1997) cited in Jungbluth et al. (2007:188) claim a hydrogen sulphide emission factor of 700 g per ton input dry matter. From this factors follow H_2S emissions of 0.70 g per m^3 biogas.

8.7 Life cycle inventories of biogas conversion in agricultural biogas plants

The unit process raw data of the anaerobic co-digestion in agricultural biogas plants is are displayed in Tab. 8.9 and Tab. 8.10. The EcoSpold meta information is shown in Tab. 8.12.

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[11] Personal communication with Beat Amman from the ara region bern ag on 05.11.2011

[12] Personal communication with Konrad Schleiss from UMWEKO GmbH on 03.01.2011

Tab. 8.9 Unit process raw data of anaerobic co-digestion in agricultural biogas plants (part I)

	Name	Location	InfrastructureProcess	Unit	biogas, from maize silage, co-digestion, at storage	biogas, from sugar beet, co-digestion, at storage	biogas, from fodder beet, co-digestion, at storage	biogas, from beet residues, co-digestion, at storage	biogas, from molasses, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage, scenario vegetable oil	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0	0	0	0			
	Unit				Nm3	Nm3	Nm3	Nm3	Nm3	Nm3	Nm3			
technosphere	silage maize IP, at farm	CH	0	kg	6.41E+0	-	-	-	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	sugar beets IP, at farm	CH	0	kg	-	6.77E+0		-	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	fodder beets IP, at farm	CH	0	kg	-	-	1.08E+1	-	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	sugar beet crown and leaf IP, at farm	CH	0	kg	-	-	-	1.95E+1	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	molasses, from sugar beet, at sugar refinery	CH	0	kg	-	-	-	-	3.04E+0	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	glycerine, from rape oil, at esterification plant, 2011	CH	0	kg	-	-	-	-	-	1.30E+0	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	glycerine, from vegetable oil, at esterification plant, 2011	FR	0	kg	-	-	-	-	-	-	1.30E+0	1	1.08	(2,1,2,1,1,2,BU:1.05);
	potato starch, at plant	DE	0	kg	-	-	-	-	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	rape meal, at oil mill	CH	0	kg	-	-	-	-	-	-	-	1	1.08	(2,1,2,1,1,2,BU:1.05);
	anaerobic digestion plant, agriculture	CH	1	unit	6.06E-8	6.41E-8	1.02E-7	1.85E-7	2.88E-8	1.23E-8	1.23E-8	1	3.06	(3,3,2,3,1,5,BU:3); 37.1% without digestate cover. Plant producing 300'000 m3 biogas per year, life time 20 a
	anaerobic digestion plant covered, agriculture	CH	1	unit	3.56E-8	3.76E-8	6.02E-8	1.09E-7	1.69E-8	7.22E-9	7.22E-9	1	3.06	(3,3,2,3,1,5,BU:3); 62.9% with digestate cover. Plant producing 300'000 m3 biogas per year, life time 20 a
	electricity, low voltage, at grid	CH	0	kWh	3.17E-02	3.35E-02	5.35E-02	9.66E-02	1.50E-02	6.42E-03	6.42E-03	1	1.13	(3,2,1,1,1,3,BU:1.05);
	electricity, biogas from maize silage, at cogen	CH	0	kWh	5.10E-02	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant with digestate cover
	electricity, biogas from sugar beet, at cogen	CH	0	kWh	-	5.39E-02	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant with digestate cover
	electricity, biogas from fodder beet, at cogen	CH	0	kWh	-	-	8.62E-02	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant with digestate cover
	electricity, biogas from beet residues, at cogen	CH	0	kWh	-	-	-	1.56E-01	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from molasses, at cogen	CH	0	kWh	-	-	-	-	2.42E-02	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from glycerine, at cogen	CH	0	kWh	-	-	-	-	-	1.03E-02	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from glycerine, at cogen, scenario vegetable oil	CH	0	kWh	-	-	-	-	-	-	1.03E-02	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from vegetable, at cogen	CH	0	kWh	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from potato pulp, at cogen	CH	0	kWh	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover
	electricity, biogas from rape meal, at cogen	CH	0	kWh	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05); Share of self produced electricity in plant without digestate cover

Tab. 8.10 Unit process raw data of anaerobic co-digestion in agricultural biogas plants (part II)

	Name	Location	InfrastructureProcess	Unit	biogas, from maize silage, co-digestion, at storage	biogas, from sugar beet, co-digestion, at storage	biogas, from fodder beet, co-digestion, at storage	biogas, from beet residues, co-digestion, at storage	biogas, from molasses, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage, scenario vegetable oil	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0	0	0	0			
	Unit				Nm3	Nm3	Nm3	Nm3	Nm3	Nm3	Nm3			
	heat, biogas from maize silage, at cogen	CH	0	MJ	1.20E+00	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from sugar beet, at cogen	CH	0	MJ	-	1.27E+00	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from fodder beet, at cogen	CH	0	MJ	-	-	2.03E+00	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from beet residues, at cogen	CH	0	MJ	-	-	-	3.67E+00	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from molasses, at cogen	CH	0	MJ	-	-	-	-	5.71E-01	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from glycerine, at cogen	CH	0	MJ	-	-	-	-	-	2.44E-01	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from glycerine, at cogen, scenario vegetable oil	CH	0	MJ	-	-	-	-	-	-	2.44E-01	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from vegetable oil, at cogen	CH	0	MJ	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from potato pulp, at cogen	CH	0	MJ	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	heat, biogas from rape meal, at cogen	CH	0	MJ	-	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
	transport, lorry 3.5-20t, fleet average	CH	0	tkm	3.20E-1	3.38E-1	5.41E-1	9.77E-1	1.52E-1	6.49E-1	6.49E-1	1	2.09	(4,5,na,na,na,na,BU:2); assumption: 50 km for agricultural products, 500 km for glycerine
emission air, unspecified	Ammonia	-	-	kg	2.79E-4	2.19E-4	3.20E-4	8.77E-5	3.06E-4	2.40E-6	2.40E-6	1	1.38	(2,3,4,3,1,5,BU:1.2); 80*% reduced emissions in plants with digestate cover
	Carbon dioxide, biogenic	-	-	kg	1.64E-02	1.64E-02	1.64E-02	1.64E-02	1.18E-02	1.64E-02	1.64E-02	1	1.33	(3,3,4,3,1,5,BU:1.05); 1% emissions from covered stock and 5 % emissions from uncovered stock
	Methane, biogenic	-	-	kg	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1	1.64	(3,3,4,3,1,5,BU:1.5); 1% emissions from covered stock and 5 % emissions from uncovered stock
	Hydrogen sulfide	-	-	kg	1.26E-03	1.09E-03	1.14E-03	2.05E-03	1.53E-03	8.83E-04	8.83E-04	1	1.57	(1,3,2,3,1,5,BU:1.5);
	Dinitrogen monoxide	-	-	kg	3.38E-4	3.57E-4	5.72E-4	1.03E-3	1.61E-4	6.86E-5	6.86E-5	1	1.63	(2,3,4,3,1,5,BU:1.5);
emission air, high population density	Heat, waste	-	-	MJ	1.50E+0	1.58E+0	2.54E+0	4.58E+0	7.12E-1	3.04E-1	3.04E-1	1	1.13	(3,2,1,1,1,3,BU:1.05); own calculations

Tab. 8.11 Amount of digestate from anaerobic co-digestion in agricultural biogas plants (only considered in scenario with digestate allocation to biogas)

Name	Location	InfrastructureProcess	Unit	biogas, from maize silage, co-digestion, at storage	biogas, from sugar beet, co-digestion, at storage	biogas, from fodder beet, co-digestion, at storage	biogas, from beet residues, co-digestion, at storage	biogas, from molasses, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage, scenario vegetable oil	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH	CH	CH	CH	CH	CH	CH			
InfrastructureProcess				0	0	0	0	0	0	0			
Unit				Nm3	Nm3	Nm3	Nm3	Nm3	Nm3	Nm3			
application, digested matter, from maize silage, on agricultural land	CH	0	kg	5.23E+0	-	-	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
application, digested matter, from beets, on agricultural land	CH	0	kg	-	5.59E+0	9.64E+0	-	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
application, digested matter, from beet residues, on agricultural land	CH	0	kg	-	-	-	1.84E+1	-	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
application, digested matter, from molasses, on agricultural land	CH	0	kg	-	-	-	-	1.87E+0	-	-	1	1.13	(3,2,1,1,1,3,BU:1.05);
application, digested matter, from glycerine, on agricultural land	CH	0	kg	-	-	-	-	-	1.19E-1	1.19E-1	1	1.13	(3,2,1,1,1,3,BU:1.05);

Tab. 8.12 EcoSpold meta information of anaerobic co-digestion in agricultural biogas plants

Name	biogas, from maize silage, co-digestion, at storage	biogas, from sugar beet, co-digestion, at storage	biogas, from fodder beet, co-digestion, at storage	biogas, from beet residues, co-digestion, at storage	biogas, from molasses, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage	biogas, from glycerine, co-digestion, at storage, scenario vegetable oil
Location	CH	CH	CH	CH	CH	CH	CH
InfrastructureProcess	0	0	0	0	0	0	0
Unit	Nm3	Nm3	Nm3	Nm3	Nm3	Nm3	Nm3
IncludedProcesses	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.	This data set includes the production of the substrate, transports of the substrates, the biogas plant infrastructure, the consumption of heat and electricity, the application of the digestates, and direct emissions to air.
LocalName	Biogas, aus Maissilage, Co-Vergärung, ab Speicher	Biogas, aus Zuckerrüben, Co-Vergärung, ab Speicher	Biogas, aus Futterrüben, Co-Vergärung, ab Speicher	Biogas, aus Rübenreste, Co-Vergärung, ab Speicher	Biogas, aus Melasse, Co-Vergärung, ab Speicher	Biogas, aus Glycerin, CoVergärung, ab Speicher	Biogas, aus Glycerin, CoVergärung, ab Speicher, Szenario Pflanzenöl
Synonyms	0	0	0	0	0	0	0
GeneralComment	The data set describes the anaerobic digestion of silage maize in co-digestion. The silage maize has a dry matter content of 0.28. A minimum of 10.4 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of sugar beets in co-digestion. The sugar beets have a dry matter content of 0.23. A minimum of 17.5 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of fodder beets in co-digestion. The fodder beets have a dry matter content of 0.15. A minimum of 11 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of beet residues in co-digestion. The beet residues have a dry matter content of 0.15. A minimum of 31.6 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of molasses from sugar beets in co-digestion. The molasses have a dry matter content of 0.72. A minimum of 4.9 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of glycerine in co-digestion. Glycerine has a dry matter content of 0.972. A minimum of 2.1 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.	The data set describes the anaerobic digestion of glycerine in co-digestion. Glycerine has a dry matter content of 0.972. A minimum of 2.1 % of the produced biogas needs to be burned in a cogeneration unit in order to meet the full heat demand and part of the electricity demand of the digestion unit.
InfrastructureIncluded	1	1	1	1	1	1	1
Category	biomass	biomass	biomass	biomass	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels	fuels	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse	Biomasse	Biomasse	Biomasse	Biomasse
LocalSubCategory	Treibstoffe	Treibstoffe	Treibstoffe	Treibstoffe	Treibstoffe	Treibstoffe	Treibstoffe
Formula							
StatisticalClassification							
CASNumber							
StartDate	2009	2009	2009	2009	2009	2009	2009
EndDate	2010	2010	2010	2010	2010	2010	2010
DataValidForEntirePeriod	1	1	1	1	1	1	1
OtherPeriodText							
Text	Data valid for Switzerland	Data valid for Switzerland	Data valid for Switzerland	Data valid for Switzerland	Data valid for Switzerland	Data valid for Switzerland	Data valid for Switzerland
Text	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.	Anaerobic digestion at mesophilic temperature.
Percent							
ProductionVolume							
SamplingProcedure	Questionnaire and literature study	Questionnaire and literature study	Questionnaire and literature study	Questionnaire and literature study	Questionnaire and literature study	Questionnaire and literature study	Questionnaire and literature study

9 Appendix B: LCI of application of digested matter on agricultural land

After the production of biogas, the digested matter is usually spread as fertiliser on agricultural land. This requires vehicles and machinery for transport and spreading and it leads to ammonia emissions into air and heavy metal emissions into soil. The filled in questionnaires show that solid digested matter is delivered over a distance between 1.5 km and 5 km with a weighted average distance of 3.0 km. Liquid digested matter is delivered over a distance between 0.5 km and 20 km with a weighted average distance of 10.5 km. The unit process raw data of application of digested matter on agricultural land is presented in Tab. 9.5.

9.1 Ammonia

As described in Section 8.2.4, 45.8 % of the ammonia content in the substrate is released into air when applying the digestates on agricultural fields. New biogas plants in Switzerland often use trail hoses for spreading liquid digested matter, which reduces the ammonia emissions about 40 % according to Edelmann (2006). We assume in the application datasets that such trail hoses are used. Hence, the ammonia emissions per kg digested matter are calculated with the following procedure: First, the share of NH_4 available nitrogen in the dry matter content is multiplied with the dry matter content of the substrate input per m^3 biogas and the amount of nitrogen is converted into ammonia with the molecular weight of the two substances. This amount of ammonia is multiplied with the emission factor of 45.8 % (see Section 8.2.4). The resulting figure is divided by the amount of digested matter per m^3 biogas and the 40 % emission reduction due to the use of trail hoses is applied. The nitrogen and ammonium content of the substrates is presented in Tab. 9.1.

Tab. 9.1 Nitrogen and ammonium content in substrates

	Nitrogen content according to the Institut für Energetik und Umwelt (2006)	NH_4-content according to according the Institut für Energetik und Umwelt (2006) and own estimations
	% TS	% TS
Maize silage	1.1-2	0.15-0.3
Sugar beets	2.6	0.2
Beet residues	0.2-0.4	0.04
Molasses	1.5	0.17

No dinitrogen monoxide emissions arise from the application of digestates, when using trail hoses (Jungbluth et al. 2010).

9.2 Heavy metals

When digested matter is applied as fertiliser on agricultural land, the heavy metal content of the biogas substrates is emitted into the soil. The heavy metal content of the substrates is displayed in Tab. 9.2 to Tab. 9.4.

In general, the heavy metal emissions from the digestates are calculated from the elemental composition of the substrates reported by the Institut für Energetik und Umwelt (2006). Missing data are completed with information from Freiermuth-Knuchel (2006).

It is considered that digestate matter from fodder beets has the same heavy metal content as digestate matter from sugar beets. The mercury content in beet residues is considered to be equal as in sugar beets.

Data of the heavy metal content of glycerine are not available, but it can be assumed that these values are low. The metal content in grease from a fat separator which amount to 44 mg copper and 290 mg zinc per kg grease according to the Institut für Energetik und Umwelt (2006) is considered for the calculation of heavy metal emissions during the application of glycerine digestates.

Tab. 9.2 Heavy metal content in silage maize

	Institut für Energetik und Umwelt (2006)	Freiermuth-Knuchel (2006)	This study
	mg/kg DM	mg/kg DM	mg/kg DM
Cd	0.2	0.1	0.1
Cr	0.5	0.7	0.7
Cu	4.8	5.0	5.0
Ni	5.0	0.5	0.5
Pb	2.0	1.6	1.6
Zn	45.5	34.5	34.5
Mn	31.0	-	31.0
Fe	67.0	-	67.0
Hg	-	0.01	0.01

Tab. 9.3 Heavy metal content in beet residues and sugar beets

	Beet residues	**Sugar Beets**
	Institut für Energetik und Umwelt (2006)	Freiermuth-Knuchel (2006)
	mg/kg DM	mg/kg DM
Cd	0.2	0.4
Cr	1.0	1.8
Cu	10.0	12.0
Ni	5.0	1.1
Pb	0.5	1.2
Zn	28.0	36.4
Mn	-	-
Fe	-	-
Hg	-	0.10

Tab. 9.4 Heavy metal content in molasses

	Institut für Energetik und Umwelt (2006)
	mg/kg FM
Cd	0.12
Cr	0.20
Cu	2.69
Ni	2.99
Pb	-
Zn	32.00
Mn	29.60
Fe	32.30
Hg	0.01
Sn	0.18

Tab. 9.5 Unit process raw data of application of digested matter on agricultural land

	Name	Location	InfrastructureProcess	Unit	application, digested matter, from maize silage, on agricultural land	application, digested matter, from beets, on agricultural land	application, digested matter, from beet residues, on agricultural land	application, digested matter, from molasses, on agricultural land	application, digested matter, from glycerine, on agricultural land	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
technosphere	slurry spreading, by vacuum tanker	CH	0	m3	1.00E-3	1.00E-3	1.00E-3	1.00E-3	1.00E-3	1	1.05	(1,1,1,1,1,1,BU:1.05);
	transport, tractor and trailer	CH	0	tkm	1.05E-2	1.05E-2	1.05E-2	1.05E-2	1.05E-2	1	2.02	(3,3,1,1,1,3,BU:2); 10.5 km average from questionnaires
emission air, high population density	Ammonia	-	-	kg	2.54E-4	1.86E-4	2.27E-5	7.81E-4	4.33E-4	1	1.39	(3,5,1,3,1,5,BU:1.2); Calculated from elemental composition of substrate. 40% reduction because of spreading with trail hoses.
emission soil, agricultural	Cadmium	-	-	kg	6.74E-8	1.11E-7	3.46E-8	1.96E-7	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Chromium	-	-	kg	2.36E-7	4.94E-7	1.73E-7	3.27E-7	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Copper	-	-	kg	1.69E-6	3.34E-6	1.73E-6	4.39E-6	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Iron	-	-	kg	2.26E-5			5.27E-5	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Mercury	-	-	kg	3.37E-9	3.23E-7	1.64E-8	1.63E-8	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Manganese	-	-	kg	1.04E-5			4.83E-5	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Nickel	-	-	kg	1.69E-6	3.01E-7	8.65E-7	4.88E-6	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Lead	-	-	kg	6.74E-7	3.23E-7	8.65E-8	-	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Tin	-	-	kg	-	-	-	2.94E-7	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate
	Zinc	-	-	kg	1.53E-5	1.01E-5	4.84E-6	5.22E-5	-	1	1.34	(3,5,1,3,1,5,BU:1.1); calculated from elemental composition of substrate

10 Appendix C: LCI of cogeneration of electricity and heat

In most agricultural biogas plants, biogas is burned in order to co-generate electricity and heat. The heat consumption in the biogas plants is usually met with the own heat generation whereas the electricity consumption is only partly met with own produced electricity and additional electricity from grid needs to be bought.

10.1 Emissions from combustion of biogas in agricultural co-generation units

Some older cogeneration units use pilot fuel, which leads to higher emission values. Newer types however use lean-burn engines with a SCR catalyst, which reduces the emissions considerably. Emission data for cogeneration unit of these newer technologies were updated and documented in Jungbluth et al. (2010). For the update of the ecoinvent data on biogas combustion, these values are applied.

In previous inventories, the emission of biogas is mainly estimated based on data of natural gas furnaces. However, newer publications show that in biogas plants partly much higher emissions occur (Bayer. Landesamt für Umwelt (Hrsg.) 2006:62ff, Nielsen & Illerup 2003:33ff, Kath 2009:3). Therefore, these emission factors are applied in this study.

The Swiss Clean Air Act[13] regulates the exhaust emissions of biogas cogeneration units with limits of 50 mg particulate matter per Nm^3, 400 mg/Nm^3 of NO_x and 650 mg/Nm^3 of CO (related to 5 % residual oxygen). The amount of nitrous oxides fluctuates considerably depending on the biogas quality (methane content). A typical 100 kW_{el} cogeneration unit with ignition engine emits about 1’100 mg/Nm^3 NO_x and 800 mg/Nm^3 CO (Ruch 2005).

In a research project a catalyst with SCR basis was developed which balances all fluctuations in the exhaust emissions from cogeneration units in biogas plants. This catalyst enables operators of cogeneration units to smoothly comply with the limits of the Clean Air Act (Ruch 2005).

In contrast to cogeneration units with very high emission factors, there are also cogeneration units available with much lower emissions which even fall below the limits in the canton Zurich of 50 mg NOx/Nm^3 and 150 mg CO/Nm^3.

Currently, no cogeneration units with catalysts are known in Switzerland. Normally, lean burn engines are used, which comply with the Clean Air Act limit of 400 mg/Nm^3. Considerably higher can be the emissions from ignition gas engines which are typically used in Germany and in which 5 to 10 % of diesel is co-burnt. With these engines it is difficult to comply with the Swiss limits (median of measurements at 450 mg/Nm^3). Therefore such ignition gas engines are a phased-out model. As far as it is known to the authors, since the last few years only lean burn engines were installed in Switzerland. Gas motors like all type of furnaces have to be checked regularly with regard to compliance with the exhaust emission limits in the Clean Air Act. (Jungbluth et al. 2010)

Within the survey about Swiss operators of biogas plants that was conducted in this project, 87.5 % of the operators declared that they installed biogas engines in their biogas plants. Only two operators use ignition engines, one with diesel and one with biodiesel. The operators declare their nitrous oxide emissions as between 300 and 900 mg/Nm3 with an average at 470 mg/Nm3 which is considerably higher than the 15 mg/Nm3 estimated by Jungbluth et al. (2007) based on natural gas furnaces. The

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[13] Luftreinhalteverordnung (LRV)

average nitrous oxide emissions from the survey are used for the dataset of the combustion of biogas in a biogas engine.

Tab. 10.1 Unit process raw data of combustion of biogas and pilot oil excluding infrastructure

	Name	Location	InfrastructurePro	Unit	operation, biogas combustion, in cogen with biogas engine	operation, biogas combustion, in cogen with ignition gas engine	operation, biogas combustion, in cogen 200kWe lean burn	operation, biogas combustion, in micro gas turbine 100kWe	operation, oil combustion, in cogen with ignition gas engine	Biogasdrevne motorer	General	ignition gas engine	ignition gas engine	gas cogeneration	biogas engine	LRV	General	ignition gas engine	ignition gas engine	gas cogeneration	biogas engine	LRV
	Location				CH	CH	CH	CH	CH	2003	2009	2006	2005	2006	2010		2009	2006	2005	2006	2010	
	InfrastructureProcess				0	0	0	0	0	Nielsen	Kath	BaxLfU	Ruch	BaxLfU	16 operators	CH	Kath	BaxLfU	Ruch	BaxLfU	16 operators	CH
	Unit				MJ	MJ	MJ	MJ	MJ	kg/MJ	kg/MJ	kg/MJ	kg/MJ	kg/MJ	kg/MJ	kg/MJ	mg/m3	mg/m3	mg/Nm3	mg/m3	mg/m3	mg/Nm3
product	operation, biogas combustion, in cogen with biogas	CH	0	MJ	1	0	0	0	0													
	operation, biogas combustion, in cogen with ignition gas	CH	0	MJ	0	1	0	0	0													
	operation, biogas combustion, in cogen 200kWe lean	CH	0	MJ	0	0	1	0	0													
	operation, biogas combustion, in micro gas turbine	CH	0	MJ	0	0	0	1	0													
	operation, oil combustion, in cogen with ignition gas	CH	0	MJ	0	0	0	0	1													
	lubricating oil, at plant	RER	0	kg	3.00E-5	3.00E-5	3.00E-5	5.00E-7	0													
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	3.00E-5	3.00E-5	3.00E-5	5.50E-7	0													
emission air, low population density	Carbon monoxide, biogenic			kg	3.05E-4	2.82E-4	3.05E-4	2.80E-5	0	2.73E-04	3.11E-04	4.61E-04	2.82E-04	1.97E-04		2.30E-04	882	1305	800	558		650
	Carbon dioxide, biogenic			kg	0.0809	8.09E-2	8.09E-2	8.09E-2	0													
	Methane, biogenic			kg	1.02E-4	1.98E-4	3.43E-4	5.40E-6	0	3.23E-04	3.63E-04	1.98E-04	0.00E+00	1.02E-04			1028	560		290		
	NMVOC, non-methane volatile organic compounds, unspecified origin			kg	1.40E-5	1.40E-5	1.40E-5	6.00E-7	2.63E-6	1.40E-05												
	Dinitrogen monoxide			kg	5.00E-7	5.00E-7	5.00E-7	1.00E-6	5.00E-6	5.00E-07												
	Sulfur dioxide			kg	2.10E-5	2.10E-5	2.10E-5	2.10E-5	1.20E-4	1.90E-05	5.83E-05						165					
	Platinum			kg	7.00E-12	0	0	0	0													
	Heat, waste			MJ	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E+0													
	Carbon monoxide, fossil			kg	0	0	0	0	1.26E-4													
	Carbon dioxide, fossil			kg	0	0	0	0	7.41E-2													
	Methane, fossil			kg	0	0	0	0	2.63E-6													
	Formaldehyde	-	-	kg	8.12E-7	3.11E-6	1.31E-6	1.31E-6	0	2.12E-05	3.28E-05	3.11E-06	0.00E+00	8.12E-07			93	8.8		2.3		
	Particulates, < 2.5 um	-	-	kg	2.06E-7	2.06E-7	2.06E-7	2.06E-7	1.50E-7	2.06E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00								
	Particulates, > 2.5 um, and < 10um	-	-	kg	4.51E-7	4.51E-7	4.51E-7	4.51E-7	4.51E-7	4.51E-07												
	Particulates, > 10 um	-	-	kg	1.97E-6	1.97E-6	1.97E-6	1.97E-6	1.97E-6	1.97E-06						1.77E-05						50
	Acenaphthene	-	-	kg	3.34E-9	3.34E-9	3.34E-9	3.34E-9	3.34E-9	3.34E-09												
	Benzo(a)pyrene	-	-	kg	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12												
	Acetaldehyde	-	-	kg	1.10E-7	1.10E-7	1.10E-7	1.10E-7	1.10E-7	1.10E-07												
	Acrolein	-	-	kg	1.00E-8	1.00E-8	1.00E-8	1.00E-8	1.00E-8	1.00E-08												
	Propanal	-	-	kg	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-08												
	Acetone	-	-	kg	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-08												
	Butanol	-	-	kg	1.00E-8	1.00E-8	1.00E-8	1.00E-8	1.00E-8	1.00E-08												
	Benzaldehyde	-	-	kg	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-8	2.00E-08												
	Nitrogen oxides			kg	1.66E-4	4.26E-4	1.41E-4	3.20E-5	5.78E-5	5.40E-04	2.55E-04	4.64E-04	3.88E-04	6.29E-04	1.66E-04	1.41E-04	723	1313	1100	1781	470	400

10.2 Cogeneration of electricity and heat

The range of capacities and the efficiency of the cogeneration units with biogas engines considered in the survey within this project is displayed and compared to the data used in Jungbluth et al. (2007) in Tab. 10.2. The average electric and thermal efficiency from the survey is considered in order to establish datasets of the cogeneration of electricity and heat with biogas from specific substrates.

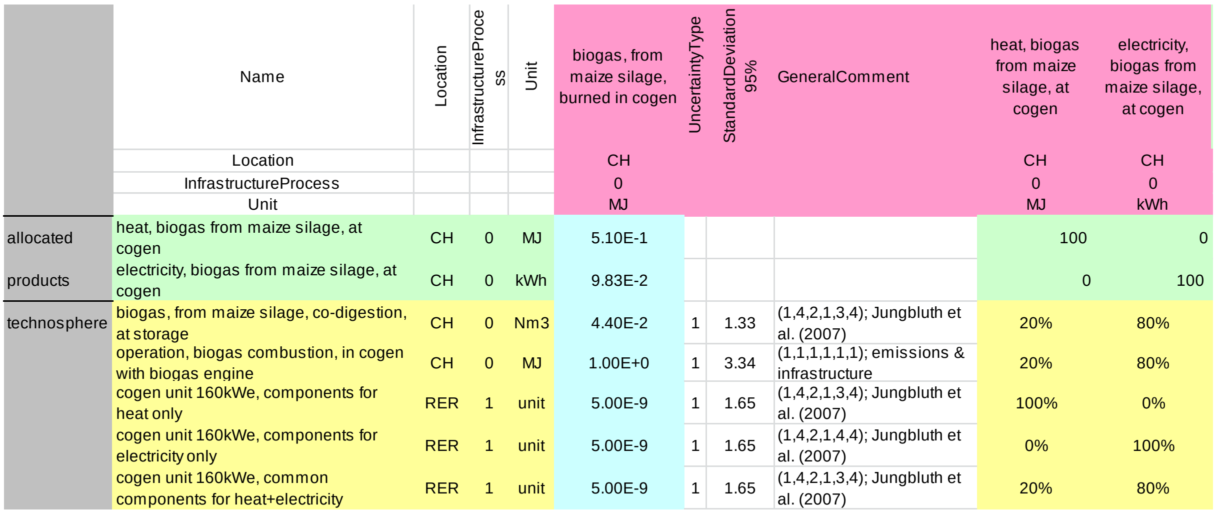
Tab. 10.2 Selected results of the survey of 16 Swiss operators compared to the data implemented by Jungbluth et al. (2007)

		Survey of 16 Swiss biogas operators (2010)			
		minimum	**maximum**	**average**	**Jungbluth et al. (2007)**
capacity	**kW**	15	250	118.6	160
electric efficiency	**%**	25%	39%	35.4%	32%
thermal efficiency	**%**	45%	64%	51.0%	55%
nitrous oxide emissions	**mg/Nm^3**	300	900	470.0	15

The inventory of the cogeneration of heat and electricity encompasses the infrastructure, the operation of the engine (including auxiliary materials and emissions into air), and the specific type of used biogas. In Tab. 10.3 the example of cogeneration of heat and electricity with biogas from maize silage is presented. Furthermore, five analogue unit process datasets of cogeneration with biogas from sugar beet, fodder beet, beet residues, molasses, and glycerine are established.

The allocation of the emissions and the shared infrastructure elements to the two products heat and electricity is based on exergy content. The exergy value of electricity is 1 and the exergy value of heat is 0.17. The multiplication of the exergy value with the heat and electricity outputs per MJ biogas input leads to an allocation of 80 % to the electricity generation and 20 % to the heat generation.

Tab. 10.3 Unit process raw data of the cogeneration of heat and electricity from biogas (example of biogas from maize silage)



	Name	Location	InfrastructureProcess	Unit	biogas, from maize silage, burned in cogen	UncertaintyType	StandardDeviation95%	GeneralComment	heat, biogas from maize silage, at cogen	electricity, biogas from maize silage, at cogen
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, biogas from maize silage, at cogen	CH	0	MJ	5.10E-1				100	0
products	electricity, biogas from maize silage, at cogen	CH	0	kWh	9.83E-2				0	100
technosphere	biogas, from maize silage, co-digestion, at storage	CH	0	Nm3	4.40E-2	1	1.33	(1,4,2,1,3,4); Jungbluth et al. (2007)	20%	80%
	operation, biogas combustion, in cogen with biogas engine	CH	0	MJ	1.00E+0	1	3.34	(1,1,1,1,1,1); emissions & infrastructure	20%	80%
	cogen unit 160kWe, components for heat only	RER	1	unit	5.00E-9	1	1.65	(1,4,2,1,3,4); Jungbluth et al. (2007)	100%	0%
	cogen unit 160kWe, components for electricity only	RER	1	unit	5.00E-9	1	1.65	(1,4,2,1,4,4); Jungbluth et al. (2007)	0%	100%
	cogen unit 160kWe, common components for heat+electricity	RER	1	unit	5.00E-9	1	1.65	(1,4,2,1,3,4); Jungbluth et al. (2007)	20%	80%

11 Appendix D: LCI of a grass refinery

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Last changes: 2010

11.1 Introduction

The grass refinery of the Biowert Industrie GmbH. produces insulation material (AgriCell), organic fertiliser (AgriFer) and biopolymers (AgriPlast) from grass silage as raw material. The grass silage is stored in a silo and later fed in a disintegration process. After the disintegration process, the grass fibres are used for AgriCell and AgriPlast production. Grass slurry is a by-product of the grass disintegration. Together with cow slurry it is used as a substrate in the biogas production. The biogas is burned in a cogeneration unit, which generates heat and electricity used for the different production processes or could be sold as grid electricity. In order to utilize digestate from the anaerobic digestion, the organic matter content is concentrated in a reversed osmosis. The products of this process can be used as organic fertilizers (AgriFer) on the grass fields. A part of the remaining process water is recycled in the grass disintegration process and the remaining is introduced in nearby surface waters. This LCI investigates the resources needed to produce these products from grass at the grass refinery.

The production process as described above creates two options for closed loop resource management. Firstly, the electricity produced in the cogeneration unit could be used meet the electricity demand of the production process. Secondly, the fertiliser AgriFer can be used in the grass cultivation.

This Chapter is based on an LCA study of the Biowert grass refinery prepared by Leuenberger & Jungbluth (2010).

11.2 Resources

The main resource for the products at the grass refinery is the grass cultivated in the region. Farmers cut and store the grass for the grass refinery in silos. The concept of Biowert Industrie GmbH includes that the digestate from the anaerobic digestion is brought back to the grass fields, where it is applied as organic fertiliser. In order to represent this closed loop resource management in the LCI of the products, the grass cultivation is evaluated in two scenarios, one including the use of AgriFer, one basing on the use of mineral fertiliser only. The electricity and heat produced in the cogeneration unit can be assumed as input in the production process.

11.3 Characterisation and use of products

11.3.1 AgriCell

AgriCells consists of grass fibres, which are treated with borax and boric acid. The product can be used as insulation material in buildings, similar to the use of cellulose fibres from recycling paper. It replaces the use of synthetically produced insulation materials such as rock or mineral wool.

11.3.2 AgriPlast

Grass fibres are mixed with polypropylene or other thermoplasts in order to enhance the stability of the pure thermoplast and reduce the material need for polypropylene granulate.

AgriPlast can be compared to other natural fibre reinforced thermoplasts or to polypropylene products.

11.3.3 AgriFer

The grass slurry is digested in a biogas plant together with other substrates, mainly biowastes and cow slurry. The remaining digestate can be used as fertilizer on the grass field, which would close the nutrient cycle on a local basis.

11.3.4 Heat and Electricity

The cogeneration unit produces heat and electricity from the biogas. The heat is used for the different process steps; the electricity is either fed into the supply grid or used in the production processes.

11.4 Life cycle inventories

11.4.1 Grass cultivation in Germany

The grass silage is produced from locally grown rye grass. In order to represent the actual cultivation strategy of local farmers, the grass cultivation is modelled specifically for the case of the Biowert grass refinery.

Only one farmer provided data for the life cycle inventory of grass cultivation. Some information was therefore completed by adding information from Biowert and other sources in order to obtain representative data basis for a standard scenario. As a future scenario, the application of AgriFer fertiliser is investigated as a strategy to close the nutrient cycle. Both scenarios base on the same assumption and data for grass cultivation, only the fertiliser use is changed from mineral fertiliser to AgriFer in the additional scenario.

The annual grass yield per hectare is 67 tons fresh matter or 20 tons dry matter. Thus, the dry matter content is 30%. Usually, the grass is grown in rotation with sugar beet and wheat. In this case, cultivation period for grass is two years. Within this cultivation period, the grass is cut four times (twice a year), without additional ploughing or sowing. The soil type is characterised by weathered loess-loam.

After the cut, the grass is transported to a silo, where it is stored for silage production. Some silos are situated in the vicinity (3 km) of the Biowert plant (60%); further amounts of grass (40%) are stored directly in the silo at the Biowert plant site. The average transport distance with a tractor from the field to the silo is set to 8.25 km.

The soil is prepared for sowing by ploughing and harrowing once in the two years of the cultivation period. Fertiliser use is limited to NPK mineral fertilisers, no pesticides are applied. For the scenario of AgriFer application, the nutrient input is partly substituted by the use of liquid and solid AgriFer. The official analysis of the digestate (Bundesgütegemeinschaft Kompost E.V. 2008) recommends the annual use of 7 tons AgriFer solid and 17 m^3 AgriFer liquid per hectare. Applying these amounts, the need for AgriFer solid would exceed the produced amount. Therefore, the use of AgriFer solid is set 3.7 tons per hectare, which is the amount that can be met by the annual AgriFer solid production. Together with the 17 m3 AgriFer liquid an overall amount of 239 kg N per hectare is applied.

The emissions into soil, water and air arising from agricultural activities have a considerable influence on the environmental impact of a crop. These are mainly influenced by the use of fertiliser and pesticide. In the case of grass cultivation, the nitrate leaching to groundwater and the ammonia emissions are key factors. Basically, emissions are quantified using different models, which use the fertiliser or pesticide input and soil properties as parameters. The modelling of both scenarios is based on the models used for ecoinvent life cycle inventories (Nemecek et al. 2007).

Tab. 11.1: Input parameter for the modelling of grass cultivation. Data per hectare of cultivation and year (2007)

Process, Input	Unit	Standard	with AgriFer use	
		ha	ha	
Lorry	tkm	56	16	100 km for mineral fertiliser, 10km for AgriFer from Biowert to field
Fodder loader	tkm	553	553	1.5-15km to silo. Tractor used for ploughing, harrowing and fertiliser application.
Barge	tkm	28	8	50km, standard distances for transport of feriliser
Ploughin	ha	0.5	0.5	Soil preparation once per two years of grass cultivation
Harrowing	ha	0.5	0.5	Soil preparation once per two years of grass cultivation
Rolling	ha	0	0	
Sowing	ha	0.5	0.5	Sowing once preparation per two years of grass cultivation
Chiselling	ha	0	0	
Fertiliser/pesticide application	ha	2	2	Fertiliser application four times in two years
Mowing	ha	2	2	Mowing four times in two years
Loading fodder loader	m3	558	558	Calculated according to ecoinvent: 120kg/m3
N-fertilizer, tot	kg	210	239	Calculated from N-input
P2O5-fertilizer, tot	kg	100	100	Calculated from P2O5-input
K2O-fertilizer, min	kg	250	215	Calculated from K2O-input
Manganese	kg	0	0	n.a.
Lime	kg	0	0	n.a.
Solid manure	kg	0	3714	AgriFer solid, max. possible input
Slurry and liquid manure	m^3	0	17	AgriFer liquid, recommended input
Yield (dm)	kg DS/h	20000	20000	Biowert Questionnaire
Amount of harvests	-	2	2	Biowert Questionnaire
Duration of plantation	a	2	2	Biowert Questionnaire
Seeds spread	kg	45	45	Biowert Questionnaire
Number of pesticide applications	-	0	0	Biowert Questionnaire
Pesticides	kg	0.00	0.00	Calculation
Water content crop	%	70.0%	70.0%	Biowert Questionnaire
NO3-N emission factor	%	27.5%	27.5%	Modelled according to ecoinvent (Nemecek et al., 2007)
N2O-N emission factor	%	2.0%	2.0%	Modelled according to ecoinvent (Nemecek et al., 2007)
NH3-N emission factor	%	4.5%	17.4%	Modelled according to ecoinvent (Nemecek et al., 2007)
Total mineral fertiliser	kg/ha	560	155	Sum of all fertilisers (in kg mineral, not total weight), data sheet Biowert
N-total, Mineral	kg	210	0	Biowert Questionnaire

Tab. 11.2: Unit process raw data of grass cultivation

	Name	Location	InfrastructureProcess	Unit	grass, Biowert, 30% dm, at farm	grass, Biowert, AgriFer, 30% dm, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
	Location InfrastructureProcess Unit				DE 0 kg	DE 0 kg			
fertilizer	agriFer, solid, at grass refinery	RER	0	kg	0	1.86E-1	1	1.32	(4,4,1,1,1,5); Recommendation digestate analysis: 7t/ha
	agriFer, liquid, at grass refinery	RER	0	m3	0	8.50E-4	1	1.32	(4,4,1,1,1,5); Recommendation digestate analysis: 17t/ha
	ammonium nitrate, as N, at regional storehouse	RER	0	kg	5.18E-3	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	3.98E-4	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	calcium ammonium nitrate, as N, at regional storehouse	RER	0	kg	2.59E-3	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	5.48E-4	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	urea, as N, at regional storehouse	RER	0	kg	1.79E-3	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	potassium chloride, as K2O, at regional storehouse	RER	0	kg	1.08E-2	4.07E-3	1	1.32	(4,4,1,1,1,5); data sheet Biowert: 86% of K2O input
	potassium sulphate, as K2O, at regional storehouse	RER	0	kg	1.75E-3	6.63E-4	1	1.32	(4,4,1,1,1,5); data sheet Biowert: 14% of K2O input
	lime, from carbonation, at regional storehouse	CH	0	kg	0	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	1.40E-3	8.48E-4	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	single superphosphate, as P2O5, at regional storehouse	RER	0	kg	1.00E-4	6.05E-5	1	1.32	(4,4,1,1,1,5); data sheet Biowert: Assumption for all P2O5 input
	thomas meal, as P2O5, at regional storehouse	RER	0	kg	2.50E-4	1.51E-4	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	triple superphosphate, as P2O5, at regional storehouse	RER	0	kg	2.05E-3	1.24E-3	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
	phosphate rock, as P2O5, beneficiated, dry, at plant	MA	0	kg	1.20E-3	7.27E-4	1	1.32	(4,4,1,1,1,5); data sheet Biowert, share according to ecoinvent
seeds	grass seed IP, at farm	CH	0	kg	1.13E-3	1.13E-3	1	1.32	(4,4,1,1,1,5); data sheet Biowert
	pesticide unspecified, at regional storehouse	CH	0	kg	0	0	1	1.32	(4,4,1,1,1,5); data sheet Biowert
	transport, lorry >28t, fleet average	CH	0	tkm	2.80E-3	7.76E-4	1	2.09	(4,5,na,na,na,na); 100 km for mineral fertiliser, 10km for AgriFer from Biowert to field
	transport, tractor and trailer	CH	0	tkm	2.76E-2	3.80E-2	1	2.09	(4,5,na,na,na,na); 8.25km transport of grass according to Biowert Questionnaire
	transport, barge	RER	0	tkm	1.40E-3	3.88E-4	1	2.09	(4,5,na,na,na,na); 50km, standard distances for transport of feriliser
	tillage, cultivating, chiselling	CH	0	ha	0	0	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	tillage, harrowing, by rotary harrow	CH	0	ha	2.50E-5	2.50E-5	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	tillage, ploughing	CH	0	ha	2.50E-5	2.50E-5	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	tillage, rolling	CH	0	ha	0	0	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	sowing	CH	0	ha	2.50E-5	2.50E-5	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	fodder loading, by self-loading trailer	CH	0	m3	2.79E-2	2.79E-2	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	fertilising, by broadcaster	CH	0	ha	1.00E-4	1.00E-4	1	1.30	(4,5,na,na,na,na); data sheet Biowert
	mowing, by rotary mower	CH	0	ha	1.00E-4	1.00E-4	1	1.30	(4,5,na,na,na,na); data sheet Biowert
resource, in air	Carbon dioxide, in air	-	-	kg	2.86E+0	2.86E+0	1	1.26	(3,4,1,1,1,5); carbon uptake of plants = 2.86 kg CO2/kgDM
resource, biotic	Energy, gross calorific value, in biomass	-	-	MJ	1.79E+1	1.79E+1	1	1.26	(3,4,1,1,1,5); energy content of harvested product=26.48 MJ/kgDM
resource, water	Water, rain	-	-	m3	3.50E-1	3.50E-1	1	1.26	(3,4,1,1,1,5); average rainfall in the region during the plantation, assumption: 700mm/m2
resource, land	Occupation, pasture and meadow, intensive	-	-	m2a	5.00E-1	5.00E-1	1	1.28	(3,4,1,1,1,5); land occupation, yield: 67'000 t FM/ha
	Transformation, from arable	-	-	m2	1.25E-1	1.25E-1	1	1.34	(3,4,1,1,1,5); 50% of total transformation
	Transformation, from pasture and meadow, extensive	-	-	m2	1.25E-1	1.25E-1	1	1.34	(3,4,1,1,1,5); 50% of total transformation
	Transformation, to pasture and meadow, intensive	-	-	m2	2.50E-1	2.50E-1	1	1.34	(3,4,1,1,1,5); transformation to meadow intensive
emission air, low population density	Ammonia	-	-	kg	5.80E-4	2.52E-3	1	1.48	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
	Dinitrogen monoxide	-	-	kg	3.21E-4	3.59E-4	1	1.70	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
	Nitrogen oxides	-	-	kg	6.73E-5	7.54E-5	1	1.70	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
emission soil, agricultural	Cadmium	-	-	kg	3.48E-7	1.82E-7	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer

	Chromium	-	-	kg	4.99E-6	3.81E-6	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
	Copper	-	-	kg	-6.48E-6	-3.66E-6	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
	Lead	-	-	kg	-2.51E-6	-2.30E-6	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
	Mercury	-	-	kg	-1.26E-7	-1.20E-7	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
	Nickel	-	-	kg	-6.35E-7	-6.24E-8	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
	Zinc	-	-	kg	-2.81E-5	-2.02E-5	1	1.70	(4,4,1,5,3,5); input-output balance for seeds, products and fertilizer
emission water, ground-	Nitrate	-	-	kg	1.28E-2	1.46E-2	1	1.70	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
	Phosphate	-	-	kg	9.19E-6	9.47E-6	1	1.70	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
emission water, river	Phosphate	-	-	kg	4.79E-5	5.05E-5	1	1.70	(4,4,1,5,3,5); model calculation for emissions based on fertilizer application
	Phosphorus	-	-	kg	2.30E-7	2.30E-7	1	1.70	(4,4,1,5,3,5); emission due to erosion

11.4.2 Grass refinery infrastructure

The infrastructure at the grass refinery is evaluated for the different buildings separately, which allows us to attribute the environmental impact of the buildings to the individual production processes.

The LCI are established for the following infrastructure:

Tab. 11.3: Overview of infrastructure of the grass refinery

Name of infrastructure	Description
Silo installation, grass storage	Concrete tank, covered by plastic canvas for grass storage
Grass disintegration	Building and machinery for the processing of grass silage to grass fibres and grass slurry
Insulation material production	Building and machinery for the processing and packing of grass fibres to AgriCell
Plastic production	Building and machinery for the production of AgriPlast
Biogas plant	Building for biogas production and digestate storage
Cogeneration unit	Building and engine material for electricity and heat production

All buildings are built on a concrete sole plate and contain a certain amount of concrete and reinforcing steel. Further materials used for the construction are mainly bricks, steel and wood. Besides the construction material, the land use is taken into account (see Tab. 11.4).

Some buildings can be clearly attributed to a production process, like for instance the biogas plant for the biogas production or the cogeneration unit to the electricity or heat production. Other buildings however, have to be allocated to the different production processes, which is carried out according to the following allocation rules:

Grass disintegration infrastructure: 50% to AgriCell production, 50% to AgriPlast production

Tab. 11.5 shows the input materials for the different buildings and summarizes the transport processes for the material transport to the construction site. The transport distances are set according to the standard distances indicated in the ecoinvent report No. 1 (Frischknecht et al. 2007a)

The life expectancy of all infrastructures is set to 20 years.

Tab. 11.4 Raw materials in buildings and infrastructure of the grass refinery

		train	lorry	silo installation	grass disintegration	insulation material production	plastic production	biogas plant	cogeneration unit	Source
	Unit	km	km							
Emaillierte Fläche	m^2							1671		39.6to à 7900kg/m^3, 2x0.33mm
steel, low-alloyed	kg	200	100		26000	300	800	30000	15000	Questionnaire Biowert; partly based on assumption
stainless steel	kg	200	100		27000		5000	21000	2000	Questionnaire Biowert; partly based on assumption
steel sheet	kg				8887.5		5332.5	17775		Questionnaire Biowert; partly based on assumption, 0.75mm, density: 7900 kg/m^3
concrete	kg	-	50	1000000	660000		30000	2240000	290000	Estimation Biowert: 1000t, ecoinvent: 0.91vol% in reinforced steel, density: http://www.crtib.lu/Leitfaden/content/DE/116/C528/
bricks	kg		50		10000	10000	40000	20000		Questionnaire Biowert; partly based on assumption
wood		-	100			1000				Questionnaire Biowert; partly based on assumption
copper		200	100		400					Questionnaire Biowert; partly based on assumption
control cabinet	unit	200	100		3.50	1.56	1.56	19.45	3.11	Entire equipment allocated to different infrastructure. AF: Share of built area
cables	m	200	100		60	26.67	26.67	333.33	53.33	75t!, 500m (über Dichte abgeschätzt), alloziert über Flächenbedarf ohne Silo
industrial area, built up	m^2			2500	450	200	200	2500	400	Questionnaire Biowert; partly based on assumption
area, uncovered	m^2			460	82.8	36.8	36.8	460	73.6	Questionnaire Biowert; partly based on assumption
area, vegetation	m^2			2960	532.8	236.8	236.8	2960	473.6	Questionnaire Biowert; partly based on assumption
transport lorry	tkm			50000	38840	630	4080	118100	16200	Standard distances
transport train	tkm			0	10680	60	1160	10200	3400	Standard distances
life expectancy of infrastructure	a			20	20	20	20	20	20	Assumption: 20 years

Tab. 11.5 Unit process raw data of the grass refinery infrastructure data sets

Name	Location	Infrastructure Process	Unit	silo installation grass storage	grass disintegration infrastructure	insulating material production infrastructure	plastic production infrastructure	anaerobic digestion plant	cogeneration plant, in grass refinery	UncertaintyType	StandardDeviation95%	GeneralComment
Location InfrastructureProcess Unit				RER 1 unit	RER 1 unit	RER 1 unit	RER 1 unit	RER 1 unit	RER 1 unit			
enamelling	RER	0	m2	0	0	0	0	1.67E+3	0	1	1.33	(2,4,1,1,3,5); 39.6to à 7900kg/m3, 2x0.33mm
steel, low-alloyed, at plant	RER	0	kg	0	3.49E+4	3.00E+2	6.13E+3	4.78E+4	1.50E+4	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
chromium steel 18/8, at plant	RER	0	kg	0	2.70E+4	0	5.00E+3	2.10E+4	2.00E+3	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
sheet rolling, steel	RER	0	kg	0	8.89E+3	0	5.33E+3	1.78E+4	0	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption, 0.75mm, density: 7900 kg/m3
concrete, normal, at plant	CH	0	m3	3.74E+2	2.47E+2	0	1.12E+1	8.39E+2	1.09E+2	1	1.33	(2,4,1,1,3,5); Estimation Biowert: 1000t, ecoinvent: 0.91vol% in reinforced steel, density: http://www.crtib.lu/Leitfaden/content/DE/116/C528/
reinforcing steel, at plant	RER	0	kg	2.91E+5	1.92E+5	0	8.72E+3	6.51E+5	8.43E+4	1	1.33	(2,4,1,1,3,5); Estimation Biowert: 1000t, Ecoinvent: 0.09 Vol% in reinforced concrete, density: http://www.crtib.lu/Leitfaden/content/DE/116/C459/
brick, at plant	RER	0	kg	0	1.00E+4	1.00E+4	4.00E+4	2.00E+4	0	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
sawn timber, softwood, planed, air dried, at plant	RER	0	m3	0	0	1.00E+3	0	0	0	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
copper, at regional storage	RER	0	kg	0	4.00E+2	0	0	0	0	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
control cabinet cogen unit 160kWe	RER	1	unit	0	3.50E+0	1.56E+0	1.56E+0	1.95E+1	3.11E+0	1	3.11	(2,4,1,1,3,5); Entire equipment allocated to different infrastructure. AF: Share of built area
cable, connector for computer, without plugs, at plant	GLO	0	m	0	6.00E+1	2.67E+1	2.67E+1	3.33E+2	5.33E+1	1	1.33	(2,4,1,1,3,5); 75t!, 500m (über Dichte abgeschätzt), alloziert über Flächenbedarf ohne Silo
Occupation, industrial area, built up	-	-	m2a	5.00E+4	9.00E+3	4.00E+3	4.00E+3	5.00E+4	8.00E+3	1	1.64	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
Occupation, industrial area, vegetation	-	-	m2a	9.20E+3	1.66E+3	7.36E+2	7.36E+2	9.20E+3	1.47E+3	1	1.64	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
Transformation, from pasture and meadow	-	-	m2	2.96E+3	5.33E+2	2.37E+2	2.37E+2	2.96E+3	4.74E+2	1	1.40	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
Transformation, to industrial area, built up	-	-	m2	5.00E+4	9.00E+3	4.00E+3	4.00E+3	5.00E+4	8.00E+3	1	2.11	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
Transformation, to industrial area, vegetation	-	-	m2	9.20E+3	1.66E+3	7.36E+2	7.36E+2	9.20E+3	1.47E+3	1	2.11	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
transport, lorry >16t, fleet average	RER	0	tkm	5.00E+4	3.88E+4	6.30E+2	4.08E+3	1.18E+5	1.62E+4	1	2.09	(4,5,na,na,na,na); standard distances
transport, freight, rail	RER	0	tkm	0	1.07E+4	6.00E+1	1.16E+3	1.02E+4	3.40E+3	1	2.09	(4,5,na,na,na,na); standard distances
disposal, building, brick, to sorting plant	CH	0	kg	0	1.00E+4	1.00E+4	4.00E+4	2.00E+4	0	1	1.33	(2,4,1,1,3,5); Questionnaire Biowert; partly based on assumption
disposal, building, reinforced concrete, to sorting plant	CH	0	kg	1.00E+6	6.60E+5	0	3.00E+4	2.24E+6	2.90E+5	1	1.33	(2,4,1,1,3,5); Estimation Biowert: 1000t, ecoinvent: 0.91vol% in reinforced steel, density: http://www.crtib.lu/Leitfaden/content/DE/116/C528/
disposal, building, electric wiring, to final disposal	CH	0	kg	0	6.00E+1	2.67E+1	2.67E+1	3.33E+2	5.33E+1	1	1.33	(2,4,1,1,3,5); 75t!, 500m (über Dichte abgeschätzt), alloziert über Flächenbedarf ohne Silo

11.4.3 Grass silage production

The grass is cut and transported to a silo. There the grass is stored for approximately 100 days. During this process it loses water, which leads to an increase of the dry matter content from 30% to 35% (source: Questionnaire). The silage is brought then to the Biowert site (transport distance: 3km) and fed into the grass disintegration process. The grass silage data set includes grass input from both production methods. The share of the two production methods can be varied according to actual or hypothetical situations.

Tab. 11.6 Unit process raw data of grass silage production

	Name	Location	Infrastruc	Unit	grass silage, 35% dm, at silo	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	grass silage, 35% dm, at silo	RER	0	kg	1			
technosphere	grass, Biowert, 30% dm, at farm	DE	0	kg	3.33E-1	1	1.21	(1,1,1,1,1,5,BU:1.05); For scenario calculation. Grass dm=30%, silage dm=35%
	grass, Biowert, AgriFer, 30% dm, at farm	DE	0	kg	3.33E-1	1	1.21	(1,1,1,1,1,5,BU:1.05); For scenario calculation. Grass dm=30%, silage dm=35%
	grass from natural meadow extensive organic, at field	CH	0	kg	3.33E-1	1	1.21	(1,1,1,1,1,5,BU:1.05); For scenario calculation. Grass dm=15%, silage dm=35%
	transport, tractor and trailer	CH	0	tkm	3.00E-3	1	2.02	(2,1,1,1,1,4,BU:2); Questionnaire: 3 km from pasture to silo
	silo installation grass storage	RER	1	unit	2.50E-9	1	3.09	(4,1,1,1,1,5,BU:3); life time: 20 years

11.4.4 Grass disintegration

The grass disintegration process separates the grass fibre from aqueous parts of the grass silage. The grass fibres are the raw material for AgriPlast and AgriCell production and the grass slurry is used as a substrate in the biogas plant.

The allocation of the materials and energy needed for the grass disintegration to the two products is carried out using the dry matter content as allocation factor. The grass fibres account for 2'500 tons of dry matter annually and the grass slurry for 825 tons. This leads to an allocation factor of 24.8% for grass slurry and 75.2 % for grass fibres, respectively.

Tab. 11.7 Input data for the modelling of the grass disintegration process

Annual Input			**Source**
Input grass silage	t/a	20000	Questionnaire Biowert
Dry matter content in grass	%	30%	Questionnaire Biowert
Dry matter content grass silage	%	35%	Questionnaire Biowert
Grass silage input dry matter content	t/a	7000	Questionnaire Biowert
process water per ton dry matter grass silage	m^3/t	5.5	Questionnaire Biowert
Electricity	kWh	1.75E+06	Questionnaire Biowert
Heat from cogeneration unit	MJ	2.40E+07	Questionnaire Biowert
Heat from natural gas	MJ	7.00E+06	Questionnaire Biowert
Annual output			
Grass fibres (dm)	t	2.50E+03	Questionnaire Biowert
Grass slurry	m^3	2.75E+04	Questionnaire Biowert
Grass slurry (dm:3%)	t	8.25E+02	Questionnaire Biowert
Share grass fibres (from dm input)	%	75.19%	Calculated
Share grass slurry (from dm input)	%	24.81%	Calculated
Life expectancy infrastructure	a	20	Assumption

Tab. 11.8 Unit process raw data of grass disintegration

	Name	Location	InfrastructureProcess	Unit	grass silage, in grass disintegration	GeneralComment	grass slurry, at grass disintegration	grass fibres, at grass disintegration
	Location				RER		RER	RER
	InfrastructureProcess				0		0	0
	Unit				kg		m3	kg
allocated products	grass slurry, at grass disintegration	RER	0	m3	2.75E+04	(1,1,1,1,1,1); Product		
	grass fibres, at grass disintegration	RER	0	kg	2.50E+06	(1,1,1,1,1,1); Product		
technosphere	grass silage, 35% dm, at silo	RER	0	kg	7.00E+6	(1,1,1,1,1,5); Questionnaire Biowert	24.81%	75.19%
	process water, at decanter	RER	0	m3	1.10E+5	(1,1,1,1,1,5); Questionnaire Biowert	24.81%	75.19%
	electricity mix, at grass refinery	RER	0	kWh	1.75E+6	(1,1,1,1,1,5); Questionnaire Biowert	24.81%	75.19%
	heat, at cogen, grass refinery	RER	0	MJ	2.40E+7	(1,1,1,1,1,5); Questionnaire Biowert	24.81%	75.19%
	heat, natural gas, at industrial furnace low-NOx >100kW	RER	0	MJ	7.00E+6	(1,1,1,1,1,5); Questionnaire Biowert	24.81%	75.19%
	grass disintegration infrastructure	RER	1	unit	5.00E-2	(2,1,1,1,1,5); Assumption	24.81%	75.19%
emission air, high population density	Heat, waste	-	-	MJ	6.30E+6	(2,1,1,1,1,5); calculation	24.81%	75.19%

11.4.5 Grass fibre processing: AgriCell and AgriPlast

The production of AgriCell and AgriPlast involves the treatment of the grass fibres with the flame retardants borax and boric acid. This is the only treatment necessary to obtain AgriCell, the insulation material. It is packed in plastic bags for transportation to the construction site.

For the production of AgriPlast, the fibres are mixed with polypropylene and processed to granulate. The AgriPlast granulate is packed in plastic bags or is directly processed in injection moulding or extrusion. The fraction of grass fibres and matrix can vary. We assume a weight ratio of 50% grass fibres and 50% polypropylene.

Tab. 11.9: Production volumes of AgriCell and AgriPlast

Production		**AgriCell**	**AgriPlast**	**Source**
Input Grass fibres (dry matter)	t/a	1.25E+03	1.25E+03	Questionnaire Biowert: Assumption 50% AgriCell, 50% AgriPlast, dry matter: 92%
Output AgriCell (incl. water content)	t/a	1410	-	Questionnaire Biowert: Assumption 50% AgriCell
Output AgriPlast (incl. water content)	t/a	-	2500	Questionnaire Biowert: Assumption 50% AgriPlast
Borax	t/a	50	-	Questionnaire Biowert: 4% of mass
Packaging material (foil)	t/a	20	15	Questionnaire Biowert: 0.147 kg per package, 141000 packages
Polypropylene	t/a		1250	Questionnaire Biowert
Electricity	kWh	2.50E+04	6.25E+05	Questionnaire Biowert
Waste, municipal waste incineration	t/a	5		Questionnaire Biowert: waste from packaging and cleaning
Infrastructure				
Life expectancy infrastructure	a	20	20	Assumption: 20 years life time

Tab. 11.10 Unit process raw data of AgriCell and AgriPlast production

	Name	Location	Infrastructur	Unit	AgriCell, at grass refinery	AgriPlast, granulate PP, at grass refinery	Uncertainty Type	StandardDeviation95%	GeneralComment
	Location				RER	RER			
	InfrastructureProcess				0	0			
	Unit				kg	kg			
product	AgriCell, at grass refinery	RER	0	kg	1.00E+00	0.00E+00			
	AgriPlast, granulate PP, at grass refinery	RER	0	kg	0.00E+00	1.00E+00			
technosphere	grass fibres, at grass disintegration	RER	0	kg	8.87E-1	5.00E-1	1	1.21	(1,1,1,1,1,3); Questionnaire Biowert: Assumption 50% AgriCell, 50%
	Borax, anhydrous, powder, at plant	RER	0	kg	3.55E-2		1	1.21	(1,1,1,1,1,3); Questionnaire Biowert: 4% of mass
	polypropylene, granulate, at plant	RER	0	kg		5.00E-1	1	1.21	(1,1,1,1,1,3); Questionnaire Biowert
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.42E-2	5.84E-3	1	1.21	(1,1,1,1,1,3); Questionnaire Biowert
	electricity mix, at grass refinery	RER	0	kWh	1.77E-2	2.50E-1	1	1.21	(1,1,1,1,1,3); Questionnaire Biowert
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.55E-3		1	1.21	(1,1,1,1,1,3); Questionnaire Biowert: waste from packaging and cleaning
	insulating material production infrastructure	RER	1	unit	3.55E-8		1	3.05	(2,1,1,1,1,3); Assumption: 20 years life time
	plastic production infrastructure	RER	1	unit		2.00E-8	1	3.05	(2,1,1,1,1,3); Assumption: 20 years life time
emission air, high population density	Heat, waste	-	-	MJ		9.00E-1	1	1.22	(2,1,1,1,1,3); calculation

11.4.6 Biogas production

The grass disintegration process results in grass fibres, which can be used for AgriCell or AgriPlast production, and grass slurry. The grass slurry is used as a substrate in the biogas plant together with cow slurry and biowaste. The biogas is burned in the cogeneration unit; the digestate is processed in reverse osmosis to obtain liquid and solid organic fertiliser AgriFer.

The supply of biowaste and cow slurry for the digestion process is accounted for with the transport of the waste and the slurry to and from the collection point and the biogenic CO_2 content.

Tab. 11.11 Unit process raw data of cow slurry supply

	Name	Location	Infrastructure	Unit	cow slurry, in anaerobic digestion, at collection point	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				m3			
product	cow slurry, in anaerobic digestion, at collection point	RER	0	m3	1			
resource, in air	Carbon dioxide, in air	-	-	kg	4.44E+1	1	1.05	(2,2,1,1,3,4,BU:1.05); calculated from Kennwertmodell naturemade and ecoinvent data for slurry in biogas plant
technosphere	transport, tractor and trailer	CH	0	tkm	1.00E+1	1	2.00	(2,2,1,1,3,4,BU:2); assumption: 10 km

The process heat for the anaerobic digestions is taken from the cogeneration unit.

All parts of the biogas plant are covered. This leads to considerably lower emission values compared to uncovered biogas plants. The values used for the modelling of the biogas production are derived from the ecoinvent data for the anaerobic digestion of grass in a covered agricultural biogas plant. In a proxy, the allocation factor is set to 90% for biogas and 10% for the digestate.

Tab. 11.12 Parameters used for the biogas production from grass

Input		Value	Source
Input grass slurry	m^3/a	27500	Questionnaire Biowert
Input cow slurry	m^3/a	10000	Questionnaire Biowert
Input bio waste	t/a	15000	Questionnaire Biowert
Electricity from cogen grass refinery	kWh/a	4.20E+05	Questionnaire Biowert
Heat from cogen grass refinery	MJ/a	9.25E+06	Questionnaire Biowert
Life expectancy biogas plant	a	20	
Annual yield			
Digestate	m^3/a	42000	
AgriFer solid	t/a	1300	Estimation Biowert:
AgriFer liquid	m^3/a	10000	Estimation Biowert:22.5% of digestion residues
Process water at decanter	m^3/a	27500	
Biogas	m^3	4600000	Questionnaire Biowert
Emissions			
CO_2	kg/m^3	6.62E-03	Calculated; 1% of CO2 in biogas emitted from covered stock
NH_3	kg/m^3	4.06E-04	Calculated; 80% of emission reduction due to stock cover
N_2O	kg/m^3	2.85E-04	Calculated; 75% of emission reduction due to stock cover
Heat waste	MJ/m^3	3.29E-01	Calculated from electricity use
CH_4	kg/m^3	4.54E-03	Calculated; 1% of methane in biogas emitted from covered stock
H_2S	kg/m^3	1.55E-03	Calculated with 0.7g H2S/kg DM

Tab. 11.13 Unit process raw data of biogas production from grass slurry, biowaste and cow slurry

	Name	Location	Infrastructure Process	Unit	grass slurry, digested in anaerobic digestion plant, at grass refinery	GeneralComment	biogas, from grass refinery, at storage	digestate, at grass refinery
	Location				RER		RER	RER
	InfrastructureProcess				0		0	0
	Unit				m3		Nm3	m3
allocated products	biogas, from grass refinery, at storage	RER	0	Nm3	4.60E+06	(1,1,1,1,1,1); Product		
	digestate, at grass refinery	RER	0	m3	4.20E+04	(1,1,1,1,1,1); Product		
technosphere	grass slurry, at grass disintegration	RER	0	m3	2.75E+4	(4,4,2,3,1,5); Questionnaire Biowert	90%	10%
	cow slurry, in anaerobic digestion, at collection point	RER	0	m3	1.00E+4	(3,1,2,1,1,5); Questionnaire Biowert	90%	10%
	biowaste, at collection point	CH	0	kg	1.50E+7	(4,4,3,3,4,5); Questionnaire Biowert	90%	10%
	electricity mix, at grass refinery	RER	0	kWh	4.20E+5	(4,4,3,3,4,5); Questionnaire Biowert	90%	10%
	heat, at cogen, grass refinery	RER	0	MJ	9.25E+6	(4,4,3,3,4,5); Questionnaire Biowert	90%	10%
	anaerobic digestion plant	RER	1	unit	5.00E-2	(4,4,3,3,4,5); 0	90%	10%
emission air, unspecified	Carbon dioxide, biogenic	-	-	kg	3.04E+4	(4,4,3,3,4,5);	90%	10%
	Ammonia	-	-	kg	1.87E+3	(4,4,3,3,4,5);	90%	10%
	Dinitrogen monoxide	-	-	kg	1.31E+03	(4,4,3,3,4,5);	90%	10%
	Methane, biogenic	-	-	kg	2.09E+4	(4,4,3,3,4,5);	90%	10%
	Hydrogen sulfide	-	-	kg	7.13E+3	(4,4,3,3,4,5);	90%	10%
emission air, high population density	Heat, waste	-	-	MJ	1.51E+6	(4,4,3,3,4,5);	90%	10%

11.4.7 Cogeneration of heat and electricity from biogas

The biogas from the biogas plant is burned in a cogeneration unit. The heat and the electricity from the cogeneration are used as processes heat and electricity input.

Tab. 11.14 Input and output parameters of biogas production

Biowert Input			Comment
Biogas in cogeneration	m^3/a	4600000	Questionnaire Biowert
lubricating oil	kg	2.98E-04	From ecoinvent DS cogen, biogas from agricultural co-fermentation
Life expectancy	a	20	Questionnaire Biowert
Biowert Output			
Electricity	kWh/a	1.03E+07	
Heat	MJ/a	3.30E+07	
Disposal lubricating oil	kg	2.98E-04	From ecoinvent DS cogen, biogas from agricultural co-fermentation

Similar as for the biogas production, some parameters of the cogeneration data sets are derived from existing data set of the ecoinvent database (Jungbluth et al. 2007). The in- and output of the lubricating oil and the air emissions are described in Subchapter 3.3.1. Furthermore, the allocation of the environmental impact to heat and electricity is carried out according to the allocation factor used in the ecoinvent data set (exergy content).

Tab. 11.15 Unit process raw data of biogas burned in the cogeneration unit

	Name	Location	Infrastructure Process	Unit	biogas, burned in cogen at grass refinery	UncertaintyTy	StandardDeviation95%	GeneralComment	heat, at cogen, grass refinery	electricity, at cogen, grass refinery
	Location				RER				RER	RER
	InfrastructureProcess				0				0	0
	Unit				Nm3				MJ	kWh
allocated products	heat, at cogen, grass refinery	RER	0	MJ	3.30E+07					
	electricity, at cogen, grass refinery	RER	0	kWh	1.03E+07					
technosphere	biogas, from grass refinery, at storage	RER	0	Nm3	4.60E+6	1	1.33	(4,4,2,3,1,5,BU:1.05); Questionnaire Biowert	13%	87%
	cogeneration plant, in grass refinery	RER	1	unit	5.00E-2	1	3.34	(4,4,3,3,4,5,BU:3); Questionnaire Biowert	13%	87%
	operation, biogas combustion, in cogen with biogas engine	CH	0	MJ	1.10E+8	1	1.65	(4,4,3,3,4,5,BU:1.05); Heating value 24 MJ/m3	13%	87%

11.4.8 AgriFer production

The digestate from the biogas production contains nutrients, which can be used as organic fertilizers. The nutrient content of the AgriFer products is shown in Tab. 11.16.

Tab. 11.16 **Nutrient content of AgriFer fertiliser products (Bundesgütegemeinschaft Kompost E.V. 2008)**

AgriFer	Unit	Liquid	Solid
Density	g/l	1.039	0.757
Dry matter content	%	0.0402	0.28
N content	%DM	0.283	0.0391
P_2O_5 content	%DM	0.0118	0.0313
K_2O content	%DM	0.1582	0.0089
MgO content	%DM	0.001	0.0146
N per m^3	kg/m^3	11.7	8.25
N per kg	kg/kg	0.0113	0.0109
P_2O_5 per m^3	kg/m^3	0.42	6.59
P_2O_5 per kg	kg/kg	0.0004	0.0087
K_2O per m^3	kg/m^3	6.55	1.82
K_2O per kg	kg/kg	0.0063	0.0024
Amount AgriFer	m^3	17	
Amount AgriFer	kg		3714.29
N input	kg	198.9	40.49
P_2O_5 input	kg	7.14	32.31
K_2O input	kg	111.35	8.91

The digestate has a high water content, which is not suitable for the fertiliser application. Consequently, the water is extracted in reverse osmosis. The extracted water is recycled as process water in the grass disintegration process and the dry matter enriched fertiliser can be applied to the grass fields in order to close the nutrient cycle. The infrastructure needed for the reverse osmosis is included in the biogas plant. The allocation factors are calculated according to the dry matter content of the products.

Tab. 11.17 **Input and output parameters of AgriFer production**

Input		Wert	TS	Source
Digestate	m^3/a	42000		Questionnaire Biowert
AgriFer liquid	m^3/a	10000	2%	Questionnaire Biowert
AgriFer solid	t/a	1300	25%	Questionnaire Biowert
Process water	m^3/a	32550	0%	Questionnaire Biowert: 77.5% des Gärrests/Permeat
Electricity demand	kWh/a	1280000		Questionnaire Biowert
Process water to waste water treatment	m^3/a	5.00E+03		
Output				
TS Input/Output				
Output AgriFer liquid	t	2.00E+02		
Output Agrifer solid	t	3.25E+02		
Output process water	t	4.91E+03		
Input grass slurry	t	8.25E+02		
Input bio waste	t	3.75E+03		15000t/a, assumption 25%
Input cow slurry	t	8.60E+02		10000m^3/a, DM: 8.6%

Tab. 11.18 Unit process raw data of AgriFer production

	Name	Location	InfrastructureProcess	Unit	digestate, in reverse osmosis	UncertaintyT	StandardDeviation95%	GeneralComment	AgriFer, solid, at grass refinery	AgriFer, liquid, at grass refinery	process water, at decanter
	Location				RER				RER	RER	RER
	InfrastructureProcess				0				0	0	0
	Unit				m3				kg	m3	m3
allocated	AgriFer, solid, at grass refinery	RER	0	kg	1.30E+06	1	1.05	(1,1,1,1,1,1); Product			
products	AgriFer, liquid, at grass refinery	RER	0	m3	1.00E+04	1	1.05	(1,1,1,1,1,1); Product			
products	process water, at decanter	RER	0	m3	2.76E+04	1	1.05	(1,1,1,1,1,1); Product			
technosphere	digestate, at grass refinery	RER	0	m3	4.20E+4	1	1.21	(1,2,1,1,1,5); Questionnaire Biowert	92.60%	7.40%	0.0E+00
	electricity mix, at grass refinery	RER	0	kWh	1.28E+6	1	1.21	(1,2,1,1,1,5); Questionnaire Biowert	92.60%	7.40%	0.0E+00
	treatment, sewage grass refinery, to wastewater treatment, class 3	CH	0	m3	5.00E+3	1	1.21	(1,2,1,1,1,5); Process water to waste water treatment	92.60%	7.40%	0.0E+00
emission air, high population density	Heat, waste	-	-	MJ	4.61E+6	1	1.21	(1,2,1,1,1,5); 0	92.60%	7.40%	0.0E+00

11.4.9 In-wall pattress

AgriPlast granulate can be used for injection moulding or extrusion of plastic parts. In order to compare AgriPlast to conventional thermoplasts, an in-wall pattress made of AgriPlast is compared to an in-wall pattress from HDPE. In-wall pattresses have to be treated with flame retardants in order to withstand burning of electronic equipment. AgriPlast contains borax and boric acid as flame retardant, whereas HDPE usually is mixed with polybromated diphenylether (e.g. DecaBDE). The ecoinvent database lacks data on flame retardants, which leads to proxy of DecaBDE with the data set “chemicals organic, at plant”. The disposal of the HDPE with additives and AgriPlast are modelled according to the MSWI tool (Doka 2009).

Tab. 11.19 Unit process raw data of in-wall pattress production

	Name	Location	InfrastructurePr	Unit	in-wall pattress, AgriPlast, at plant	in-wall pattress, HDPE, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER			
	InfrastructureProcess				0	0			
	Unit				kg	kg			
product	in-wall pattress, AgriPlast, at plant	RER	0	kg	1	0			
	in-wall pattress, HDPE, at plant	RER	0	kg	0	1			
technosphere	AgriPlast, granulate PP, at grass refinery	RER	0	kg	1.00E+0		1	1.05	(1,1,1,1,1,1,BU:1.05); company data
	polyethylene, HDPE, granulate, at plant	RER	0	kg		9.88E-1	1	1.24	(2,2,1,3,3,4,BU:1.05); Assumption: 75% pure HDPE, 25% flame retardant enriched HDPE (e.g. HBCD)
	chemicals organic, at plant	GLO	0	kg		1.25E-2	1	1.58	(4,2,1,3,4,4,BU:1.05); Assumption for flame retardant: 1-10% of flame retardant enriched plastic, Antimontrioxide/Bromine. Used value: 5%
	injection moulding	RER	0	kg	1.00E+0	1.00E+0	1	1.21	(1,1,1,1,1,5,BU:1.05); company data
	transport, freight, rail	RER	0	tkm	2.00E-1	2.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); standard distances for PP
	transport, lorry >16t, fleet average	RER	0	tkm	1.00E-1	1.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); standard distances for PP
	disposal, AgriPlast PP, to municipal incineration	CH	0	kg	1.00E+0		1	1.24	(2,2,1,3,3,4,BU:1.05); AgriPlast to incineration (50% PP, 50% grass fibres)
	disposal, HDPE, flame protected, to municipal incineration	CH	0	kg		1.00E+0	1	1.58	(4,2,1,3,4,4,BU:1.05); Disposal of HDPE in in-wall pattress

12 Appendix E: LCI of biogas purification, distribution and use as fuel

The inventories of biogas purification, distribution and combustion in passenger cars are modelled in order to enable a comparison of methane from different biogas substrates with liquid biofuels that are for example presented by Zah et al. (2007).

Due to the fact that operators of biogas plants burn biogas in cogeneration units in order to supply the anaerobic digestion unit with heat and electricity, only the amount of biogas that is not required for covering the digestion unit’s heat demand can be purified to biomethane. In this calculation, the heat consumption of the digestion unit is the limiting factor, since the entire heat demand is met with the production of the cogeneration unit in contrast to electricity that is not only consumed from the cogeneration unit but also from grid. Tab. 12.1 shows the maximum share of biogas from different substrates available for purification.

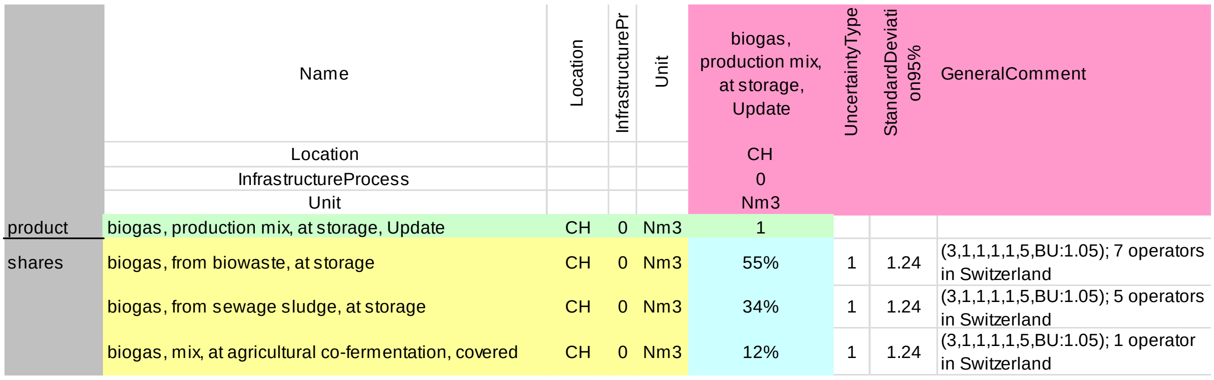
Tab. 12.1 Maximum share of biogas available for purification after subtraction of share of biogas required for producing the heat required in the anaerobic digestion unit

	Maize silage	Sugar beet	Fodder beet	Beet residues	Molasses	Glycerine
Minimum share of biogas required in cogeneration unit	10.4%	11.0%	17.5%	31.6%	4.9%	2.1%
Maximum share of biogas available for purification	89.6%	89.0%	82.5%	68.4%	95.1%	97.9%

12.1 Biogas mix for purification

Most operators of biogas plants in Switzerland burn the biogas in a cogeneration unit in order to produce heat and electricity. In the year 2010, only 13 operators purified their biogas to biomethane that was fed into the natural gas grid or sold in a pumping station. Based on these operators, we created the biogas mix in Tab. 12.2 with information about their substrates and their production capacities (see Tab. 12.5 on page 84).

Tab. 12.2: Unit process raw data of the biogas mix for purification in Switzerland



	Name	Location	InfrastructurePr	Unit	biogas, production mix, at storage, Update	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	biogas, production mix, at storage, Update	CH	0	Nm3	1			
shares	biogas, from biowaste, at storage	CH	0	Nm3	55%	1	1.24	(3,1,1,1,1,5,BU:1.05); 7 operators in Switzerland
	biogas, from sewage sludge, at storage	CH	0	Nm3	34%	1	1.24	(3,1,1,1,1,5,BU:1.05); 5 operators in Switzerland
	biogas, mix, at agricultural co-fermentation, covered	CH	0	Nm3	12%	1	1.24	(3,1,1,1,1,5,BU:1.05); 1 operator in Switzerland

12.2 Purification technologies

In Switzerland, biogas is purified with three different technologies: pressure swing adsorption (PSA), glycol washing, and amino washing. Tab. 12.4 shows the unit process raw data of these technologies excluding the biogas input.

12.2.1 Amino washing

Up to date information about a purification plant using amino washing and operating in Switzerland are available from EMPA (2009). The amount of electricity and heat consumed, as well as the amount of amine (monoethanolamine) and tap water used for the washing, and the amount of activated carbon (charcoal) and thermal oil (lubricating oil) for desulphurisation is taken from this publication. The amount of used tap water is treated as sewage in a wastewater treatment plant. The amine is considered to be disposed in a hazardous waste incineration after use. Several publications report that less than 0.1 % of the methane content in the raw biogas is emitted into air in the amino washing process (EMPA 2009; Urban et al. 2009).

12.2.2 Glycol washing

Glycol washing is used in biogas plants in Romanshorn, Bischofszell, and Pratteln (see Fig. 3.2). Urban et al. (2009) report an electricity consumption of the glycol washing process of 0.24-0.3 kWh per m^2 raw biogas. Schulte-Schulze (2006) mentions an electricity consumption of 0.32 kWh per m^2 raw biogas. The purification plant in Romanshorn has an annual electricity consumption of 120’000 kWh and an annual purification of 187’509 Nm^3 of raw biogas which results in a specific electricity consumption of 0.97 kWh per Nm^3 biomethane, if considering a biogas input of 1.5 m^3 per m^3 purified biomethane. The purification plant in Pratteln has an annual electricity consumption of 504’162 kWh and a production of 626'885 Nm^3 biomethane, resulting in a specific consumption of 0.81 kWh per Nm^3 biomethane. Hence, the average electricity consumption of glycol washing in Switzerland is 0.89 kWh/m^3 biomethane which is significantly higher than what can be derived from literature sources.

The washing agent used in the glycol washing process is a mixture of dimethyl ether and polyethylene glycol. The density of the washing agent varies between different formulations, but is around 1 kg/l (Clariant 2002). In the Biogas plant Pratteln, 110 litre of washing agent were refilled in 2010.[14] In relation to the biomethane production of 626'885 m^3 in the same year, this results in a washing agent consumption of 0.18 g/m^3. Since no specific information of the detailed composition of washing agent is available, it is assumed that the two components each have a share of 50 %. It is assumed that the washing agent is disposed in a hazardous waste incineration after its end of life. According to Urban et al. 2009, 1 % of the methane content in the raw gas is emitted into air. We apply an emission factor of 2.6 % of the methane content in the raw gas, calculated from up to date information from a Swiss operator.[15]

12.2.3 PSA

The most common technology of biogas purification in Switzerland is pressure swing adsorption (PSA). Urban et al. (2009) report an electricity consumption of the PSA process of 0.22 kWh per m^2

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[14] Biopower-Anlage Pratteln, Biogasaufbereitung, Betriebskennzahlen Jahr 2010, personal information from Mike Keller from the Biopower Nordwestschweiz AG, on 21.02.2011.

[15] ARA Region Romanshorn Biogasaufbereitung - Energieflussdiagramm 2010, personal information from Heinz Greuter from Erdgas Romanshorn, on 31.01.2011.

raw biogas. Schulte-Schulze (2006) mentions an electricity consumption of 0.25 kWh per m^2 raw biogas. We apply a value of 0.23 kWh per m^2 raw biogas, which results in 0.35 kWh per m^2 purified biomethane. A detailed study published by Baier et al. (2008) analysed the methane emissions of a PSA plant in Switzerland and revealed that 2.6 % of the methane content in the raw biogas are emitted into air during the purification process.

12.2.4 General assumptions

Since, the amino washing process and the PSA process also require a desulphurisation step, the same amount of activated carbon and lubricating oil is taken into account as in the amino washing process. Activated carbon is usually impregnated with 2.5 % of potassium iodide, in order to remove hydrogen sulphides from the biomethane.[16]

The generic value of infrastructure facilities is taken from Jungbluth et al. (2007).

Tab. 12.3 shows the average composition of raw biogas, waste gas, and purified biomethane from different technologies. The datasets refer to 1 m^3 of purified biomethane. The compositions of raw biogas, waste gas and biomethane from PSA is obtained from Jungbluth et al. (2007). The hydrogen sulphide content in the biomethane from PSA is adjusted to 0.0003 % as declared by Rütgers (general) cited in Jungbluth et al. (2007). And the composition of biomethane from amino and glycol washing is calculated from composition of biomethane from PSA and the higher methane share as reported by Urban et al. (2009).

The amount of waste heat is calculated from the energy consumption. The carbon dioxide emissions are calculated from the carbon dioxide input in the raw biogas (1.5 m^3 biogas/m^3 biomethane; 33.5 vol% carbon dioxide share) and the carbon dioxide output in the purified biomethane (0.5 vol% - 2 vol%). The methane emissions are calculated by applying the methane emission factors from literature on the methane input from the raw biogas. Hydrogen sulphide emissions are calculated from the H_2S content in the waste gas reported by in Jungbluth et al. (2007) and 0.5 m^3 waste gas per m^3 purified gas. We assume that the retained sulphur dioxide is oxidised to sulphur dioxide and emitted into air. The amount of sulphur dioxide is calculated from the difference between the hydrogen sulphide input from raw biogas and hydrogen sulphide output in the purified biomethane and the waste gas.

Tab. 12.3: Average composition of raw biogas, waste gas, and biomethane from different purification technologies

Component	Raw biogas	Waste gas	Biomethane		
			from amino washing	from glycol washing	from PSA
Methane	63.30%	6%	99%	97%	96%
Carbon dioxide	33.50%	91%	0.5%	1.5%	2%
Nitrogen	3.2%	3%	0.3%	0.8%	1%
Hydrogen sulphide	0.0005%	0.0004%	0.0001%	0.0002%	0.0003%

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[16] http://www.gutmbh.de/Aktivkohle.htm (access on19.10.2011)

Tab. 12.4: Unit process raw data of biogas purification technologies (excluding biogas input). Dataset refer to 1 m^3 purified biomethane.

	Name	Location	InfrastructureProcess	Unit	biogas purification, to methane, 99 vol-%, amino washing process	biogas purification, to methane, 97 vol-%, glycol washing process	biogas purification, to methane, 96 vol-%, pressure swing adsorption	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				Nm3	Nm3	Nm3			
product	biogas purification, to methane, 99 vol-%,	CH	0	Nm3	1	0	0			
	biogas purification, to methane, 97 vol-%,	CH	0	Nm3	0	1	0			
	biogas purification, to methane, 96 vol-%,	CH	0	Nm3	0	0	1			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	2.75E-1	8.88E-1	3.55E-1	1	1.09	(2,3,2,3,1,4); literature
	natural gas, burned in boiler atm. low-NOx condensing non-modulating <100kW	RER	0	MJ	3.16E+0	-	-	1	1.09	(1,4,1,3,1,5); EMPA (2009)
	monoethanolamine, at plant	RER	0	kg	2.08E-3	-	-	1	1.09	(1,4,1,3,1,5); EMPA (2009)
	dimethyl ether, at plant	RER	0	kg	-	8.77E-5	-	1	3.01	(3,2,1,3,1,5); 50% of genosorb
	triethylene glycol, at plant	RER	0	kg	-	8.77E-5	-	1	1.16	(3,2,1,3,1,5); assumption from amino washing
	charcoal, at plant	GLO	0	kg	2.08E-4	2.08E-4	2.08E-4	1	3.09	(1,4,1,3,3,5); EMPA (2009)
	lubricating oil, at plant	RER	0	kg	1.50E-4	1.50E-4	1.50E-4	1	1.09	(1,4,1,3,3,5); EMPA (2009)
	potassium hydroxide, at regional storage	RER	0	kg	3.98E-6	3.98E-6	3.98E-6	1	3.09	(4,5,1,5,1,5); activated carbon impregnation with 2.5 % of potassium iodide for H2S removal
	tap water, at user	CH	0	kg	2.08E-3	-		1	1.12	(1,4,1,3,1,5); EMPA (2009)
	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	2.08E-6	-		1	2.02	(1,4,1,3,1,5); EMPA (2009)
	disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	0	kg	2.08E-3	1.75E-4		1	1.52	(4,2,1,3,1,5); used washing chemicals
	chemical plant, organics	RER	1	unit	4.00E-10	4.00E-10	4.00E-10	1	3.31	(3,4,3,3,4,5); generic value
	transport, lorry 3.5-20t, fleet average	CH	0	tkm	1.22E-4	2.69E-5	1.81E-5	1	2.09	(4,5,na,na,na,na); standard distance 50km
	transport, freight, rail	CH	0	tkm	1.47E-3	3.22E-4	2.17E-4	1	2.09	(4,5,na,na,na,na); standard distance 600km
emission air, high population density	Heat, waste	-	0	MJ	4.15E+0	3.20E+0	1.28E+0	1	1.09	(2,3,2,3,1,4); calculated from energy consumption
	Carbon dioxide, biogenic	-	0	kg	4.99E-1	4.79E-1	4.69E-1	1	1.12	(4,3,1,1,1,5); calculated from difference between input and output
	Methane, biogenic	-	0	kg	6.92E-4	1.56E-2	1.80E-2	1	2.02	(1,3,1,1,1,5); Emission factor in literature
	Hydrogen sulfide	-	0	kg	2.31E-6	2.31E-6	2.31E-6	1	1.52	(4,3,1,1,1,5); calculated from H2S content in waste gas
	Sulfur dioxide	-	0	kg	1.31E-5	8.77E-6	6.60E-6	1	1.13	(4,1,1,1,1,5); retained sulphur is oxidised

12.2.5 Purification technologies in Switzerland

The biogas purification facilities that were operating in Switzerland in 2009 are listed in Tab. 12.5. We estimated their production capacity based on data from the IEA Bioenergy Task 37[17] and information about the individual plants available on the internet. Two operators feed their biomethane in a filling station for vehicles whereas the other operators feed their biomethane into the natural gas grid. The purification plant in Bischofszell is not operating any more in the year 2011.

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[17] Personal information from Arthur Wellinger from Nova Energie on 31.01.2011

Tab. 12.5 Biogas purification facilities in Switzerland

	location	substrate	year of installation	plant capacity in 2010	methane use
				m3/h	
pressure swing adsorption	Rümlang	greenery, waste food, etc.	1998	30	Filling station
	Otelfingen	greenery, waste food, etc.	1998	50	Filling station
	Samstagern	greenery, waste food, etc.	1997	50	Natural gas grid
	Emmen	sewage sludge	2005	75	Natural gas grid
	Widnau	manure, vegetables, greenery, waste food etc.	2007	200	Natural gas grid
	Bern	sewage sludge	2008	300	Natural gas grid
	Utzenstorf	biowaste	2009	150	Natural gas grid
	Lavigny	biowaste	2008	120	Natural gas grid
amino washing	Obermeilen	sewage sludge	2008	60	Natural gas grid
	Volketswil	biowaste	2010	250	Natural gas grid
glycol washing	Pratteln	greenery, waste food, etc.	2006	300	Natural gas grid
	Bischofszell	*sewage sludge*	*2007*	*120*	*Natural gas grid*
	Romanshorn	sewage sludge	2007	30	Natural gas grid

Based on Tab. 12.5, we calculated the capacity weighted shares of 56 % biogas purified using pressure swing adsorption, 18 % using amino washing, and 26 % using glycol washing. Tab. 12.6 shows the unit process raw data of purified biogas. According to Jungbluth et al. (2007), 1.5 m^3 of biogas is required in order to produce 1 m^3 of purified biomethane. In this study we calculate with a methane content of 63.3 % in the raw biogas and a minimum methane content of 96.0 % in the purified biomethane. Therefore, 1.52 m^3 biogas is required for 1 m^3 of purified biomethane.

Tab. 12.6 Unit process raw data of purified biomethane

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol-%, from biogas, at purification, Update	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	methane, 96 vol-%, from biogas, at purification, Update	CH	0	Nm3	1			
technosphere	biogas purification, to methane, 99 vol-%, amino washing process	CH	0	Nm3	1.79E-1	1	3.01	(3,1,1,1,1,1); 2 plants operating in 2010
	biogas purification, to methane, 97 vol-%, glycol washing process	CH	0	Nm3	2.59E-1	1	1.16	(3,1,1,1,1,1); 3 plants operating in 2010
	biogas purification, to methane, 96 vol-%, pressure swing adsorption	CH	0	Nm3	5.62E-1	1	3.09	(3,1,1,1,1,1); 8 plants operating in 2010
	biogas, production mix, at storage, Update, Parameters	CH	0	Nm3	1.52E+0	1	1.09	(2,5,2,1,3,5); raw gas input

12.3 Distribution and combustion in passenger car

The unit process data of the biomethane distribution and the passenger car transportation with a biogas-operated vehicle are considered with ecoinvent datasets described by Jungbluth et al. (2007) without any modifications.