Sustainability aspects of biobased applications

Comparison of different crops and products from the sugar platform

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Colophon

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Abstract

The biobased economy focuses on the use of biomass for chemicals, materials, fuels and energy. The expectation is that especially in the field of chemicals the sustainability gain can be large. In literature, however, the amount of data in this field is rather limited. Therefore, in this study, we compare different uses of biomass. In order to allow for a systematic comparison the study focuses on three different chemicals that can be produced from sugar. In this way it is also, in principle, possible to compare different crops for the production of the same product.
The study focuses on the production of PLA (polylactic acid, a bioplastic), ethanol, and biopolyethylene (bio-PE, which is produced via ethanol). These three products can presently be produced from biomass and therefore form realistic cases. All three products are produced from sugars, and thus the systems can be decoupled at the sugar step. The sugar can be produced from different crops. In this study we compare five different crops, wheat, maize, sugar beet, sugar cane, and Miscanthus. The system studied is introduced in Chapter 2.
The sustainability aspects that we studied are non-renewable energy use (NREU), greenhouse gas (GHG) emission in the crop-product chain and direct land use for producing the bio-materials. The methodology of the study is presented in Chapter 3. Chapter 4 focuses on the data used as input for the study.

While in current agricultural practice some crops are harvested almost completely (e.g. Miscanthus), for others only a smaller part of the plant is made use of, and the other part of the biomass is left in the field the field (e.g. wheat straw). When studying the amount of energy and greenhouse gas that can be saved by turning a crop into a non-food product, for the second type of crop the results are bound to look worse compared to the first type, if current agricultural practices are applied. As a consequence, their use may be discouraged.
However, also agricultural co-products such as wheat straw could be used for materials or energy production. Against this background this report sets out with the assumption that *all* agricultural co-products are used for energy purposes, thereby replacing fossil energy (we refer to this method as "energy system expansion method"). This approach is chosen as default for the calculations presented in Chapter 5 and it also applies for the co-products that are produced during processing in the factory. Giving credit to the potential use of *all* co-products, a level playing field is created, when comparing the results across the crops. In addition to the results of these calculations which are presented in Chapter 5, Chapter 6 contains the outcome of an analysis which assumes that typical amounts of agricultural co-products are left in the field. Our default calculations also assume that all produced heat can be used, either in the processing plant or in case of excess heat outside this plant, e.g. in adjacent industry ("ideal energy integration").

From the study five main conclusions can be drawn.

1. When comparing the options in terms of their NREU per tonne of product, the studied bio-based products (PLA, ethanol and bio-based PE) score clearly better than their petrochemical alternatives. This is not only true for the default calculations but also for current agricultural practice. Also the greenhouse gas emission reduction is positive for all three biobased products, both for the default calculation as well as for the current agricultural practice.

2. If all co-products are being made use of, the difference between first and second generation crops(wheat and maize versus Miscanthus) crops becomes negligible. We can conclude that the use of *all* co-products instead of the current practice offers major potentials to reduce the NREU and GHG emissions in the chains. Before putting this into practice it must, however, be studied which level of the use of the total amount of co-products would be detrimental for soil carbon levels and soil fertility and whether there are any other tradeoffs (e.g. with feed production). Furthermore, we did not take land use change into account (whether direct or indirect). Land use change can alter the GHG scores completely (overall and between crops) and thus any conclusion on GHG based on the results of this report is still premature.

3. In our world, where the availability of fertile land is limited, it makes most sense to choose a crop and a product that leads to the highest saving in NREU and GHG per hectare. The production of ethanol for the replacement of fuels scores as the option with the lowest savings per hectare for all crops. The production of bioplastics leads to a higher NREU and GHG saving for all crops.

4. When comparing the bioplastics, PLA comes out as the preferred choice. PLA scores better than bio-PE in savings per hectare, because more of the functional groups built-in in the biomass are retained in the end product.

5. Based on the results for PLA, ethanol and PE made from crops that are typically cultivated in The Netherlands (i.e., wheat, maize and sugar beet) the results for NREU and GHG emissions per hectare point out sugar beet as preferred crop, because it offers for all applications by far the largest savings per hectare of agricultural land.

This research project has been carried out within the Policy Support Research Programme for the Ministry of Agriculture, Nature and Food Quality, in the theme Biobased Economy and the Energy Transition. (BO-12.05-002-008).

Content

1 Introduction

The biobased economy focuses on the use of biomass for chemicals, materials, fuels and energy. The expectation is that especially in the field of chemicals the sustainability gain can be large (Patel *et al.*, 2006). In literature, however, the amount of data in this field is rather limited. Therefore, in this study, we compare different uses of biomass. In order to allow for a systematic comparison the study focuses on three different chemicals that can be produced from sugar. In this way it is also, in principle, possible to compare different crops for the production of the same product.

The study focuses on the production of PLA (polylactic acid, a bioplastic), ethanol, and biopolyethylene (bio-PE, which is produced via ethanol). These three products can presently be produced from biomass and form realistic cases[1]. All three products are produced from sugars, and thus the systems can be decoupled at the sugar step.
The sugar can be produced from different crops. In this study we compare five different crops. Figure 1-1 schematically shows the structure of the product chains.

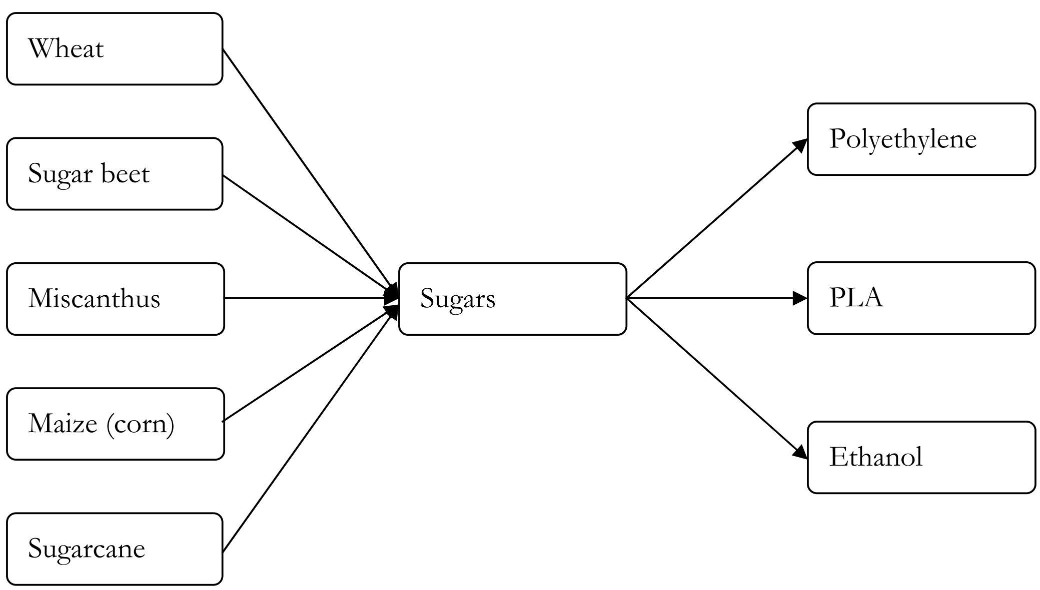

Figure 1-1, schematic structure of the studied product chains

[1] *Polyethylene is presently produced from fossil feedstock, directly from ethylene. A commercial production unit for the production of BioPE is presently being constructed in Brazil. Ethanol can also be produced from fossil resources and is in that case also produced from ethylene. Presently, commercial ethanol production both from fossil feedstock and from biomass exists. PLA is only produced from biomass, and will in this study be compared with LDPE and PET, which are fossil based and are used for the same end-products.*

In view of the time and budget available, the study is limited to energy use, greenhouse gas emissions and land use, although also some attention is given to soil carbon issues.

Research questions that we aim to answer in this study are:

- Do PLA, PE or ethanol from a biobased feedstock (fermentable sugar in our study) offer lower scores on non-renewable energy use and GHG emission than their counterparts made from fossil fuels?
- How do the different products (fuels or different materials) compare in terms of sustainability?
- Which feedstock will give the best balances?
- Is it worthwhile to stimulate the chemical industry in the NL to produce these chemicals from biomass instead of fossil sources?

Cultivation of wheat, maize (corn), sugar beet and Miscanthus will be based on data for the Netherlands. The sugarcane case will be taken from the literature from Brasil. The production data for the products are based on a variety of sources including companies producing bio-based products, literature and LCA databases (for more details see Chapter 4).

2 Definition of the systems

2.1 Production of fermentable sugars

Fermentable sugars can be present as such in agricultural crops (sucrose in sugar beet and sugar cane) or derived from other components; from starch (present in wheat and maize) or from cellulose (present in Miscanthus). Typical for agricultural crops is that only a part of the biomass can be used as or for production of fermentable sugars, other components result in co-products. These co-products can be distinguished in two types. Agricultural co-products result from the harvest, like leaves and straw. They deliver only small amounts of fermentable sugars, but can in the future be used for second generation conversion technologies, in which fermentable sugars are produced from lignocellulose. The other type of co-products result from processing the main products, they remain when the fermentable sugars are extracted or fermented, like stillage. Agricultural co-products at present can be used for other purposes (e.g. straw for bedding) or left in the field (and then they are usually called residues). Processing co-products are mainly used as feed components or converted to energy.

In many current agricultural practices, a substantial amount of agricultural co-products (e.g. sugar beet leaves) is left on the field or it is returned to the field after further use (as is the case for straw, which is partly used in stables as horse bedding). In other agricultural practices the whole crop or a large part of it is harvested and further processed, like in sugar cane and Miscanthus. In current chains of the latter two crops the biomass that cannot be converted into fermentable sugars is used to generate extra energy, like power and heat. It is therefore not amazing that these crops score better in environmental impact studies than the ones where only the starch-containing or the sugar-containing part of the crop is removed from the field. One may argue that this is not a fair comparison because the agricultural residues could be harvested as well and used to generate energy (as done with wheat straw in Denmark). In order to create a level playing field, the default calculations performed in this study assume that all left-over agricultural co-products are used for energy purposes. We assume that these surplus agricultural co-products are used to raise power and heat and that this is used in the (adjacent) plant producing the fermentable sugars from the agricultural crops and converting the fermentable sugars to the target products. An eventual power surplus can be delivered to the public grid, in case of a heat surplus it depends on the utilization possibilities near the production plant whether this energy can be added to the energy balance of the crop-product chain. To summarize, we assume in our default calculations (Chapter 5) first the complete use of all agricultural co-products for energy purposes and second ideal energy integration. In this manner, all agricultural products are made use of, which might resemble more the practice in a fully developed bio-based economy, and all crops are "treated" in the same way. Two ways of energy production are distinguished: 1) combustion for dry co-products (e.g. straw and bagasse) and anaerobic fermentation to biogas followed by combustion for wet co-products (e.g. beet leaves and stillage). Biogas production has the advantage that the nutrients present in the co-product can be recycled, this option is standard part of the calculations. Ashes from combustion are discarded because legislation does not allow recycling on agricultural land.

In addition we conducted a second calculation which follows the current practice of leaving a certain share of the agricultural co-products on the field. The rationale behind this calculation is that there is increasing evidence that a certain share of the agricultural co-products must be left on the field because it is essential for keeping soil carbon at a sustainable level (Hanegraaf *et al*. 2009). We follow this reasoning and assume that agricultural co-products which have been left in the field in the past will be dealt with in the same manner also in future. These calculations will be presented in Chapter 6.

In our calculations, also the co-products which are produced when processing the agricultural products (e.g. the pulp formed after extracting sugar from beets or distiller's dry grains (DDGS) formed when converting wheat into ethanol) are converted into energy.

2.2 Crops and production chains

Five crops for the production of fermentable sugars were studied. The flow charts of the five production chains studied are given in Figure 2-1 to 2-5.

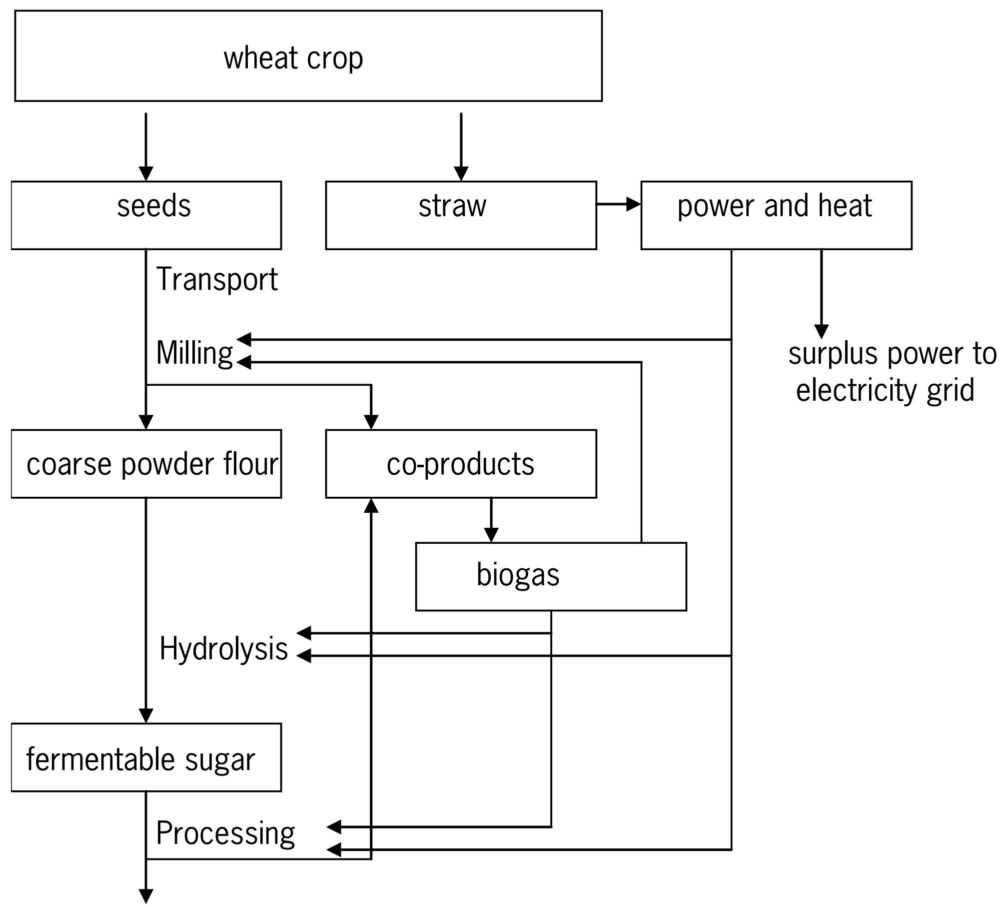

Figure 2-1: Flow chart for production of fermentable sugar from winter wheat

The cultivation of wheat is assumed to be taking place in the Netherlands. Wheat is the most common field crop in the Netherlands despite its low revenues. It has low costs, a fairly stable yield and price and can fill a large part of crop rotations without major problems. Straw is partly left on the field and partly used in agriculture, it is not yet used for energy production. However for our study we assume that all straw is collected and used for the production of power and heat. Grains are usually milled dry to separate the bran from the coarse powder flour which contains beside starch also protein and other components. The starch, a poly-saccharide can be hydrolysed to mono-saccharides, the fermentable sugars. The co-products bran and stillage are supposed be used for the production of biogas by anaerobic fermentation. The biogas is converted to power and heat to be used in processing.

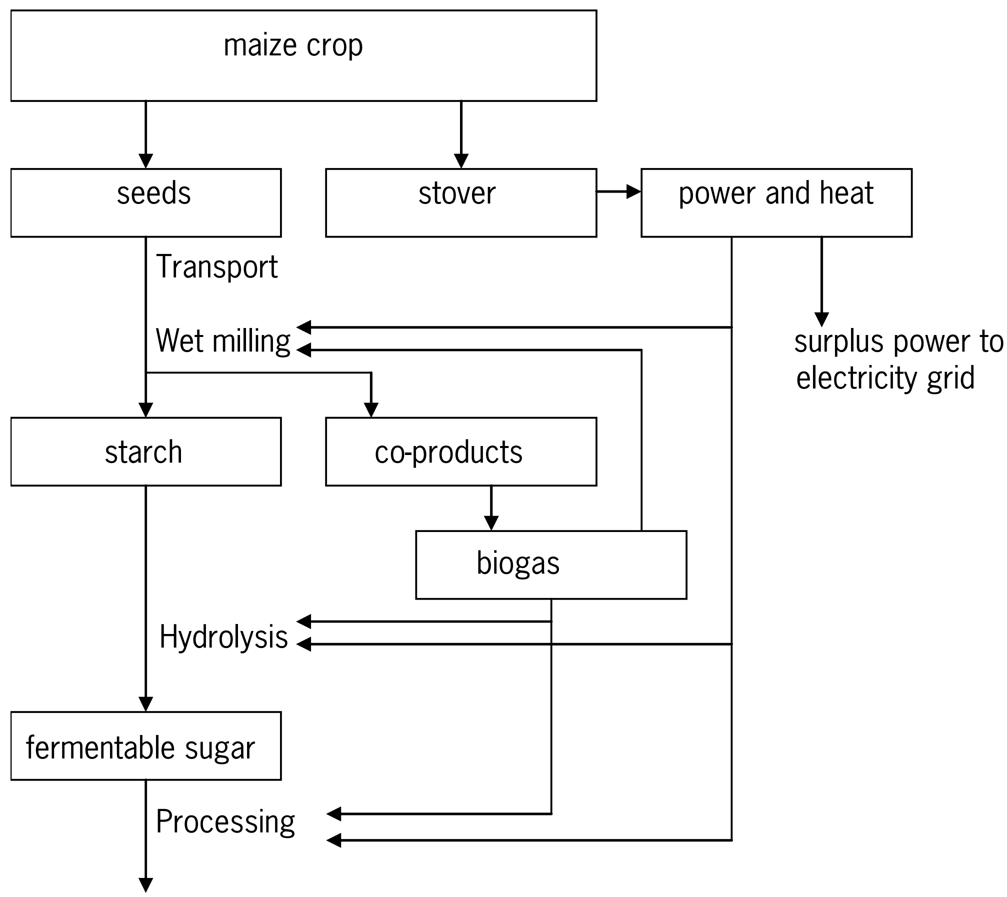

Figure 2-2: Flow chart for production of fermentable sugar from maize

The cultivation of maize is assumed to be taking place in the Netherlands. Traditionally, seed maize could not be grown in the Netherlands because the climatic conditions do not permit the development of sufficiently ripe seeds. Recently developed, early ripening varieties, however, are better adapted to our climate. Due to a better utilisation of the growing season, maize can give higher yields than wheat. On the other hand the costs are higher because of the high moisture content of the seeds. The straw ('stover') is left on the field; harvesting is possible but not cost-effective because the straw can not be stored without drying. However for our study we assume the stover is collected and used for the production of heat and power. The grains are usually milled wet to separate the starch from the other components. Starch is hydrolysed to produce fermentable sugars. The co-products from milling are supposed be used for the production of biogas by anaerobic fermentation. The biogas is converted to power and heat to be used in processing.

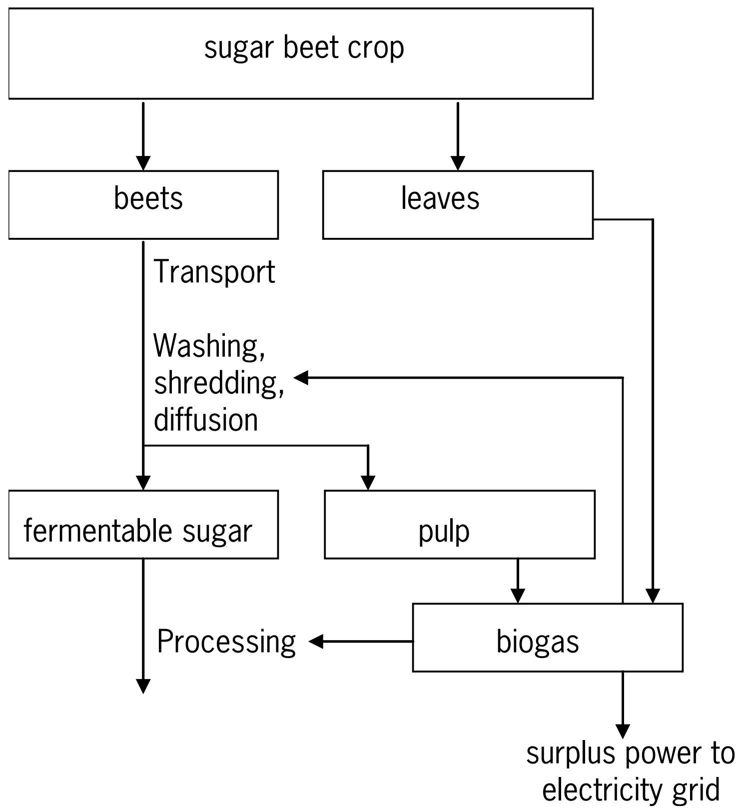

Figure 2-3: Flow chart for production of fermentable sugar from sugar beet

The cultivation of sugar beet is assumed to be taking place in the Netherlands. Sugar beet production area in the Netherlands is decreasing fast because of yield increase and decreasing protection due market liberalisation. A further decrease and eventually a total disappearance is to be expected. Since the sugar beet crop has a very high yield and a high sugar content it could be attractive for biobased purposes. The leaves are left on the field but could be used for the production of biogas, as we assume in this study. Beet leaves have a very high moisture content resulting in high transport costs and the need for preservation to prevent rotting. Beets are washed and shredded to separate the pulp from the juice, after filtering with lime this juice contains 15% sugar and 2% other dry components The sugar is sucrose, a di-saccharide, which is directly fermentable. Pulp is usually used as animal feed, freshly ensiled or dried, but it can also be used for fermentation to biogas, as we assume in this study. Also the leaves are supposed to be used for biogas production. The biogas is converted to power and heat to be used in processing. Depending on the actual process, an eventual power surplus can be delivered to the electricity grid.

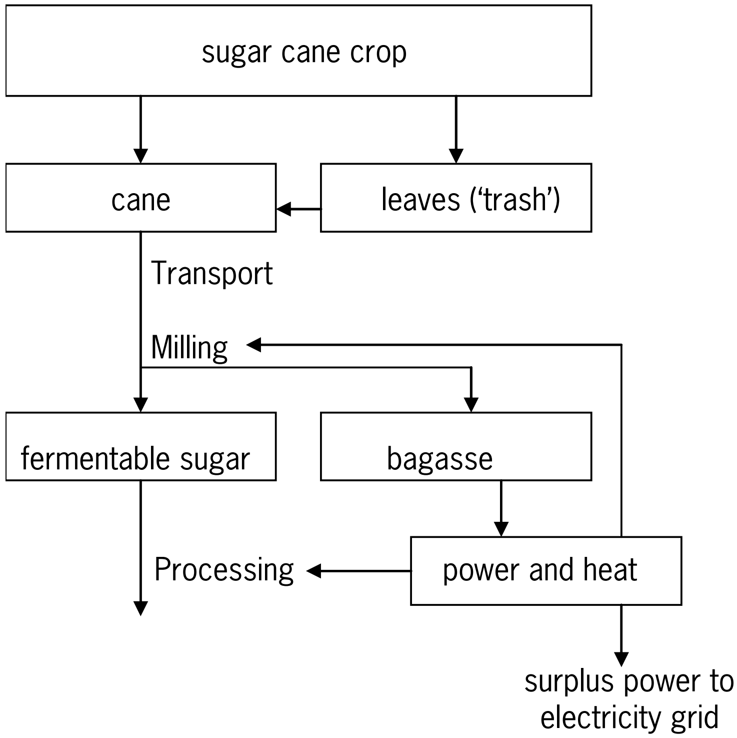

Figure 2-4: Flow chart for production of fermentable sugar from sugar cane.

The cultivation of sugar cane is assumed to be taking place in Brazil. Sugar cane is a perennial crop with a growth cycle of mostly six years with five harvests; the first harvest is two years after the last harvest before replanting. Stalks are cut manually or mechanically and leaves are removed and left in the field. Harvesting including leaves ('trash') is possible and is expected once energy production from the leaves becomes cost-effective. For this study we assume this last practice. Sugar cane stalks are processed by cleaning, slicing, shredding and milling. Sugar cane juice is the main product of milling; the by-product is sugar cane fibre, which is called bagasse. Bagasse, eventually with the leaves is used as a primary fuel source in the sugar mills. Combustion of the bagasse produces sufficient power and heat to cover the needs of a typical sugar mill. Surplus power and heat are usually not produced because of lack of market demand, for the future an increasing demand for electricity is to be expected with more power generation from bagasse and leaves as a result. Depending on the plant surplus heat and/or electricity can thus be generated which is sold to industrial users and/or to the grid. The juice extracted from sugar cane has an average sucrose content of 12 – 13% and can be fermented after filtering (Ockerman, 1978, Macedo *et al.*, 2008).

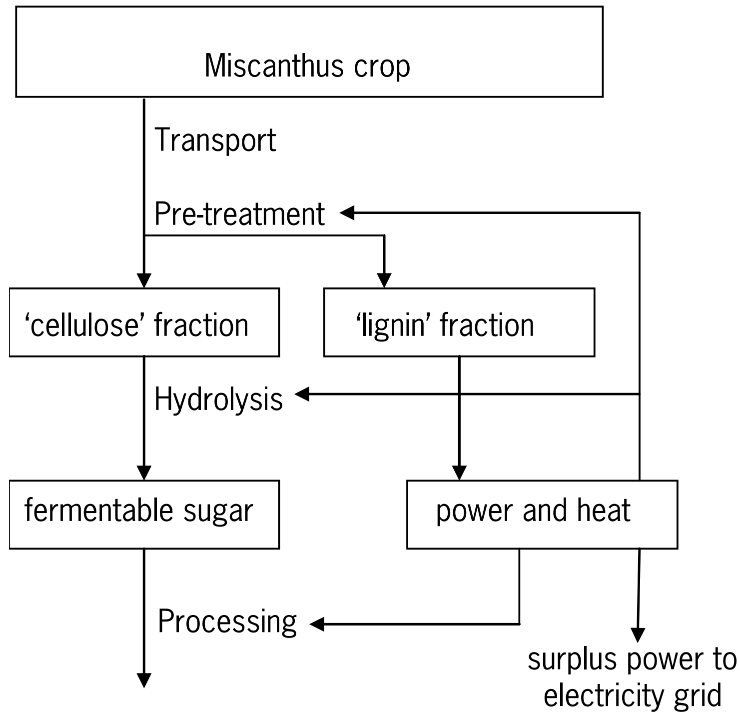

Figure 2-5: Flow chart for production of fermentable sugar from Miscanthus

The cultivation of Miscanthus is assumed to be taking place in the Netherlands. Harvest is assumed to be taking place in early spring when most leaves have fallen. Therefore, the yield is circa one third lower than the maximum yield reached in autumn (Lewandowski *et al.*, 2003). Despite the lower yield, harvest in early spring is preferred because of the high moisture content in autumn, resulting in high transport and drying costs. Furthermore with spring harvest most nutrients will be retrieved in the roots of the crop or will be recycled with the fallen leaves. Therefore, less fertilizer is needed. At the same time the absence of minerals will prevent problems with molten ashes in the burning facility.
Miscanthus is a perennial crop with a growth cycle of 15 to 20 years. Miscanthus is a 'ligno-cellulose' crop, and for that matter comparable with straw and wood, with cellulose as the component that can deliver fermentable sugars after hydrolysis. In a pre-treatment the cellulose is separated from the other components, mainly hemicellulose and lignin. The hemicellulose and lignin fraction is used to generate power and heat,

2.3 Products

For each end product we study two production processes, each converting sugar to the target chemical: for ethanol and PE a currently used process and a process including expected innovations, for PLA a process that was used and studied in 2004 and the currently used process, in which a number of innovations are effectuated.

2.4 Polylactic Acid (PLA)

PLA is one of the first biobased polymers to find broad application in a number of consumer products. PLA is used for packaging materials such as food containers and bottles, and in films also for packaging, Albert Heijn for instance uses PLA for a number of organic ("biologische") products. The Dutch company Synbra has developed a green foam from PLA that can replace polystyrene foam ("piepschuim"). PLA is also processed into fibres, from which clothing, carpets and duvet filling are made. PLA for non-medical applications is presently only produced by NatureWorks, but new producers are presently setting up production plants (Shen *et al.*, 2009). PLA (see Figure 2-6) is an aliphatic polyester produced via polymerisation of the renewable fermentation product lactic acid. With the setup of NatureWorks' (formally Cargill Dow) production plant for polylactic acid (PLA) in 2002 (140.000 t. p.a.), PLA became the third type of bio-based polymer that was commercialised and is now produced on a large scale. In November 2007, PURAC started up a lactic acid plant in Thailand with a capacity of 100,000 t. p.a. In 2008, PURAC started to produce in Spain both L-lactide and D-lactide which are both precursors of PLA (see below).

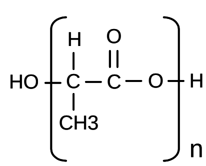

Figure 2-6: PLA molecule

The physical and mechanical properties of PLA make it a good candidate as replacement for petrochemical thermoplastics, especially polyethylene terephthalate (PET) in several application areas. PET has a production volume in Europe alone of over 3 Mtonnes per year. While the high price of PLA long restricted its use to medical and specialty applications, recent breakthroughs in lactide and polymerisation technology opened up possibilities for the production of PLA in larger volumes.

PLA is produced from lactic acid. Lactic acid is produced from fermentable sugar. The efficiency of conversion is typically greater than 95% on carbohydrate substrate (Datta *et al.*, 1995). The fermentation can be performed in either a batch or a continuous process.

Two main routes have been developed to convert lactic acid to high molecular weight polymer: the indirect route via lactide, the product of which is generally referred to as poly(lactide), and direct polymerisation by polycondensation, producing poly(lactic acid) (see Figure 2-7). Both products are generally referred to as PLA (Södergård & Stolt, 2003).

The first route is employed both by NatureWorks and PURAC, which are the two key players in PLA production. They apply a continuous process using ring-opening polymerisation (ROP) of lactide (Gruber & O'Brien, 2002).
In the second route, the direct polymerisation of lactic acid, lactic acid is converted directly to high molecular weight PLA by an organic solvent-based process (Gross & Kalra, 2002). This process was applied by Mitsui Toatsu. Mitsui Toatsu stopped the production in 2003 and since then this route is not applied anymore.

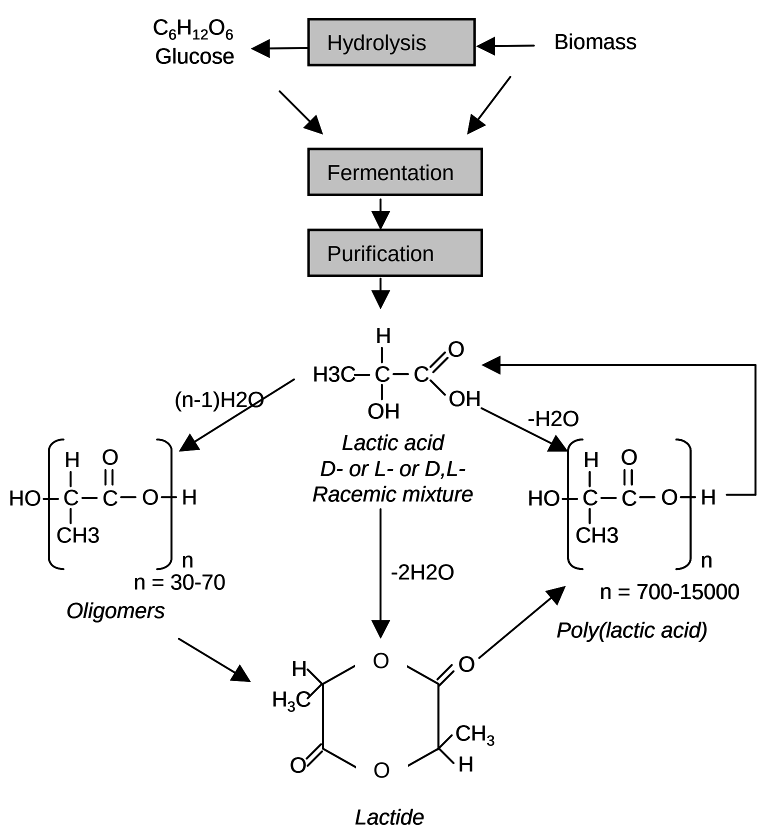

Figure 2-7 **Production of PLA from fermentable sugar**

2.5 Bio-ethanol

Fementable sugar is anaerobically fermented to ethanol according to the following reaction:

$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2$

As shown in Figure 2-8, ethanol is distilled in order to remove water and to yield an azeotropic mixture of hydrous ethanol (at 95.5 vol.-%) (Wheals *et al.*, 1999). Distillation generates another by-product, which is called vinasse, and is generally used as a fertilizer (Wheals *et al.*, 1999). Ethanol is then dehydrated at high temperatures over a solid catalyst to produce ethylene (Zimmermann & Walzl, 2000):

$CH_3CH_2OH \rightarrow CH_2{=}CH_2 + H_2O$

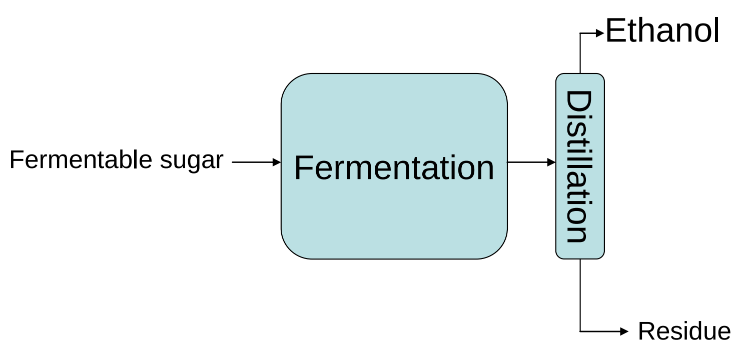

Figure 2-8 Production of Ethanol from fermentable sugar

2.6 Bio-based Polyethylene (PE)

The emergence of bio-based polyethylene (Figure 2-9) on the market is not an entirely new phenomenon. A small but significant amount of India's ethanol, for example, was used in the 1970s to derive ethylene and to produce polyethylene (PE), polyvinyl chloride (PVC) and styrene (World Bank, 1980). In the 1980s, companies like Braskem, Solvay and Dow produced, with subsidies from the Brazilian government, in total 150,000 t.p.a of ethylene (presumably from sugarcane); these were converted to bio-based PE and PVC (Schuts, 2008). Bio-based plastic production ceased when oil prices fell to 20 US$ per barrel (http://en.wikipedia.org/wiki/File:Brent_Spot_monthly.svg) in the early 1990s and bio-based polyethylene was again replaced by petrochemical polyethylene. Given the substantially higher current oil price, the production of bio-based polyethylene has again become attractive. In principle, the same technology is being used as some decades ago (Figure 2-10). In 2007, two large Brazilian companies, namely Braskem (200,000 t.p.a), and the joint venture of Dow and Crystalsev (350,000 t.p.a), announced to produce bio-based polyethylene on a large-scale

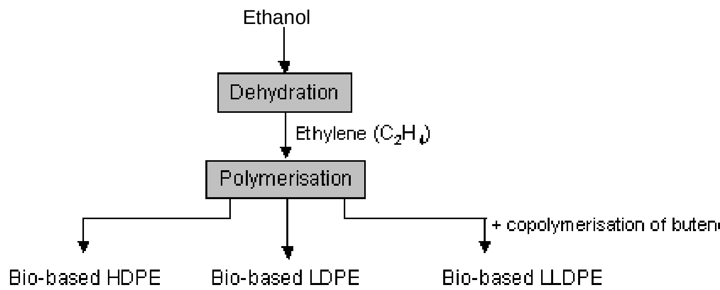

Figure 2-10 Schematic overview of the production of bio-based PE

(Braskem, 2007, Dow, 2007b). In total (550,000 t.p.a) this amount represents somewhat less than 1% of the worldwide polyethylene production (approx. 65 million tonnes).

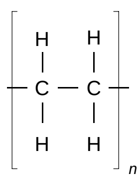

Figure 2-9 Building block of polyethylene (PE)

From 2010 onwards bio-based polyethylene will be produced in Brazil at industrial scale from bioethanol, which is made from sugar cane. Bio-based polyethylene can, however, also be derived from ethanol produced from any other crop yielding fermentable sugar (see section 2.2.2).

Polyethylene is by far the most important product made of ethylene. The production of fossil based polyethylene in Europe alone amounts to over 15 Mtonnes per year. There are different types of polyethylene (PE), with the most important being High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE) and Linear Low Density Polyethylene (LLDPE). LLDPE is a copolymer of ethylene and butene, hexene or octene. Apart from these polymers, ethylene is used in large quantities to produce PVC, PET, PS and polyols for polyurethanes (PUR).

3 Methodology

3.1 Reference systems, functional units and system boundaries

As explained in the introduction, one of the key research questions to be answered is whether bio-based PLA, PE and ethanol require less non-renewable energy and cause less greenhouse gas emissions than their counterparts made from fossil fuels. The fossil fuel-based product chosen as counterpart for

- PLA is amorphous polyethylene terephthalate (PET; for comparison, petrochemical low density polyethylene, LDPE, will be reported in addition).
- bioethanol is petrochemical ethanol (for chemical applications) and petrol (gasoline; for fuel use in cars)
- bio-based polyethylene (PE) is petrochemical PE.

The chosen functional unit is one tonne (1 t) of product. This choice implies that we do not correct for differences in material properties between PLA and PET, e.g. in terms of strength, resulting in different material requirements for a given application (e.g. a plastic film or a panel). Bio-based PE and petrochemical PE are chemically identical and therefore have the same material properties. The same holds also for bio-based ethanol as compared to petrochemical ethanol. Regarding the use of ethanol as biofuel we do account for the difference in calorific value compared to petrol. Due to the lower calorific value of bioethanol this means that we compare 1 tonne of bioethanol with 0.67 t of petrol.

With regard to system boundaries the analysis is limited to the system "cradle-to-factory gate" for the polymers and likewise for ethanol used for chemical purposes. Regarding the fuel application the use phase is included as just explained. The choice of the system "cradle-to-factory gate" for the polymers and for ethanol implies that the assessment of waste management (with the various technologies that are available) is beyond the scope of this study.

3.2 Dealing with co-products

In most bio-based production chains, only a part of the crop is processed to biofuel or biopolymers while co-products like straw, beet pulp and DDGS are used for other purposes, for instance as animal feed. Hence, also only a part of the energy use and GHG emissions should be assigned to the main product and the other part should be assigned to the co-products, this is called allocation. The choice which part of the emissions is assigned to which product greatly influences the outcome of the study.
Performing allocation, however, is a complex problem for which different methods exist. According to ISO 14044 (ECS, 2005-a, ECS, 2005-b) allocation is preferably avoided by 1)

dividing the unit process to be allocated into two or more sub-processes or 2) expanding the product system to include the additional functions related to the co-products. ISO 14044 proceeds by saying that, where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions. Preference is given by ISO to apply partitioning using physical relationships between the various products (possible examples are mass, energy content or exergy); wherever this is not possible, other relationships including the economic values (prices) are recommended.

Following ISO, we aim at avoiding allocation. To do so, system expansion is applicable more frequently than division of the system into subsystems. In the case of system expansion the bio-based production system (e.g. bioethanol from wheat) should be compared to a reference system not only producing the *main* product from a fossil fuels (i.e., petrol) but to an extended system, also producing a product comparable to the *co-product* of the biobased production system (for example, since the wheat-bioethanol chain yields DDGS as a co-product, the system should be extended by a product that typically replaces DDGS).
However, as explained in Section 2.1 we have made a slightly different choice in order to be able to compare the crops. We assume in our default calculations that energy is produced from *all* co-products, thereby replacing fossil energy. When combining this assumption with the system expansion approach, this means that, for example, wheat straw is combusted to produce steam and power (and thus replaces a mix of fossil fuels), and biogas produced from DDGS (see Figure 2-1) replaces natural gas. It should be noted that the calculation method applied does not represent the current agricultural practice (i.e., we assume energy production by combustion of co-products that are at this moment in practice used for other purposes). However, the calculation method was chosen because it creates a level playing field for comparing different crops.

It is a complication of the system expansion approach that it can lead to very different results depending on how the system is expanded (e.g. by assuming soy cultivation on recent tropical rainforest areas in Latin America as opposed to rapeseed cultivation in Western Europe). Different assumptions can therefore relatively easily result in controversies which could even lead to litigation. It is primarily for this reason that the European Commission, in its Biofuel Directive (EC, 2009), states that the "substitution method"[2] is appropriate for the purposes of policy analysis, but not for the regulation of individual economic operators and individual consignments of transport fuels". The Directive proceeds by saying: "In those cases the energy allocation method is the most appropriate method, as it is easy to apply, is predictable over time, minimises counter-productive incentives and produces results that are generally comparable with those produced by the substitution method." At the same time, the Biofuel Directive does not, by any means, rule out the application of the system expansion method because it states: "For the

[2] *which is the system expansion approach*

purposes of policy analysis the Commission should also, in its reporting, present results using the substitution method."

We have a few arguments for nevertheless choosing the system expansion approach. First this study represents a policy analysis and we are *not* calculating the impacts of specific products produced by individual companies. Second the choice of the system expansion approach is in line with ISO. Third, by assuming that all co-products are used for energy purposes in an integrated site (i.e under the circumstances of a fully developed bio-based economy), we exclude a large number of options which would need to be considered otherwise; this substantially reduces the uncertainty involved.

As stated above and explained in Section 2.1 we assume in our default calculations that energy is produced from all co-products. These default calculations are presented in Chapter 5. In Chapter 6, we then present the results of a second calculation which is more in line with current agricultural practises. Maize stover, sugar beet leaves and sugar cane leaves are normally left in the field. Wheat straw is partly used in agriculture and mostly returned to the field after use in the form of straw or manure. Removing these co-products for energy production decreases the addition of soil carbon, with the risk of soil organic matter decreasing to an unsustainable level.

3.3 Carbon sequestration and Global warming potential

The characterisation factors applied to assess the effect of CO_2, N_2O and CH_4 on global warming were developed by the Intergovernmental Panel on Climate Change (IPCC, 2001). The Global warming potential (GWP) is expressed in CO_2 equivalents for various time horizons (20, 100 and 500 years). The time horizon of 100 years is most widely used and is also chosen in this study, it implicates a GWP of 296 kg CO_2-eq. per kg N_2O and 21 kg CO_2-eq. per kg CH_4.

Using Figure 3-1 we now discuss the difference between bio-based products and petrochemical products with regard to *carbon sequestration*. To this end, we limit ourselves for the remainder of this section (3.3) to the *carbon* mass balance (in Figure 3-1 expressed in terms of CO_2). We do, however, acknowledge that the *form* of carbon is critical in determining the GWP emissions (CH_4 has a much higher global warming potential than CO_2) and we have accounted for this fact in our own calculations, the results of which we will present later in this report.

For bio-based products we assume the production from sustainably harvested biomass. The CO_2 emissions for the system cradle-to-factory gate can then simply be calculated by deducting the biogenic carbon physically embedded in the product (as CO_2, C_4) from the fossil CO_2 emissions

(C_3). The accurate values of C_3 and C_4 are relatively easy to calculate[3]. For this study the rest of the chain is not taken into account.

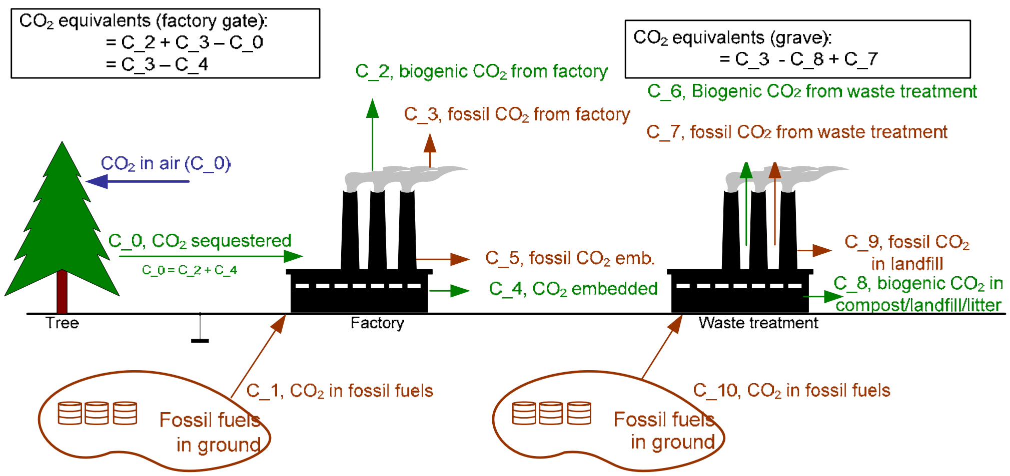

Figure 3.1: Cradle-to-grave CO2 emissions of bio-based and petrochemical products

For petrochemical products, no biogenic CO_2 is sequestered (C_0 = 0), so the total emissions for cradle-to-factory gate (see formula in Figure 3-1) are equal to C_3.

It should be noted that GWP can be negative for the system boundary cradle-to-factory gate, namely when the amount of carbon embedded in the bio-based product (C_4) is larger than the carbon emitted from the use of fossil fuels (C_3).

Emissions of methane (CH_4) and nitrous oxide (N_2O) are not shown in Figure 3-1 but are also taken into account. Nitrous oxide is predominantly emitted during the agricultural production of bio-based raw materials (e.g. maize) as a result of fertiliser production and application. Methane can be emitted during any of the stages, and plays an important role in waste treatment (e.g. C_6) where it can critically change the overall GWP.

3.4 Modelling crop cultivation and the production of fermentable sugar

Calculations of energy use and GHG emissions during crop production, transport and the conversion to fermentable sugar were made with the model 'E-CROP', which is developed in the past years to assess a number of sustainability aspects of biomass-bioenergy chains (Conijn &

[3] *As an alternative, the (net) release of CO_2 equivalents for the system cradle-to-factory gate can theoretically be calculated as the total CO_2 emitted (biogenic CO_2 + fossil CO_2) minus the CO_2 sequestered in the harvested biomass (C_0; see Figure 2-2). This calculation method can be applied when the available data for the biogenic CO_2 emissions are accurate. However, it is often rather difficult to trace biogenic emissions across the process chain, and therefore the method described above is used.*

Corré, 2009; Corré & Conijn, 2009). Land use changes, direct or indirect, can have large effects on GHG emissions, but were not yet taken into consideration because of their complicated effects on the GHG emissions (Conijn & Corré, 2009). Also the effects of changes of the current agricultural practises on the soil carbon dynamics were not taken into account in the calculations. In future research these aspects can be incorporated to present a more complete picture of the effects on the GHG emissions.

3.5 Modelling the production of bio-based products

To calculate the energy requirements and the GHG emissions related to the conversion of fermentable sugar to PLA, bioethanol and polyethylene, we make use of earlier modelling work which we performed in the context of the study "BREW" (Patel et al., 2006). The objective of the BREW project was to assess the medium-tem and long-term opportunities and risks for producing bulk chemicals from renewable resources by means of biotechnology. To this end, detailed environmental and economic assessments (in specific terms, i.e. per tonne of product) were performed for the 21 White Biotechnology products. For this purpose more than 40 flowsheets were prepared and the respective material balances were set up. The calculations were organized in a modular basis: similar to the approach taken in this report various types of feedstocks (fermentable sugar from maize, sugar cane and lignocellulosics) were combined with the various chemical processes leading to the 21 products.
In this report we make use of the modelling framework developed in the BREW project (called BREWtool) with some modifications:

- Instead of using the data on the production of fermentable sugar as developed for the BREW project we use the data developed by PRI using the E-CROP model (see Section 3.3)
- We updated some data on the conversion of fermentable sugar to chemicals, namely the datasets for PLA production and for bio-based polyethylene (see Chapter 4 for details).

3.6 Public power generation

For public power generation, average data were used representing the efficiency and the CO_2 emission intensity in Western Europe (i.e., no country-specific data were used; the data used originated from IEA Energy Balances (2003). Energy use is calculated by summing primary energy consumption in public (grid) electricity plants for all energy types (separately for non-renewable and renewable energy). This is then divided by the figure for gross power generated in public power plants. Summing the non-renewable energy use (NREU, i.e. the total of fossil and nuclear energy) and REU (renewable energy use) gives the total energy use per unit of gross power generated; the reciprocal of this gives the efficiency for (gross) power generation. Net power generated is calculated by subtracting figures in the IEA balance for own use in electricity plants (power used by the power plant itself), CHP (combined heat and power) and heat plants and distribution losses from the figure for gross power generated. Dividing the total primary energy consumption by the net power generated leads to a higher total specific energy use and a corresponding lower efficiency. When the energy requirement for energy (ERE) is taken into account (this is the amount of energy needed to exploit, pre-process and transport the energy), the total specific energy use can be assumed to increase by a factor 1.07 (average ERE factor for mixed fuels) and the efficiency of power generation decreases accordingly, resulting in an efficiency for the entire process chain of 33.4%.

The total CO_2 emission is calculated by multiplying the primary energy consumption in public electricity plants by the carbon (as CO_2) emission factor for each energy type and summing these up. Dividing this by gross and net power generated and multiplication by the ERE factor 1.07 gives the overall CO_2 factor, amounting to 116 kg CO_2/GJ_{el}.

It should be noted that combined heat and power (CHP) offers further opportunities for energy efficiency improvement which have not been accounted for in a comprehensive manner because the implementation depends on the concrete circumstances.

4 Input data used

4.1 Data on fermentable sugar production

Data on NREU and GHG emission for the production of fermentable sugar and for the production of energy from co-products were generated with the PRI model 'E-CROP'. In the calculations four steps are distinguished: 1) agricultural production, 2) transport of products and agricultural co-products (e.g. straw, leaves) to a processing plant, 3) processing of products to fermentable sugar and 4) using the agricultural co-products and processing co-products (e.g. beet pulp, bagasse) for power and heat. Model input data were taken from Corré & Conijn (2009) for wheat and Miscanthus, KWIN (2006) and Groten (2003) for maize, Corré & Langeveld (2008) for sugar beet, and Macedo *et al.* (2008) for sugar cane. Model input data for sugar cane were adapted to describe the current potential production on the basis of the current production combined with 'best practise' harvest techniques. A summary of the model input and output data is presented in table 4.1. For sugar cane and Miscanthus no data are available for the internally used amount of energy generated from the crop itself but only for the power surplus when producing ethanol and estimates had to be made on the basis of total dry matter production.

Table 4.1: Summary of input and output data for the production of fermentable sugars.

		wheat	maize	sugar beet	sugar cane	Miscanthus spring	Miscanthus autumn
Yield	ton ha^{-1} yr^{-1}	8.40	10.63	74.0	75.0	14.7	55
Dry matter production	ton ha^{-1} yr^{-1}	7.14	7.44	17.0	20.0	12.5	18.3
Fermentable sugar contents	% of d.m.	75	75	73.5	52	49	49
Fermentable sugar yield	ton ha^{-1} yr^{-1}	5.00[1]	5.58[1]	12.05	11.00	6.21	8.96
Co-product yield	ton ha^{-1} yr^{-1}	4.30	16.3	40	30	0	0
Co-product dry matter	ton ha^{-1} yr^{-1}	3.56	6.50	5	10	0	0
Transport distance	km	50	50	90	30	50	50
D.m. co-products[2]	ton ha^{-1} yr^{-1}	2.14	1.86	4.50	8.50	6.25	9.3
Energy prod. biogas	GJ ha^{-1}	27.9	24.2	98.9	0	0	0
Electricty biogas	GJ ha^{-1}	7.0	6.1	24.7	0	0	0
Heat biogas	GJ ha^{-1}	16.7	14.5	59.3	0	0	0
Heat demand biogas	GJ ha^{-1}	2.2	1.9	7.9	0	0	0
Heat avail. biogas	GJ ha^{-1}	14.5	12.6	51.4	0	0	0
Electricity heat/power	GJ ha^{-1}	12.1	22.1	0	60	23	34
Heat heat/power	GJ ha^{-1}	36.4	66.3	0	180	67	100
Electricity total avail.	GJ ha^{-1}	19.1	28.2	24.7	60	23	34
Heat total avail.	GJ ha^{-1}	50.9	78.9	51.4	180	67	100
Energy inputs							
Agriculture	GJ ha^{-1}	14.8	43.5[5]	14.7	15.0	11.1	78
Transport	GJ ha^{-1}	1.8	3.3	10.6	5.8	1.7	5
Pre-process	GJ ha^{-1}	5.8	6.5[6]	8.3	8	30	443
Processsing co-products-pr.[3]	GJ ha^{-1}	2.2	1.9	7.9	14	4.7	7.0
Processing co-products-ag.[4]	GJ ha^{-1}	2.7	4.9				
Total	GJ ha^{-1}	27.3	60.3	41.5	43	48	133
GHG emiss.							
Agric. CO_2	kg CO_2-eq. ha^{-1}	900	3120[5]	1120	1400	764	5700
Agric. N_2O	kg CO_2-eq. ha^{-1}	1740	1910	1220	700	480	960
Transport	kg CO_2-eq. ha^{-1}	130	250	800	430	121	370
Pre-process	kg CO_2-eq. ha^{-1}	430	480[6]	470	450	2300	3300
Processsing co-products-pr.[3]	kg CO_2-eq. ha^{-1}	130	110	450	1100	350	500
Processing co-products-ag.[4]	kg CO_2-eq. ha^{-1}	210	380				
Total	kg CO_2-eq. ha^{-1}	3540	6250	4060	4100	4100	10830

[1]: starch, for wheat and for maize: 5.5 and 6.1 tonnes of fermentable sugar respectively. [2]: dry matter yield of co-products from processing of agricultural crops. [3]: processing of co-products from processing of agricultural crops. [4]: processing of agricultural co-products. [5] including drying of corn and straw, possibly residual heat can be used. [6] figure based on dry milling of wheat.

4.2 Data for the chemical conversions

While the methodology for calculation of the environmental impacts per tonne of fermentable sugar has been explained in Paragraph 4.1, this paragraph briefly addresses the background data used for the chemical conversion to the target products. The main data sources used are the BREW study, personal communication with NatureWorks and with other experts in the field (especially on bioethanol), literature surveys and the EcoProfiles of PlasticsEurope.

For PLA, we refer to the calculations as generic ("PLA generic 2005" and "PLA generic 2009") because data on the core process were kindly provided by NatureWorks while energy use for the core process is based on own modelling and data related to most inputs were taken from other sources (e.g. EcoInvent). The process "PLA generic 2005" refers to polycondensation of lactic acid, with the lactic acid being produced via anaerobic fermentation of dextrose; workup via unspecified process involving neutralisation & acidification; the type of process applied is still state-of-the-art for other bio-based processes. The process "PLA generic 2009" represents PLA production by polymerisation of lactic acid produced with a new lactic acid production technology (in place since December 2008).

When reviewing the process data used in the BREW study for the dehydration of bioethanol to ethylene, we considered the process energy requirements too low and therefore replaced them by the heat of reaction. Apart from the cases listed in Table 4-2 further cases were studied; these are, however, not presented in this report because the results do not differ substantially and because they do not lead to additional conclusions.

In the past, NatureWorks compensated a part of their of environmental impacts by purchasing certificates for power produced from wind energy. Other producers apply similar approaches, e.g. by purchasing carbon credits related to afforestation. While there are good reasons for such company decisions, they are frequently criticized as false compensation of the environmental impacts, which could also be pursued by manufacturers of petrochemical plastics. This is probably the main reason why the British Standards Institute in their "Publicly Available Specification (PAS) No. 2050 forbids carbon offsetting. In this project we exclude renewable energy credits and carbon credits for another reason, namely because we aim to focus on the chemical technology rather than the optimization of the energy supply system.

PLA (bio-based)	PLA generic 2005	Poly(lactic acid) via polycondensation of lactic acid. Lactic acid via anaerobic fermentation of dextrose; workup via unspecified process involving neutralisation & acidification; core process data received from NatureWorks. This type of process is still state-of-the-art for other bio-based processes.
	PLA generic 2009	Poly(lactic acid) via polycondensation of lactic acid; new lactic acid production technology since December 2008. Core process data received from NatureWorks represent newest technology.
Petrochem. PET and LDPE	Petchem. PET Amorphous	Amorphous poly(ethylene terephthalate) by polymerisation of ethylene and purified terephthalic acid (PlasticsEurope)
	Petchem. LDPE	Low Density Polyethylene (PlasticsEurope)
Bio-based ethanol	Current state-of-the-art	Bio-ethanol via anaerobic continuous fermentation on dextrose substrate; workup via distillation; Generic Approach (today)
	Future	Bio-ethanol via anaerobic continuous fermentation on dextrose substrate; workup via pervaporation; Generic Approach (future)
Petrochem. ethanol and petrol	Petrochemical ethanol Petrol (gasoline)	Hydration of ethylene produced by steam crackling Petrol produced in a refinery
Bio-based polyethylene	Current state-of-the-art	Polyethylene by polymerisation of ethylene; ethylene by dehydration of bioethanol (in BREW acc.to company information; here based on heat of reaction). Bioethanol via process "Current state-of-the-art", see above
	Future	Polyethylene by polymerisation of ethylene; ethylene by dehydration of bioethanol (in BREW acc.to company information; here based on heat of reaction). Bioethanol via process "Future", see above
Petrochem. polyethylene	Petrochemical ethylene	Polyethylene by polymerisation of petrochemical ethylene; ethylene by steam cracking of hydrocarbons, in particular of naphtha (PlasticsEurope)

Table 4-2: Cases assessed in this report – biobased PLA, ethanol and polyethylene in comparison with their petrochemical counterparts

5 Results when all co-products go to energy

5.1 Introduction and general assumptions

As explained above, we assume as default that energy is produced from *all* co-products, thereby replacing fossil energy. This "energy system expansion method" has been applied both to calculate the environmental impacts related to the production of fermentable sugar and its subsequent conversion into bulk chemicals and fuels (see below). The concept of the energy system expansion method is hence that all co-products are considered to be used for energy purposes (e.g. to produce process power and heat) and that a credit is given for the avoided fossil fuel use and its environmental impacts. If there is a surplus of power this can be delivered to the public grid, resulting in additional credits for energy use and GHG emissions. If there is a surplus of heat, we likewise assign in our default calculations a credit for the avoided NREU and GHG emissions. However, it depends on the local circumstances whether or not the heat can be used for other industrial processes (since the storage of process heat is practically not possible). We report in the form of an uncertainty bar the case where an eventual surplus of heat is discarded. In more detail, the following assumptions were made for the use of the co-products:

- Wheat: the straw is burnt in a biomass plant to generate power and heat, co-products from processing are fermented to biogas, which is used in a CHP plant to produce power and heat.
- Maize: straw and co-products from maize processing are used in the same way as in the case of wheat.
- Sugar beet: the leaves and the pulp are used to produce biogas and the biogas is used to produce power and heat in a CHP plant.
- Sugar cane: the stalks are harvested including the leaves ('trash'), leaves and bagasse are burnt to generate power and heat.
- Miscanthus: after separation of the cellulose fraction from the crop the 'co-products' are used to generate power and heat.

5.2 The production of fermentable sugars

As shown in Figure 5-1 and Figure 5-2 the environmental impacts differ substantially across the five routes for producing fermentable sugar. The net values given above the bars fully account for the co-produced surplus process heat as credit. As mentioned above, it may not always be possible to make use of this surplus heat. In this case the credits are lower and the NREU values are accordingly larger; the values in brackets above each bar refer to the situation that there is no use at all for the surplus heat.

The (net) environmental impacts (NREU and GHG), expressed per tonne fermentable sugar, are highest for fermentable sugar made from sugar beet and Miscanthus harvested in autumn; they are clearly lower for maize, wheat and Miscanthus harvested in spring. Fermentable sugar from sugar cane causes the lowest NREU and GHG values across the feedstocks studied and maize is the crop with the lowest values for the production of fermentable sugar in the Netherlands. However, the climatic conditions in the Netherlands are not ideal because the summer is not always long and dry enough for the maize to reach the required level of ripeness and moisture. Considering this drawback, wheat can be considered as closest substitute (5-1).

We first discuss the energy requirements (bar sections above the zero line in Figure 5-1 and 5-2) and as subsequent step, the energy yields (bar sections below the zero line). The energy requirements for cultivation and pre-processing of the crop are the largest energy users (see green and light blue sections). For maize, the main reason is the very high moisture content of seeds and straw at harvest, making intensive drying necessary. For sugar beet and sugar cane, the raw sugar needs to be purified by crystallization before being fed to lactic acid fermentation stage (see red bar section), while there is no need for purification in the case of ethanol production; there is also no need for a comparable purification step for starch-based crops. For Miscanthus, pre-processing energy is required to convert the lignocellulosics to fermentable sugars (light blue bar section). The default case for Miscanthus cultivation in the Netherlands is to harvest it in spring. The Miscanthus yield is larger in autumn but much extra energy is then required for drying the crop (green bar section). This leads to clearly higher energy use and emissions for fermentable sugar made from Miscanthus harvested in autumn. As already mentioned, the yield is higher for Miscanthus production in autumn compared to spring; this applies to both sugar production and agricultural co-products (yielding energy credits) and therefore the credits per tonne of fermentable sugar remain unchanged compared to Miscanthus cultivation in spring (bar sections below the zero line are identical for the two Miscanthus cases).

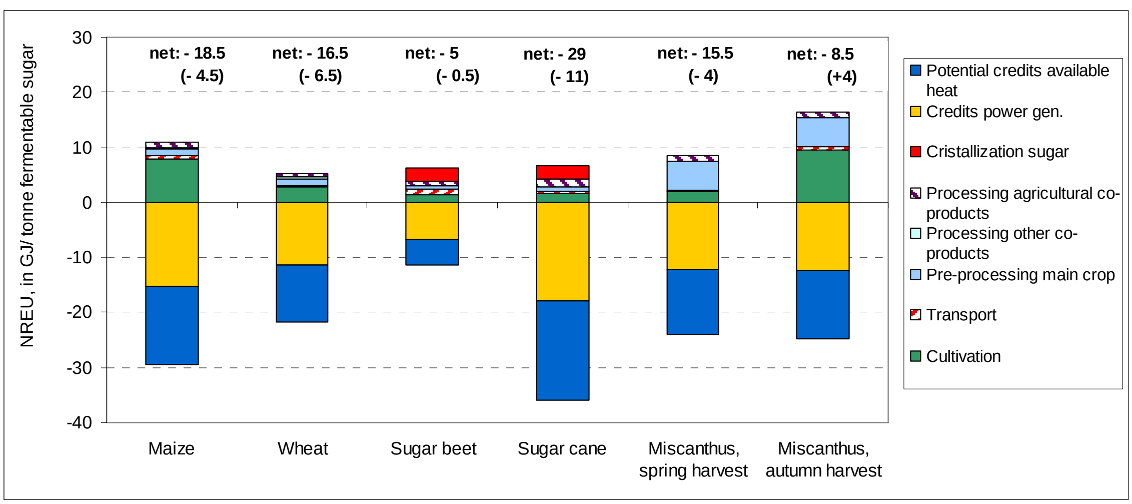

Figure 5-1: Non-renewable energy use (NREU) for the production of 1 tonne of fermentable sugar from various agricultural feedstocks (see text for values given above the bars); *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation)

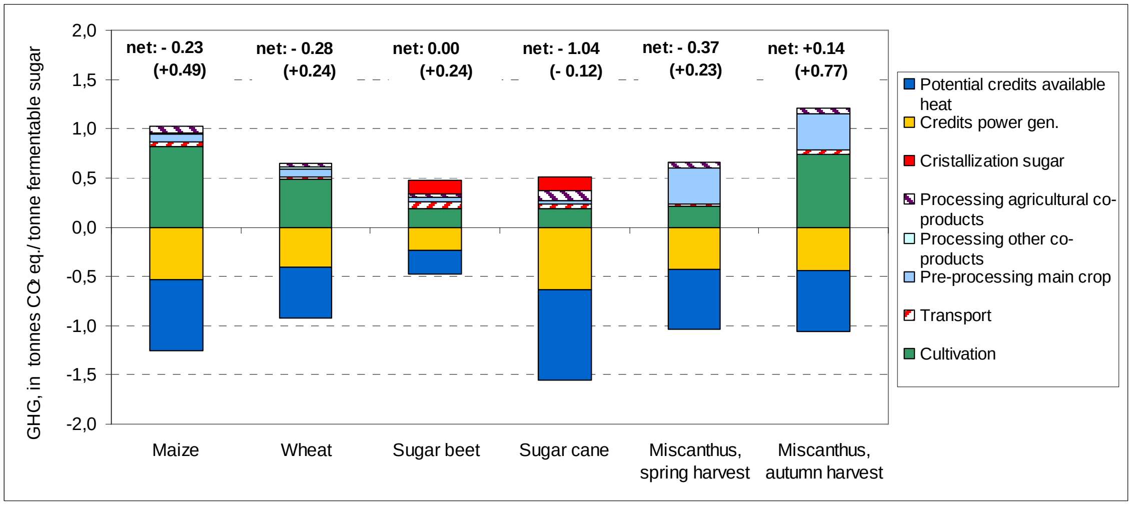

Figure 5-2: Greenhouse gas emissions (GHG) caused by the production of 1 tonne of fermentable sugar from various agricultural feedstock (see text for values given above the bars); *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation); no carbon sequestration assumed, i.e. embodied carbon has *no*t been deducted.

In most cases the energy yields (bar sections below the zero line) are larger than the energy needs (bar sections above the zero line). The energy yields differ very substantially across the various types of crops.

Based on Figure 5-1 and Figure 5-2, one would give clear preference to fermentable sugar from wheat and especially maize as compared to sugar beet. It must, however, be noted that this comparison refers to one tonne of fermentable sugar; therefore it does not take into account the difference in sugar yields across the crops. The amount of land needed to produce one tonne of sugar thus differs substantially across the crops. For example, the amount of land needed to produce one tonne of fermentable sugar is approximately twice as high for maize and wheat compared to sugar beet (or, vice versa, the yield of fermentable sugar from sugar beet is approximately twice as high; see values printed red in Figure 5-3). As a consequence, Non-renewable energy use (NREU) per hectare of land (as shown in Figure 5-3) differs less across the crops than NREU per tonne of fermentable sugar (Figure 5-1). We will revert to this point at the end of this chapter and in Chapter 6 (see sections "Savings per tonne of agricultural land").

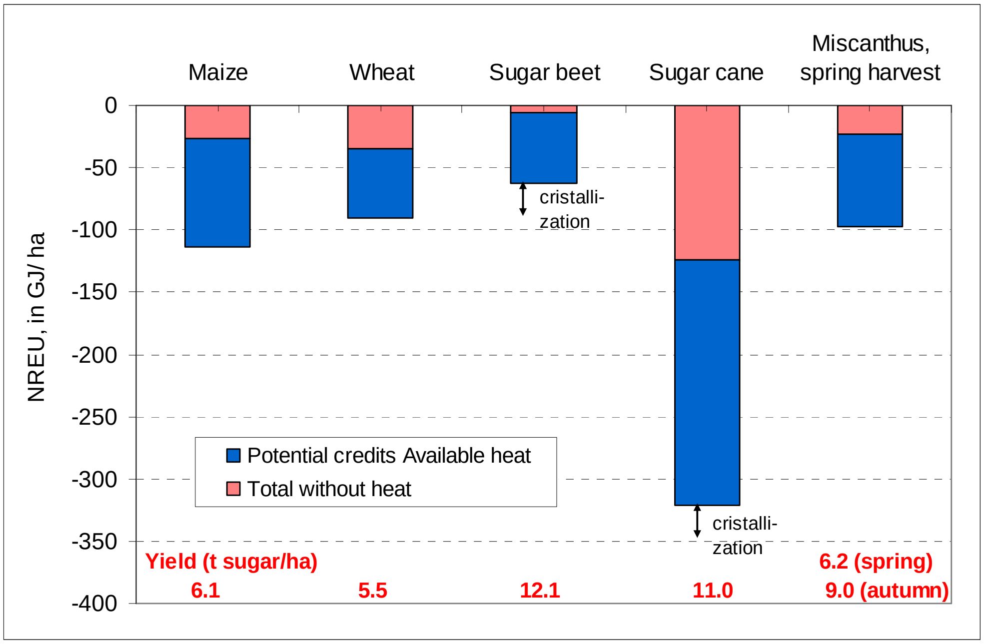

Figure 5-3: Non-renewable energy use (NREU) per hectare of agricultural land (see text for values given below the bars); *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation); extra energy for purification of the sugar by cristallization may or may not be necessary depending on the product.

5.3 Polylactic acid (PLA)

As mentioned in Chapter 4, the process ("PLA generic 2005" represents the process operated by NatureWorks until recently (no purchases of wind energy credits are considered in this process). The type of process applied is still state-of-the-art for other bio-based processes. We first discuss the results for this technology before moving on to the more advanced technology as currently operated (see Figure 5-4 and Figure 5-5). If wheat or maize is used as feedstock, 75% to 80% of the NREU and of the GHG emissions of petrochemical plastics (PET and LDPE) are saved; this is equivalent to 60 to 65 GJ/t PLA and 1.5 to 2.7 t CO_2 eq./t PLA. For sugar beet, the savings are 55%-70% for NREU and GHG emissions (40-45 GJ/t and 1.1 to 2.3 t CO_2 eq./t PLA). The two Miscanthus cases score somewhere in between the values for starch-based feedstocks and sugar beet. While the cases discussed make use of crops that grow in temperate climate, sugar cane grows only in tropical climate zones, explaining its much lower environmental footprint (savings of 80 GJ/t and 2.7 to 3.9 t CO_2 eq./t PLA). It should be noted that, in line with the methodology explained in section 3.2 for the system "cradle-to-factory gate", the embodiment of bio-based carbon in PLA has been taken into account as negative emission of 1.8 t CO_2 eq./t PLA.

We now discuss the results for the more advanced technology as applied today , i.e. "PLA generic 2009". The NREU results are approximately 15 GJ/t lower and the GHG emissions are approx. 1.2 t CO_2 eq. lower per tonne of product compared to the process "PLA generic 2005". This makes today's technology ("PLA generic 2009") even more advantageous compared to the petrochemical processes (max. savings for sugar cane amount to 95 GJ/t and max. 3.8 to 5.0 t CO_2 eq./t PLA).

The data used for the conversion of fermentable sugar to PLA were kindly provided by NatureWorks, but the results presented in Figure 5-4 and Figure 5-5 for maize starch are nevertheless much lower than the energy and carbon footprint published by NatureWorks (42 GJ/t PLA and 1.3 t CO_2 eq./t PLA for the current technology package according to NatureWorks' website (NatureWorks, 2010); the respective values for PLA-05 (to be compared to "PLA generic 2005") are 50.8 GJ/t PLA and 2.02 t CO_2 eq./t PLA acc. to Vink et al., 2007). The essential reason for these differences is that the environmental impact per tonne of fermentable sugar is much lower in this study than in NatureWorks' analyses (for NREU net -18.5 GJ/t acc. to Figure 5-1 as opposed to 6.2 GJ/t in NatureWorks' analyses; quoted in Patel et al., 2006). This is a consequence of our assumption that all agricultural co-products are used for energy purposes.

The results discussed so far are based on an important assumption, i.e. that all surplus process heat can be fully used. This is only possible if the combined LA/PLA plant is located on an industrial site with other plants requiring steam or if the agricultural residue (esp. straw and stover) is transported to a different site where the process heat can be made of. If this is not the case and the surplus process heat therefore cannot be utilized, the NREU and GHG emissions are clearly larger (by up to 18 GJ/t for "PLA generic 2005" and up to 24 GJ/t for "PLA generic 2009"; they are represented by the upper level of the error bars in Figure 5-4 (not for sugar beet/"PLA generic 2005" because all heat is used within the process).

Contrary to the petrochemical products, agricultural land is needed to grow the crops required for the bio-based products. Land use requirements are lowest for sugar beet and sugar cane, followed by the autumn harvest of Miscanthus (as discussed, the disadvantage of Miscanthus autumn in comparison with Miscanthus spring is the additional energy use for drying the crop; see Figure 5-6). Compared to these options the land use requirements for the spring harvest, maize starch and wheat starch are relatively high (by a factor of two in the most extreme cases). The land use requirements of "PLA generic 2005" are marginally lower than "PLA generic 2009" due to slight improvements in product yields.

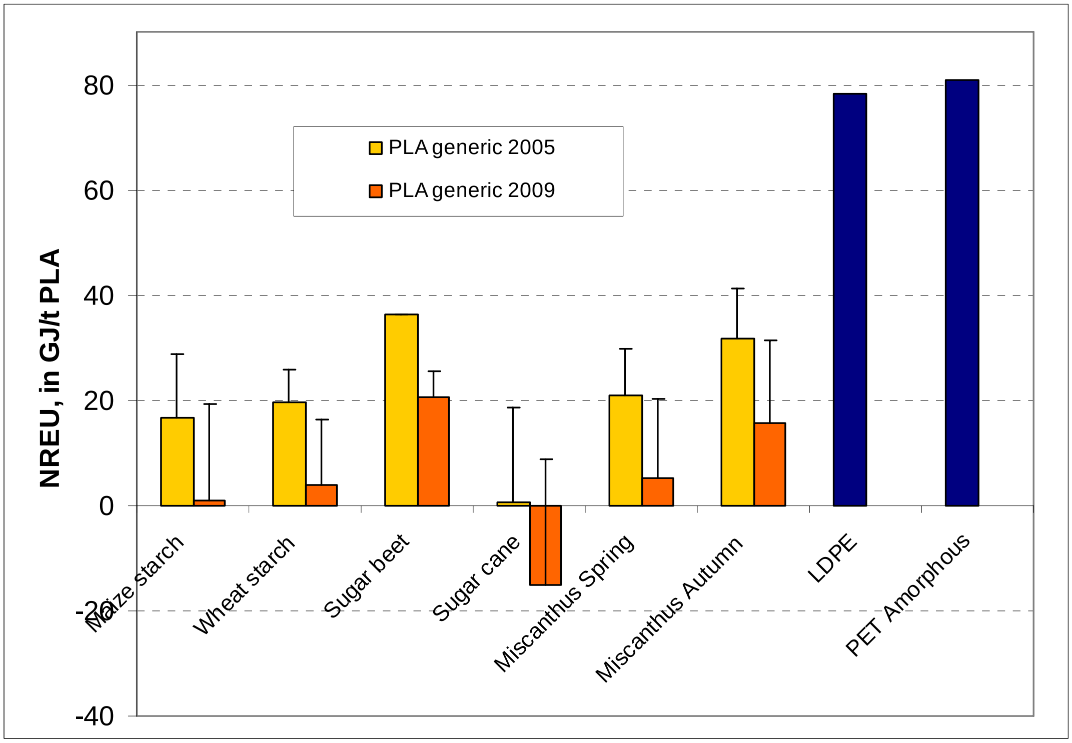

Figure 5-4: Non-renewable energy use required for the production of 1 tonne of PLA (sugar production included) and its petrochemical counterparts, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation); The error bars represent the case when surplus heat can not be used, no error bar for sugar beet/"PLA generic 2005" because all heat is used within the process. The blue bars represent the fossil case.

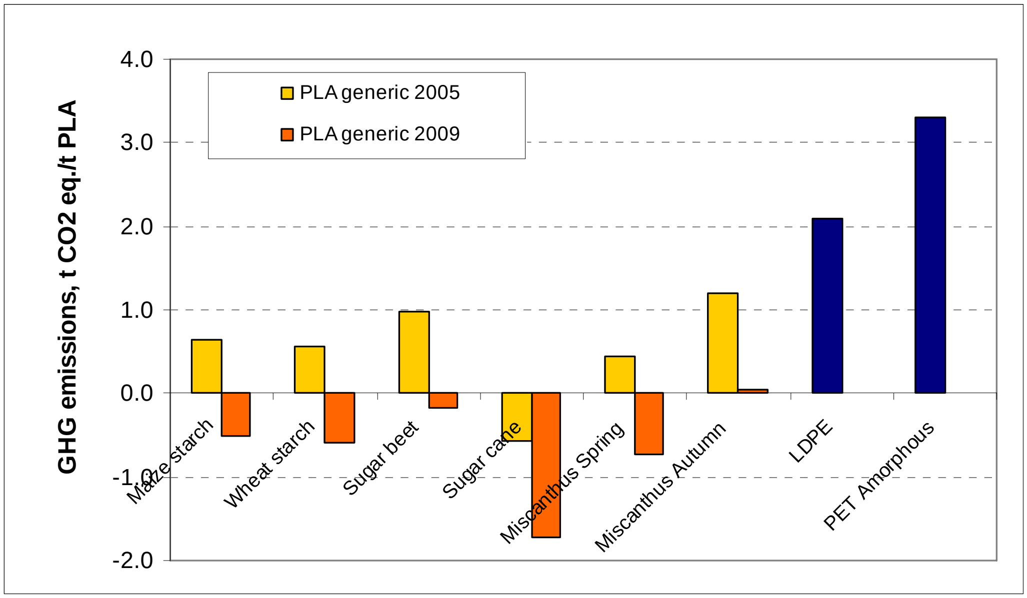

Figure 5-5: GHG emissions for the production of 1 tonne of PLA and its petrochemical counterparts, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). The blue bars represent the fossil case.

To summarize the most important findings, PLA scores much better than its petrochemical counterparts (in first instance PET, potentially also LDPE[4]) for both non-renewable energy use and GHG emissions. This is particularly the case for feedstocks based on maize, wheat, Miscanthus harvested in autumn and sugar cane

[4] *The differences in score for GHG between LDPE an PET are caused by the fact that it costs more process energy to produce PET than PE, the fact that they score similar in NREU is caused by the fact that the embedded energy in PET is lower than in PE, and this accidentally almost levels out with the process energy difference between the two materials.*

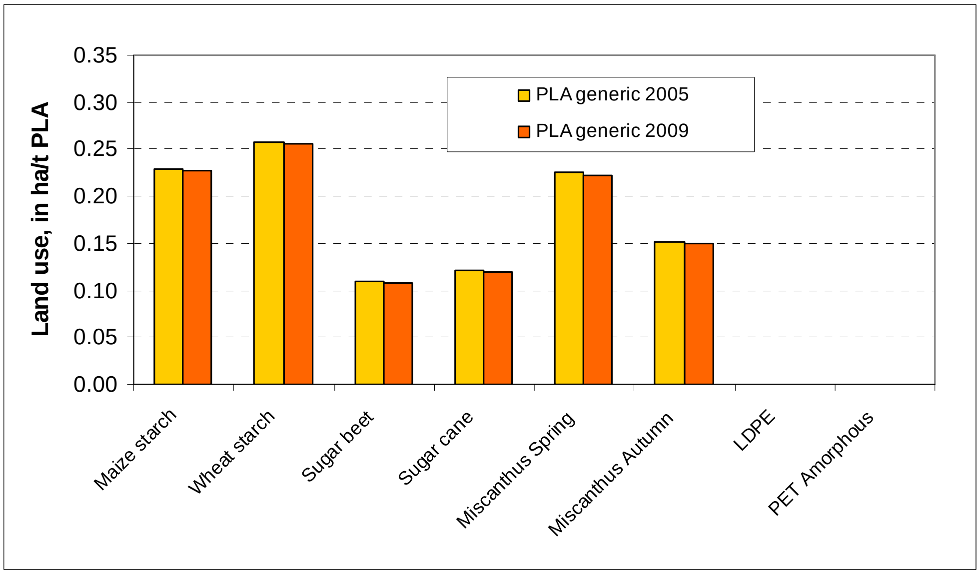

Figure 5-6: Agricultural land use for the production of 1 tonne of PLA, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). LDPE and PET do not use land.

5.4 Bio-ethanol

As shown in Figure 5-7, the NREU for the production of petrochemical ethanol (via ethylene produced by steam cracking) is 60 GJ/t; petrochemical ethanol is used as chemical intermediate and is therefore the adequate reference for bio-based ethanol used for chemical purposes. If bio-based ethanol is used as fuel, it should be compared to petrol, for which the NREU is somewhat more than 30 GJ/t. Using the data for fermentable sugar presented at the beginning of Chapter 5, all bio-based process routes leading to ethanol are net energy sources; in other words. they *co-produce* more steam or power than they *consume* (this avoids the use of non-renewable energy, which is the explanation for the negative values in Figure 5-7). The negative values in the bio-based chains are very substantial reaching up to approximately -35 GJ NREU/t ethanol in the case of maize starch and approximately -60 GJ NREU/t ethanol in the case of sugar cane. . The achievable NREU savings by sugar beet and Miscanthus are relatively low when comparing the results across the various types of crops (Figure 5-7); but ethanol production from sugar beet and Miscanthus still represents a net energy source (NREU ≤ -7 GJ/t as opposed to approximately 30 GJ for petrol and 60 GJ per tonne of petrochemical ethanol), resulting in remarkable overall savings (40 GJ/t and 70 GJ/t respectively).
Total savings when substituting the petrochemical ethanol by the bio-based ethanol amount to nearly 90 to 95 GJ NREU/t ethanol for maize and approximately 120 GJ/t ethanol for sugar cane.

By analogy with the results for NREU, all greenhouse gas emissions for bio-based ethanol are negative for the system cradle-to-factory gate. This is possible because the impacts from fossil fuel use and N_2O emissions from fertilizer application are relatively small compared to the energy credits and the CO_2 equivalents embodied in the bioethanol (extracted during photosynthesis, see Figure 3-1; equivalent to 1.9 t CO_2 eq./t ethanol). For all bio-based routes the savings are very substantial compared to the petrochemical options. The ranking of the various bio-based options is very similar compared to the results for NREU but the differences across them are less pronounced for greenhouse gas emissions.

The pattern of the land use requirements for bio-based ethanol (Figure 5-9) is very similar to PLA but per tonne of product, land use is generally at least by a factor of 1.5 higher in the case of ethanol.

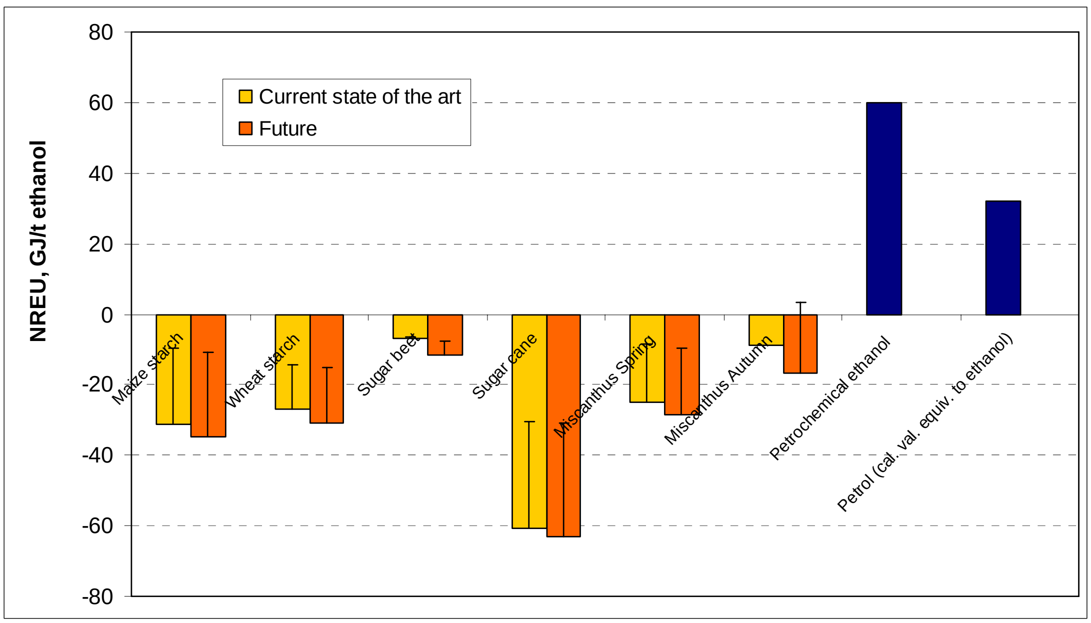

Figure 5-7: Non-renewable energy use required for the production of 1 tonne of ethanol and its petrochemical counterparts, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the “energy system expansion method” (default calculation). The blue bars represent the fossil case.

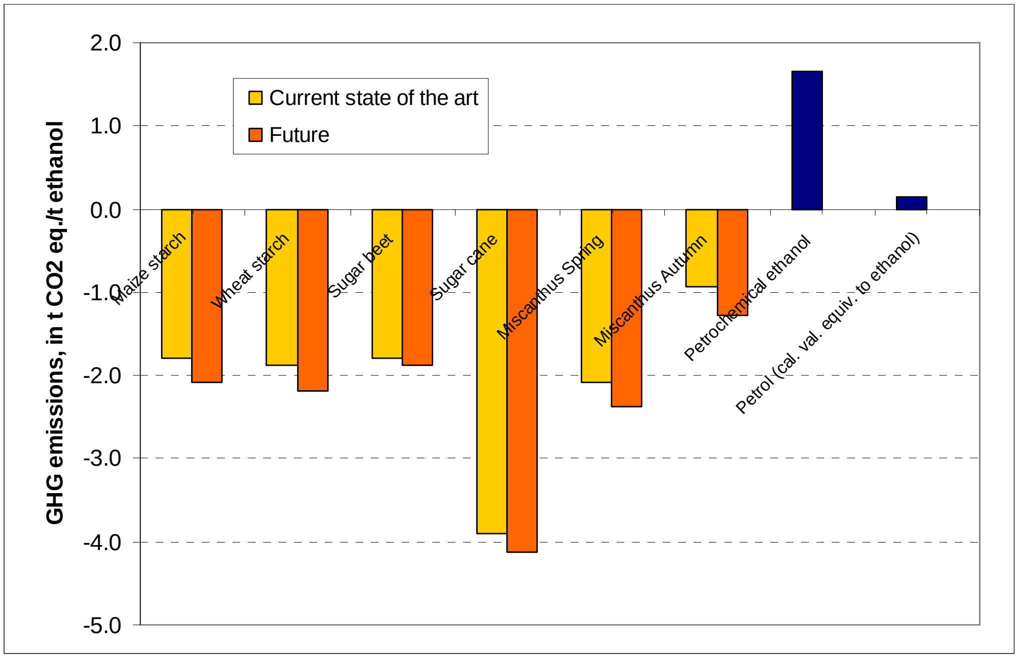

Figure 5-8: GHG emissions for the production of 1 tonne of ethanol and its petrochemical counterparts, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). The blue bars represent the fossil case.

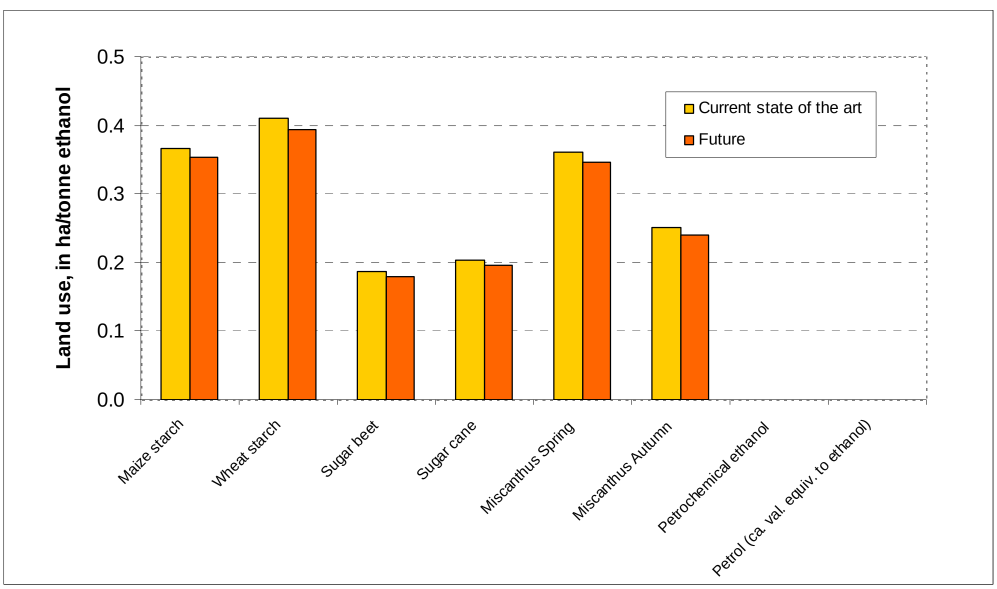

Figure 5-9: Agricultural land use for the production of 1 tonne of ethanol, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). Petrochemical ethanol and petrol do not use land.

5.5 Bio-based polyethylene

Since bio-based polyethylene is made by dehydration of bio-based ethanol and subsequent polymerisation of the ethylene, it is not surprising that the patterns for NREU, GHG emissions and land use are very similar for bio-based ethanol and for bio-based ethylene. However, the values are more extreme; this means that, per tonne of product, total NREU and GHG emission savings are larger for polyethylene compared to ethanol and the land use requirements are larger for polyethylene. The reason is that 1.65 tonnes of ethanol are needed per tonne of polyethylene and that each tonne of ethanol comes along with a net energy saving (see negative values in Figure 5-1); these savings overcompensate the process energy use related to the conversion of ethanol to polyethylene via ethylene. This explains why very outstanding NREU savings of between 80 GJ/t and 170 GJ/t are achieved compared to petrochemical polyethylene. Likewise, also total GHG emission reductions are remarkable (between 2.9 and approximately 8 t CO_2 eq. per tonne). It should be noted that, in line with the methodology explained in section 3.2 for the system "cradle-to-factory gate", the embodiment of bio-based carbon in bio-based PE has been taken into account as negative emission of 3.1 t CO_2 eq./t PE. Both the savings for NREU and GHG emissions are clearly beyond the levels achievable per tonne of PLA (compare Figure 5-10 and 5-11 with Figure 5-4 and 5-5). The trade-off is, however, the larger land use, which is by more than a factor of 2 higher for polyethylene compared to PLA.

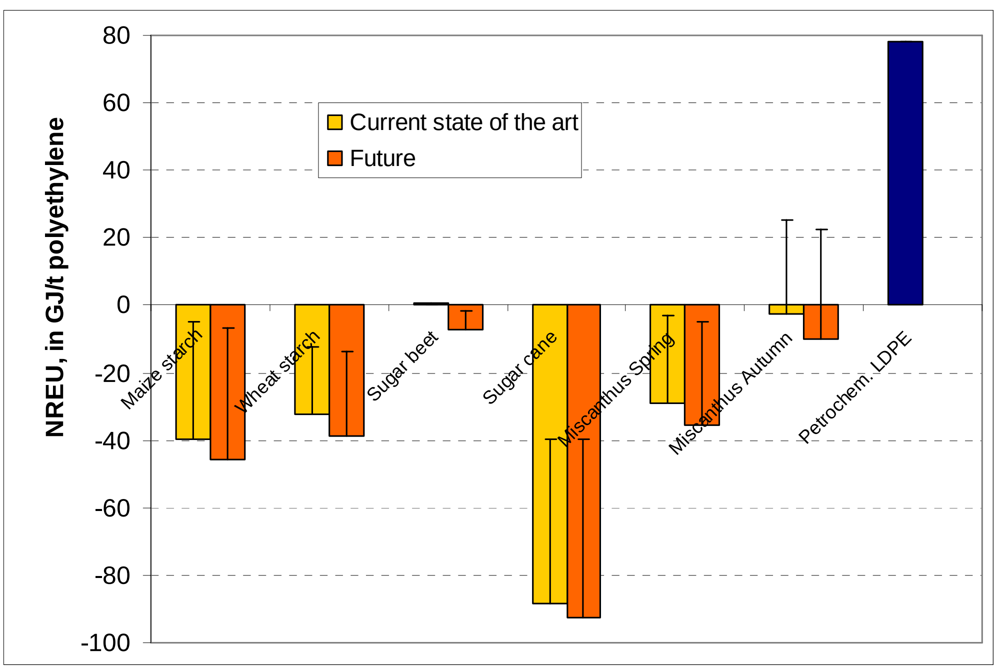

Figure 5-10: Non-renewable energy use required for the production of 1 tonne of polyethylene and its petrochemical counterpart, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). The blue bar represents the fossil case.

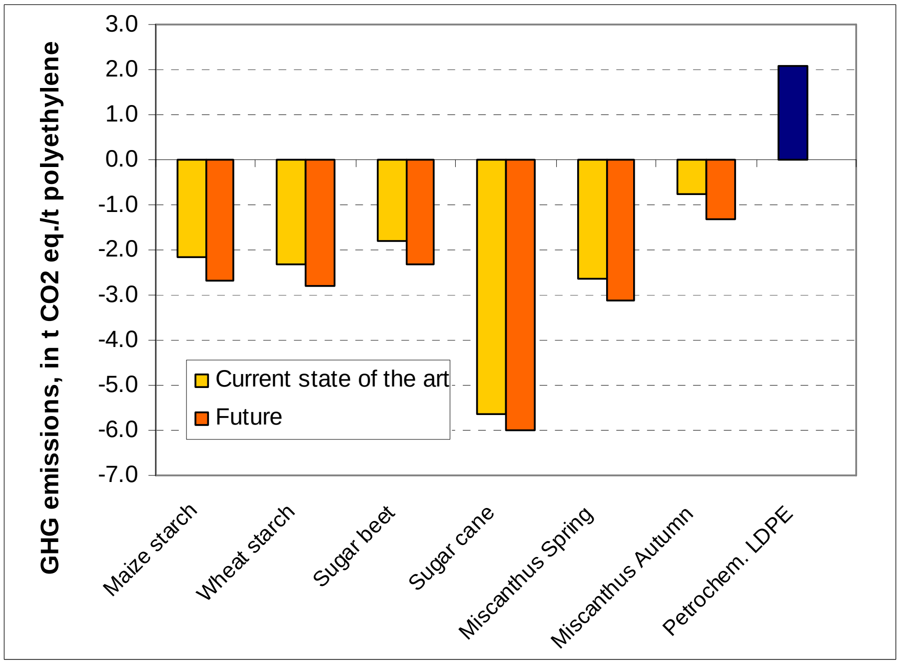

Figure 5-11: GHG emissions for the production of 1 tonne of bio-based polyethylene and its petrochemical counterpart, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation). The blue bar represents the fossil case.

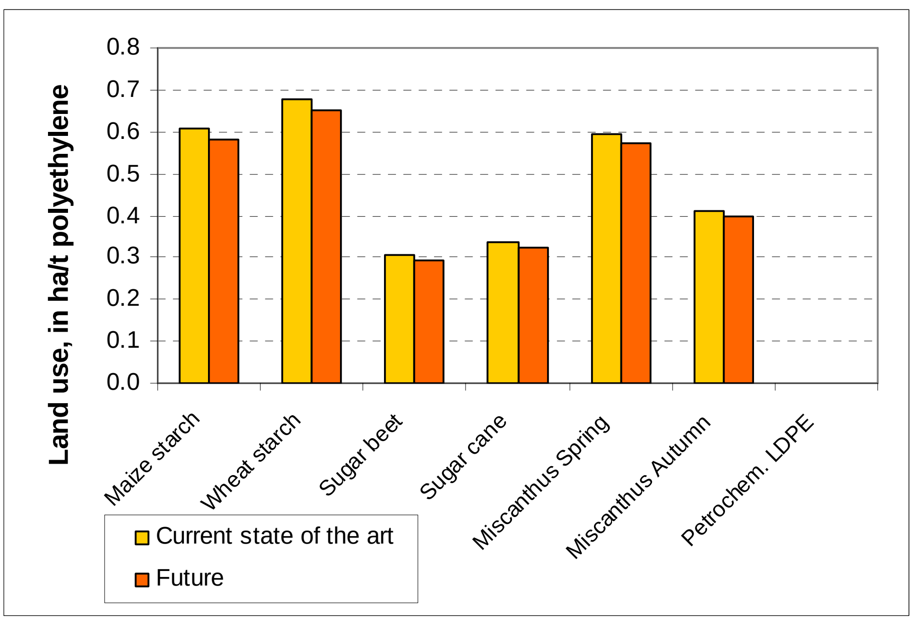

Figure 5-12: Agricultural land use for the production of 1 tonne of bio-based polyethylene, cradle-to-factory gate; *all* bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation).

5.6 Savings per hectare of agricultural land

Comparing the two polymers, PE and PLA, the results on NREU and GHG per tonne product presented above are clearly in favour of bio-based PE as compared to PLA because the NREU savings and GHG emission reductions per tonne of PE are generally at least around 50% larger compared to PLA. However, less PE is produced per ton biomass, and thus more land is required for the production of bio-based PE. The trade-off can be analysed by dividing the NREU savings by the land use (by analogy for GHG emission reduction). As shown in Table 5-1, the NREU savings per hectare are generally at least by one third larger for PLA compared to PE. This is primarily due to the large land use requirements: while PE requires two to three times the amount of land of PLA[5], the energy and GHG savings compared to the petrochemical reference are less than a factor of two for all options studied. For some of the feedstocks, notably sugar beet the NREU savings are even substantially higher than one third for PLA compared to PE (e.g., more than 60% for sugar beet[6] for "PLA generic 2005"). It is admissible to compare "PLA generic 2005" to "PE current" because the technology applied in "PLA generic 2005" is still state-of-the-art for other bio-based processes).

To conclude, in a world where land would be abundant production of PE would lead to a higher NREU reduction. However, in a realistic world, where land needs to be shared between a number of goals, the production of a product that leads to the highest NREU saving per hectare is most desirable; for the products studied in this report, this is the case for PLA.

It is less efficient to use the land and the biomass for energy purposes: For example, the calorific value (higher heating value, HHV) of the Miscanthus that can be harvested from one hectare is approximately 220 GJ, i.e. substantially less than PLA generic 2009.

Also ethanol for fuel purposes shows smaller energy savings than the other applications for all crops studied. Ethanol to replace petrochemical ethanol however scores better than PE.

NREU savings per hectare (GJ/ha)	PLA		PE		Ethanol compared to petrol		Ethanol compared to pchem ethanol	
	PLA generic 2005	PLA generic 2009	current	future	current	future	current	future
Maize starch	280	350	190	210	170	190	250	270
Wheat starch	240	300	160	180	140	160	210	230
Sugar beet	410	560	250	290	210	240	360	400
Sugar cane	660	800	490	530	460	490	590	630
Miscanthus Spring	270	340	180	200	160	180	240	260

Table 5-1: Comparison of the land use efficiency of the production of bio-based PLA and bio-based PE); all bio-based co-products are assumed to be used for energy purposes according to the "energy system expansion method" (default calculation).

[5] *The underlying reason is that in PLA more of the atoms that were built in by the crop are retained in the final product: the repeat unit of PLA is $C_3O_2H_4$, the repeat unit of PE is CH_2, this means that in PLA almost twice as much of the original mass is retained.*

[6] *The different feedstocks perform different due to the difference in" fermentable sugar/co-product" ratio, this leads to difference ratio's of energy saved per hectare.*

Sugar cane is the crop that gives the best NREU savings for all the different applications studied; for the crops that can be produced in the Netherlands sugar beet gives the highest NREU savings per hectare for all applications studied. Miscanthus scores relatively low compared to these two crops.

6 Results when current agricultural practice is assumed

6.1 Introduction and general assumptions

While the results presented in Chapter 5 assume that all agricultural co-products are used, this does not represent the situation nowadays, with certain amounts of agricultural residue being left on or being returned to the field. This may be necessary for the long term in order to ensure sufficient soil carbon content, soil fertility or for other reasons. We therefore present in this chapter results representing typical current agricultural practices. The amount of harvestable material left in the field is very different for the different crops, according to line 6 of table 4.1 (co-product dry matter yield) it varies from 0 for Miscanthus to 10 ton ha^{-1} yr^{-1} for sugar cane. Consequently, the effects on heat and power generation from biogas and biomass combustion, energy input and GHG emission are also different for the different crops.

6.2 The production of fermentable sugars.

As Figure 6-1 and 6-2 show, the analysis results in a totally different overall picture compared to the default calculations (for use of *all* agricultural residues; Chapter 5). If typical amounts of agricultural residue are left on the field, the impacts on NREU and GHG are quite similar for maize, wheat and sugar beet, compared to which sugar cane and especially Miscanthus score clearly better, because the amount of agricultural residues not harvested for the processing is relatively high for the annual crops. According to this analysis, Miscanthus (spring harvest) is the preferred crop for the production of fermentable sugar in the Netherlands (the autumn harvest of Miscanthus is not shown in this discussion chapter because it scores clearly worse than the spring harvest; see Chapter 5; moreover the results for Miscanthus shown in this chapter are identical to those in Chapter 4 because Miscanthus is harvested and processed as entire crop).

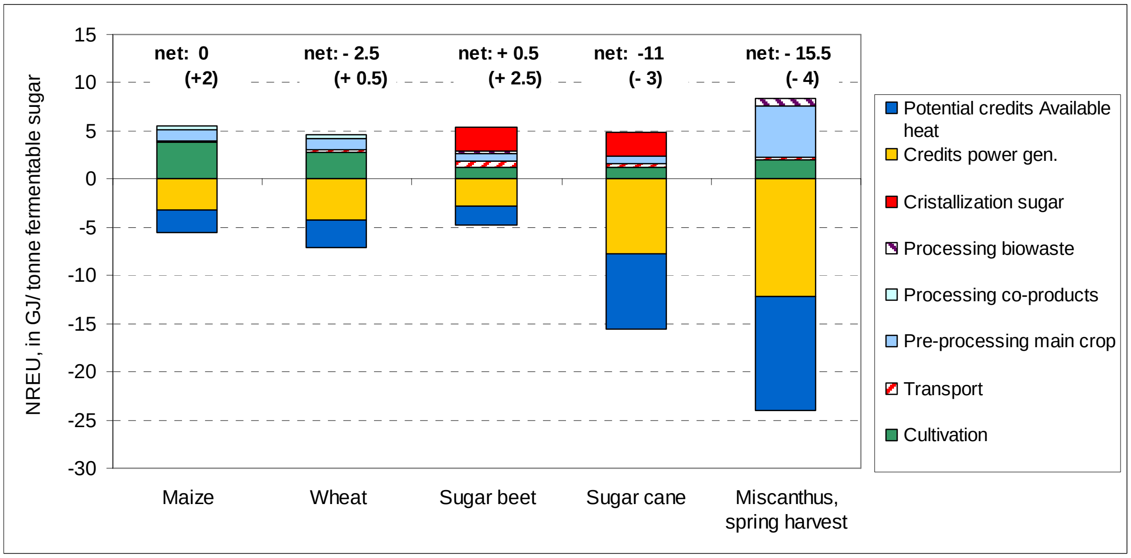

Figure 6-1: Non-renewable energy use (NREU) for the production of 1 tonne of fermentable sugar from various agricultural feedstock (see text for values given above the bars); agricultural residue left on field (sensitivity analysis)

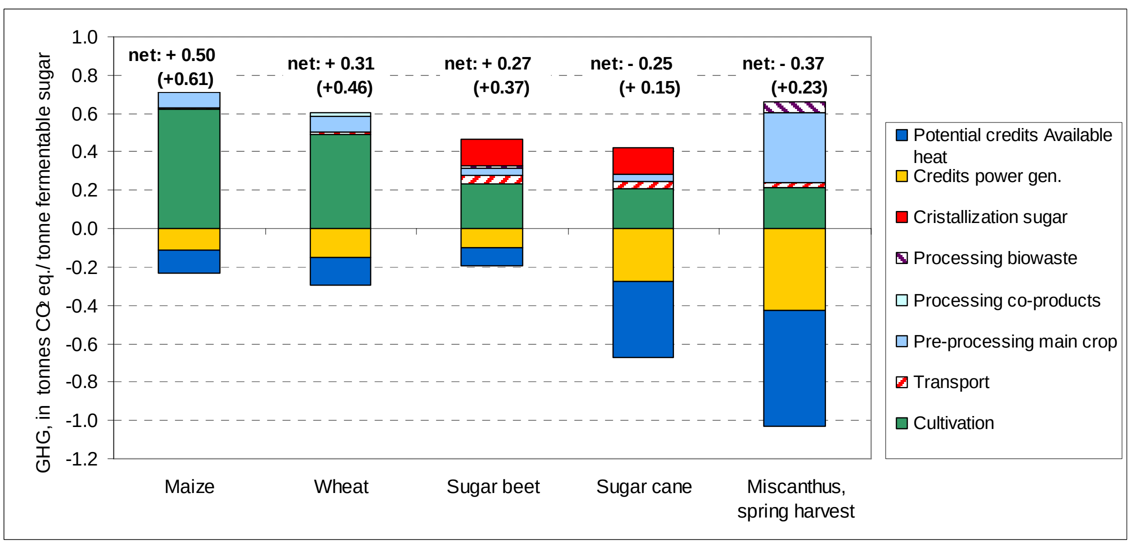

Figure 6-2: Greenhouse gas emissions (GHG) caused by the production of 1 tonne of fermentable sugar from various agricultural feedstock (see text for values given above the bars); agricultural residue left on field (sensitivity analysis)

6.3 PLA

The process "PLA generic 2005" requires approximately 40% to 50% less non-renewable energy (Figure 6-3) than petrochemical plastics (PET and LDPE) for feedstocks derived from maize, wheat and sugar beet. For sugar cane, the savings are approximately 65% and for Miscanthus harvested in spring they amount to nearly 75%. NatureWork's current technology (denoted as "PLA generic 2009") offers savings which are approximately 20 percent points larger (e.g. 60% to 70% less NREU for maize, wheat and sugar beet). When comparing GHG emissions, maize, wheat and sugar beet save approximately 20% to 35% compared to LDPE, while 50% to 60% are saved compared to PET (Figure 6-4). Sugar cane saves 70% to 80% while Miscanthus harvested in spring offers GHG savings of even 80% to 90% (in both cases lower percentage to LDPE, higher percentage relative to PET).

Compared to the process "PLA generic 2005", NatureWork's current technology (denoted as "PLA generic 2009") offers savings which are 50 to 60 percent points larger relative to LDPE and approximately 35 percent points larger compared to PET. To summarize, NatureWork's current technology offers savings of approximately 60% to 90% for NREU and even larger savings for GHG emissions. Across all technologies and all feedstocks, the NREU savings range from 35 GJ/t PLA up to 75 GJ/t and the respective GHG savings are 0.4 to 2.8 t CO_2 equivalents/t PLA in comparison with LDPE and 1.6 to 4 t CO_2 equivalents/t PLA in comparison with PET.

All results discussed so far refer to the case that all produced heat is used. If this is not possible, the maximum savings still amount to at least 75% (for NREU and Miscanthus harvested in spring).

While the choice of the agricultural feedstock does influence the results, the difference is less than 5 GJ NREU/t PLA and less than 0.4 t CO_2 equivalents/t PLA for feedstocks derived from maize, wheat and sugar beet. Only if Miscanthus in spring and sugar cane are included, the choice of the feedstock influences strongly the results.

The land use requirements are not discussed here (and neither for ethylene and polyethylene) because they do not differ from the default calculations in Chapter 5.

The comparison of the results presented in this chapter (agricultural coproducts are left on the field) with the default calculations (all agricultural coproducts are used) shows large differences for wheat, maize and sugar cane (20-30 GJ/t difference). For sugar beet the difference is relatively small (approx. 10 GJ/t) and for Miscanthus, there is no difference because the entire crop is anyway used. Making full use of all agricultural residues from wheat, maize and sugar cane hence reduces the impacts per tonne of PLA very substantially (by at least half). This strategy should be followed unless there are limitations from the point of view of soil carbon and other (partly related) factors.

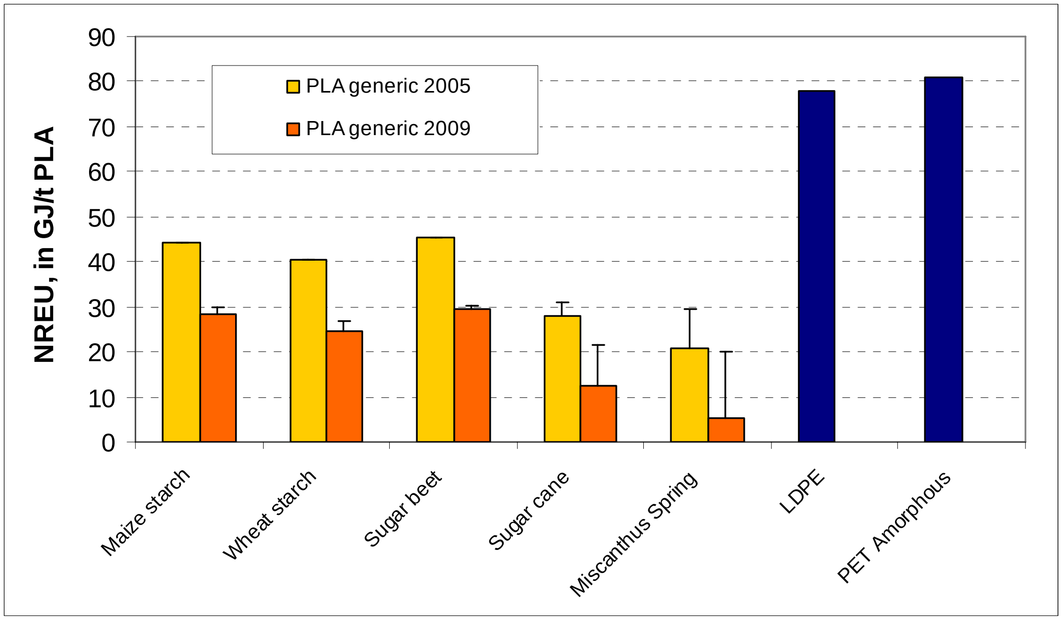

Figure 6-3: Non-renewable energy use required for the production of 1 tonne of PLA (sugar production included) and its petrochemical counterparts, cradle-to-factory gate, agricultural co-products left on field (sensitivity analysis). The blue bars represent the fossil case.

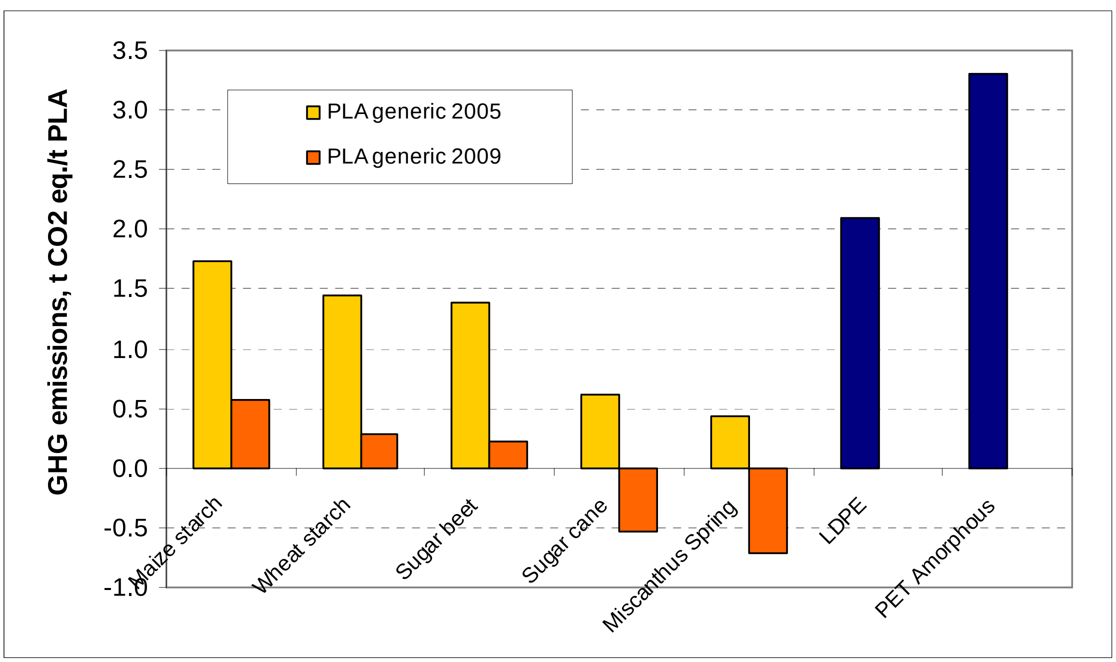

Figure 6-4: GHG emissions for the production of 1 tonne of PLA and its petrochemical counterparts, cradle-to-factory gate, agricultural co-products left on field (sensitivity analysis). The blue bars represent the fossil case.

When comparing our results in Chapter 5 with those published by NatureWorks, we found very large differences which we explained with the use of all agricultural residues in our default calculations. We would expect the difference now to be much lower, which is actually the case (for comparison with Figure 6-3 and 6-4: 42 GJ/t PLA and 1.3 t CO_2 eq./t PLA for the current technology package according to NatureWorks' website (NatureWorks, 2010); the respective values for PLA-05 (to be compared to "PLA generic 2005") are 50.8 GJ/t PLA and 2.02 t CO_2 eq./t PLA acc. to Vink et al., 2007). The results according to Figure 6-3 and 6-4 are still lower than NatureWorks', which is again caused by the lower environmental impact per tonne of fermentable sugar in this study as compared to NatureWorks' analyses (for NREU net zero GJ/t acc. to Figure 6-1 as opposed to 6.2 GJ/t in NatureWorks' analyses; quoted in Patel et al., 2006).

6.4 Bio-ethanol

Compared to petrol, bioethanol saves at least approx. 65% NREU (at least 20 GJ/t) when made from sugar beet, wheat or maize (lower value for current, higher value for future technology; see Figure 6-5). For sugar cane and Miscanthus (spring harvest) as feedstock, ethanol becomes a net producer of energy, resulting net negative NREU values. When compared to petrochemical ethanol, all NREU savings are substantially larger, equalling at least 85% for the current state-of-the art and (even higher for future technology).
All greenhouse gas emissions for bio-based ethanol are negative for the system cradle-to-factory gate. This is possible because the impacts from fossil fuel use and N_2O emissions from fertilizer application are lower than the energy credits and the CO_2 equivalents embodied in the bioethanol (extracted during photosynthesis; Figure 6-6). In comparison to petrol, the savings are relatively modest if maize, wheat or sugar beet are used as feedstock even in combination with future technology (up to approx. 1.0 t CO_2 eq /t bioethanol). Bioethanol from sugar cane and Miscanthus offer very substantial savings compared to petrol both with current and future technology. In comparison to petrochemical ethanol, the savings are larger reaching from 1.8 t CO_2 eq./t bioethanol (lowest value for current technology) up to more than 4 t CO_2 eq./t.

The comparison of the results presented in this chapter (agricultural co-products are left on the field) with the default calculations (all agricultural co-products are used) shows very substantial differences for wheat (30 GJ/t), maize (40 GJ/t difference) and sugar cane (also 40 GJ/t difference). For sugar beet the difference between the results of Chapter 5 and Chapter 6 amounts to 10-15 GJ/t and for Miscanthus, there is no difference because the entire crop is anyway used. Making full use of all agricultural residues from wheat, maize and sugar cane hence reduces the impacts per tonne of ethanol very substantially, turning ethanol production from a net user of NREU into a net source of energy (negative NREU values). Also the GHG emissions decrease very substantially. As for PLA, the use of agricultural residues should be pursued unless there are limitations from the point of view of soil carbon and other (partly related) factors.

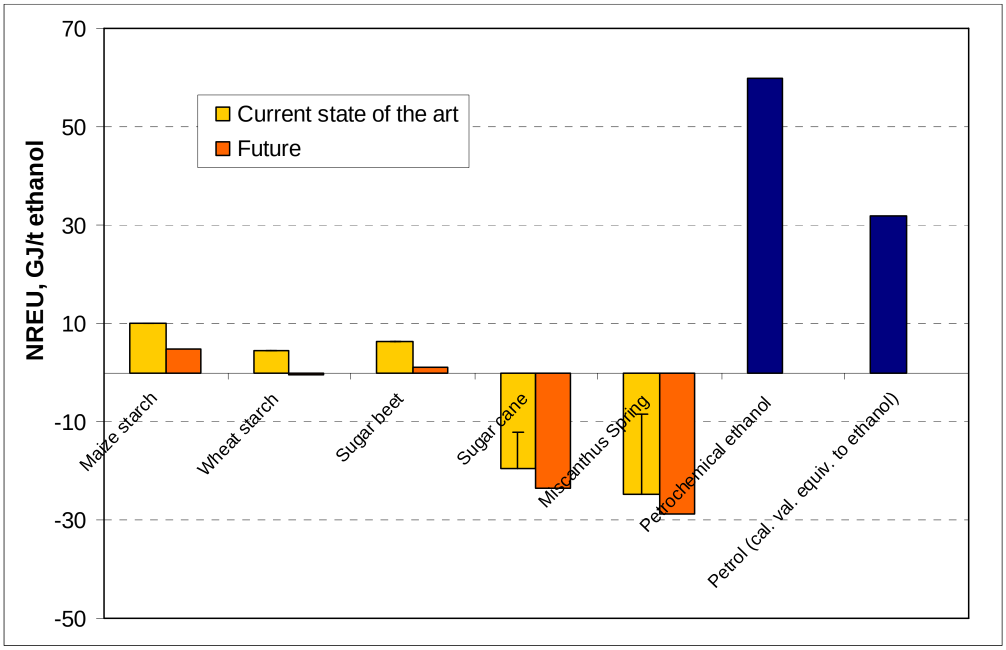

Figure 6-5: Non-renewable energy use required for the production of 1 tonne of ethanol and its petrochemical counterparts, cradle-to-factory gate, agricultural co-products left on field (sensitivity analysis). The blue bars represent the fossil case.

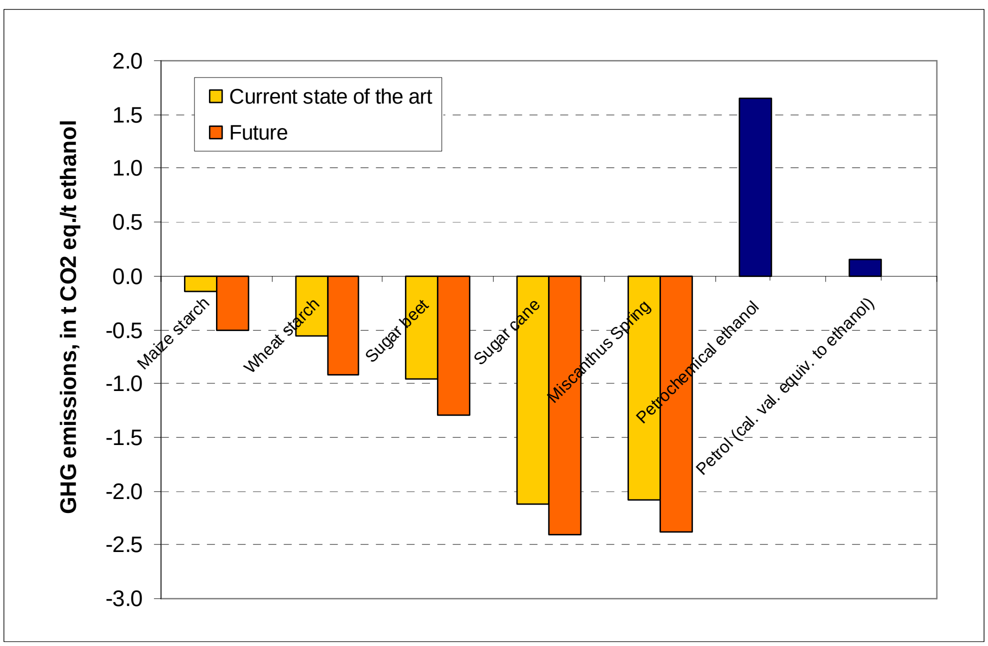

Figure 6-6: GHG emissions for the production of 1 tonne of ethanol and its petrochemical counterparts, cradle-to-factory gate, agricultural co-products left on field (sensitivity analysis). The blue bars represent the fossil case.

6.5 Bio-based polyethylene

Polyethylene made from bioethanol that was manufactured with current state-of-the-art technology allows to save between 60% and 75% NREU for sugar beet, maize and wheat compared to petrochemical PE; for sugar cane and Miscanthus, bio-based polyethylene production becomes even a net energy source (negative NREU values; see Figure 6-7). Across all options, the savings range from approximately 50 to 110 GJ per tonne of polyethylene; this is 30 to 60 GJ/t less compared to the use of all agricultural residues.

By analogy with ethanol, all greenhouse gas emissions for bio-based polyethylene are negative for the system cradle-to-factory gate (with the exception of production from maize starch with current technology) because the impacts from fossil fuel use and fertilizer application are lower than the CO_2 equivalents embodied in the bioethylene (Figure 6-8). The GHG savings range from between 1.5 and more than 5 t CO_2 eq. per tonne; this is 1.4 to 3.0 t CO_2 eq. per tonne less compared to the use of all agricultural residues. Nevertheless the savings are very substantial both for NREU and GHG emissions.

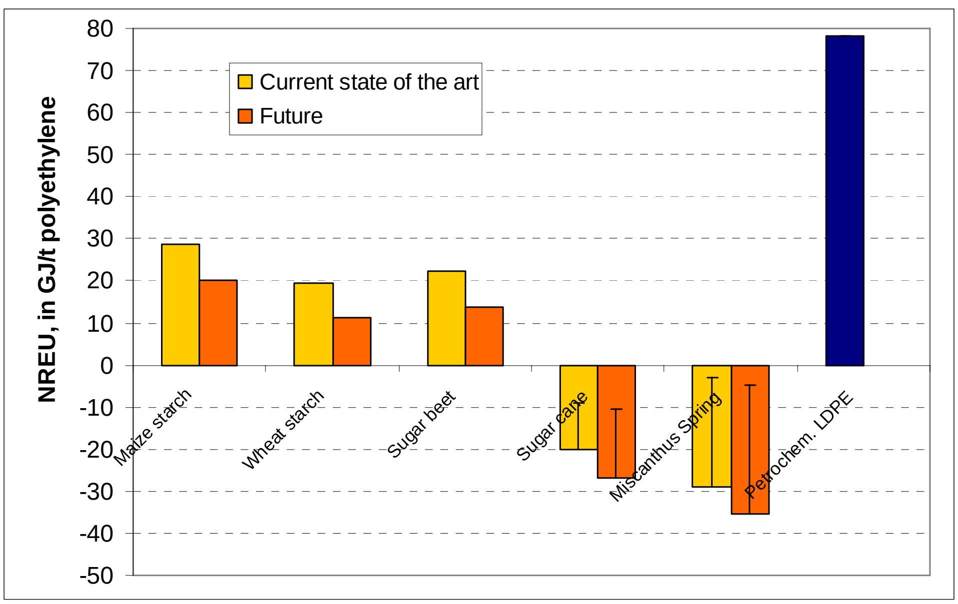

Figure 6-7: Non-renewable energy use required for the production of 1 tonne of polyethylene and its petrochemical counterpart, cradle-to-factory gate, agricultural residue left on field (sensitivity analysis); no error bars are given for maize starch, wheat starch and sugar beet because all heat is used within the process. The blue bar represents the fossil case.

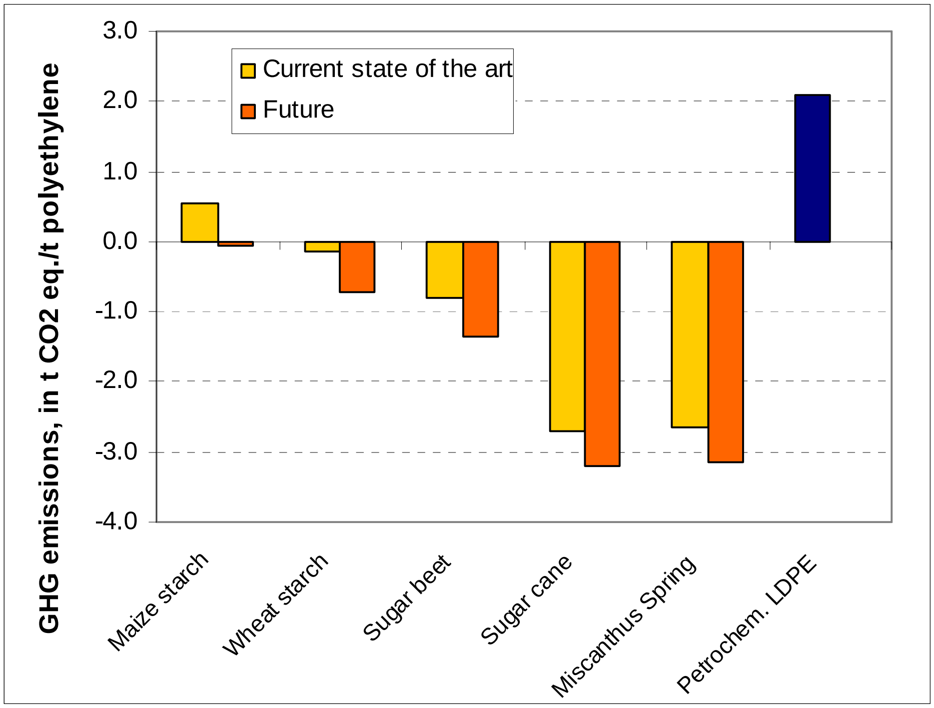

Figure 6-8: GHG emissions for the production of 1 tonne of bio-based polyethylene and its petrochemical counterpart, cradle-to-factory gate, agricultural residue left on field. The blue bar represents the fossil case.

6.6 Savings per hectare of agricultural land

By analogy with Table 5-1, Table 6-1 shows the NREU savings per hectare of land for the case that typical amounts of agricultural residues are left on or returned to the cultivated land.

NREU savings per hectare (GJ/ha)	PLA		PE		Ethanol		Ethanol compared to pchem ethanol	
	PLA generic 2005	PLA generic 2009	current	future	compared to petrol current	future	current	future
Maize starch	160	230	80	100	60	80	140	160
Wheat starch	160	220	90	100	70	80	140	150
Sugar beet	330	480	180	220	140	170	290	330
Sugar cane	440	570	290	320	250	280	390	430
Miscanthus Spring	270	340	180	200	160	180	240	260

Table 6.1: Comparison of the land use efficiency of the production of bio-based PLA and bio-based PE; agricultural residue left on field (sensitivity analysis)[7]

[7] *The different feedstocks perform different due to the difference in" fermentable sugar/co-product" ratio, this leads to difference ratio's of energy saved per hectare.*

In line with the conclusion drawn from Table 5.1, the NREU savings per hectare are generally at least by one third larger for PLA compared to PE. Again this is primarily due to the fact that more PLA is produced per ton of biomass and thus due to the large land use requirements of PE: while PE requires two to three times the amount of land of PLA, the energy and GHG savings compared to the petrochemical reference are less than a factor of two for all options studied. (as mentioned earlier, it is admissible to compare "PLA generic 2005" to "PE current" because the technology applied in "PLA generic 2005" is still state-of-the-art for other bio-based processes).

Compared to the case presented in chapter 5, where all co-products are converted into energy, the order of crops has changed. Sugar cane still scores best, but sugar beet and Miscanthus are now competing for the second place; moreover, Miscanthus now shows a clearly better performance than maize and wheat. This is due to the fact that for Miscanthus still all biomass harvested in spring is used for the production of the products (producing the same results as in chapter 5), whereas for the grains straw is now left in the field.

7 Discussion and conclusions

While in current agricultural practice some crops are harvested as entire plant (e.g. aboveground part of Miscanthus minus a short stubble), for others part of the biomass that can be harvested is left in the field (e.g. wheat straw). When studying the amount of energy and greenhouse gas that can be saved by turning a crop into a non-food product, for the second type of crop, the results are bound to be lower compared to the first type, if current agricultural practices are applied. As a consequence, their use may be discouraged.

However, also agricultural co-products such as wheat straw could be used for materials or energy production. Against this background this report sets out with the assumption that *all* co-products (both agricultural co-products and co-products that are produced during processing in the factory) are used for energy purposes, thereby replacing fossil energy (we refer to this method as "energy system expansion method"). This approach is chosen as default for the calculations presented in Chapter 5. Giving credit to the potential use of *all* co-products, a level playing field is created, when comparing the results across the crops. In addition to the results of these calculations which are presented in Chapter 5, Chapter 6 contains the outcome of an analysis which assumes that typical amounts of agricultural co-products are left in the field. Removing and using all co-products for energy production may have important drawbacks because it may deprive the soil of organic matter and nutrient inputs (as compared to leaving part of the plant production). This may have effects on the sequestration of carbon in the soil and on soil fertility, but these have not been investigated in this study. The effects of the choice underlying Chapter 5 and especially the results on GHG emissions are therefore not completely taken into account.

Due to data constraints only non-renewable energy use (NREU), greenhouse gas (GHG) emissions from the chain[8] and land use were studied; this is a limitation of this study, which needs to be overcome by future work.

When comparing the options in terms of their NREU per tonne of product, the studied bio-based products (PLA, ethanol and bio-based PE) score clearly better than their petrochemical alternatives. This is not only true for the default calculations but also for current agricultural practice. If, instead of the current typical practice, *all* agricultural co-products are used (default calculations), the advantage compared to the petrochemical products nearly doubles for wheat and maize as chosen crops. For sugar cane, the effect of using all co-products is somewhat smaller but the additional gains are still very remarkable. For sugar beet, the advantage is relatively limited and for Miscanthus, it is zero (because anyway the entire plant is used). The main reason for this effect is the amount of co-products, which in this case are converted into energy and this has been attributed to the bio-based materials as credits. More co-products thus lead to a lower NREU (but more co-products also implies less products produced per ton

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[8] *CO_2 emissions from the soil are not taken into account*

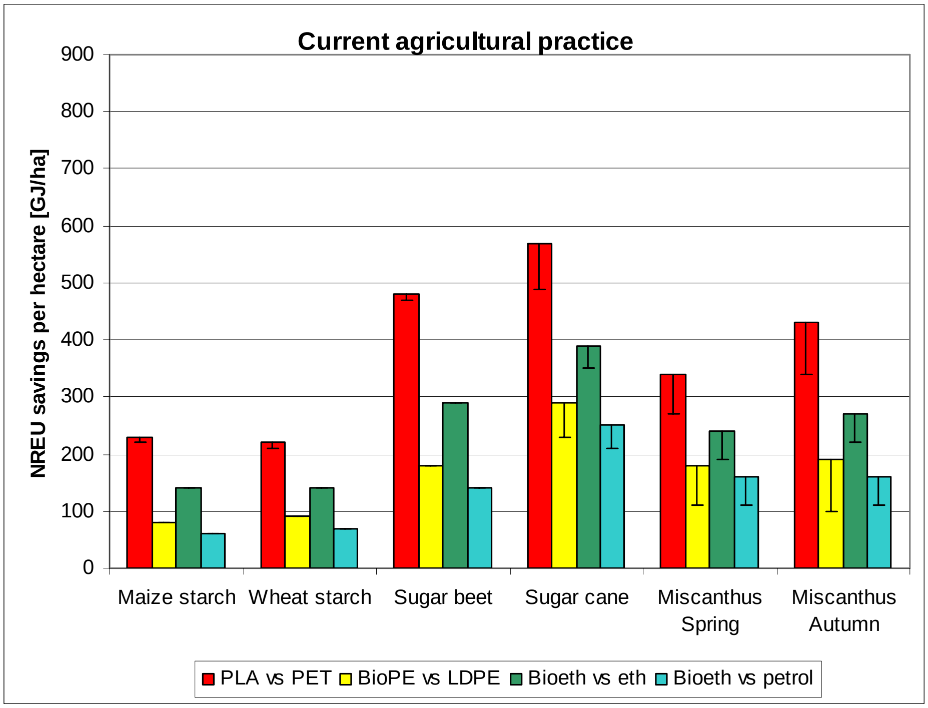

Fig. 7-1. Non-renewable energy savings per hectare for PLA, bioPE and bioethanol compared to their petrochemical counterparts, assuming current agricultural practice.

biomass). In the petrochemical chains the situation is different because only that amount of fossil source is used that suffice for the production of PET, PE and ethanol.

The comparison of NREU on the basis of tonnage produced product overlooks the fact that there is a difference in yield per hectare between the different crops and also that much more fermentable sugar is needed to produce a ton of bioPE compared to a ton of PLA. This difference becomes very visible when the values are expressed per hectare. Figure 7-1 and figure 7-2 show the non-renewable energy saved per hectare for each of the products compared to their petrochemical counterpart, in the case of current agricultural practice and in the case that all co-products are converted into energy, respectively. For PLA the data "PLA generic 2009" are taken and for bioPE en bioethanol the data for current state of the art are used. It is clear that in this comparison the production of PLA comes out as the preferred choice. This can be logically understood by realising that in PLA most of the atoms that were originally built in by the crop are retained in the produced material. Furthermore, for the Dutch situation, sugar beet comes out as the preferred crop, both for current agricultural practice and also when assuming all co-products are converted into energy.

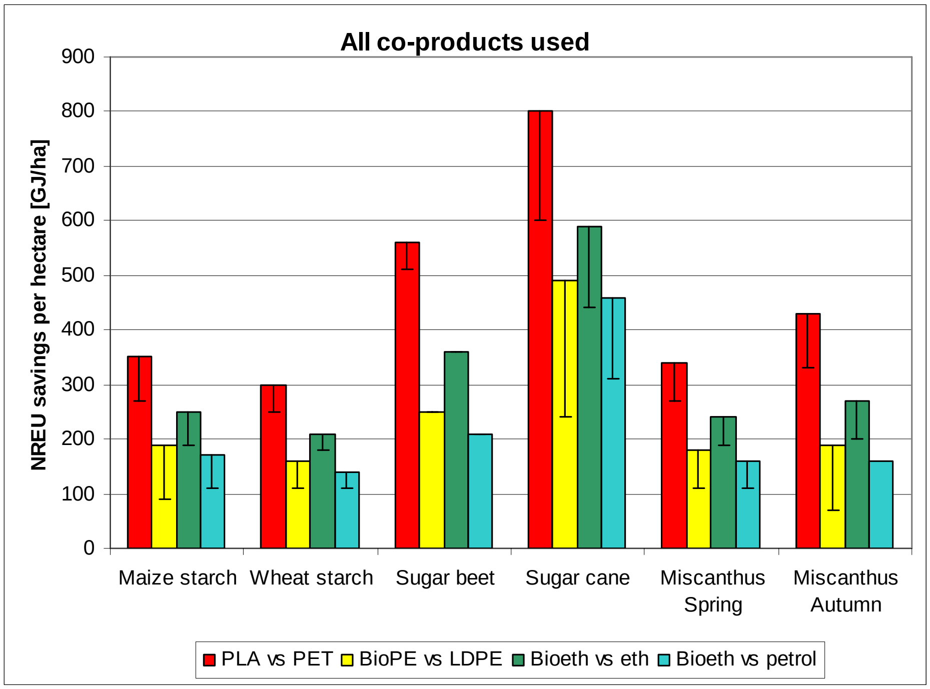

Fig. 7-2. Non-renewable energy savings per hectare for PLA, bioPE and bioethanol compared to their petrochemical counterparts, assuming all co-products are converted to energy.

The error bars indicate the case in which the excess heat that is generated during the process can not be used. This changes the absolute numbers of the savings that can be reached, but not the overall conclusions. However, sugar beet is hardly affected by not using the excess heat (because most heat is already used in the process, no excess heat is available) and the difference between sugar beet and sugar cane becomes much smaller. All other crops lose a substantial part of their NREU savings if excess heat is not used.

For GHG emissions, the findings are more complicated because the environmental impacts of the two reference materials LDPE and PET (references for PLA) differ substantially (see footnote on page 36). Per tonne of product, doubling of the GHG savings by transition from the current practice to the use of *all* co-products is found if PET is chosen as reference, while the additional savings are more limited for LDPE as reference. Similarly, for ethanol, we find a doubling in comparison with petrochemical ethanol, while the additional benefits are less pronounced if petrol is chosen as reference. We did not take land use change into account (whether direct or indirect). Land use change can alter the GHG scores completely (overall and between crops) and thus any conclusion on GHG based on the results of this report is still premature.

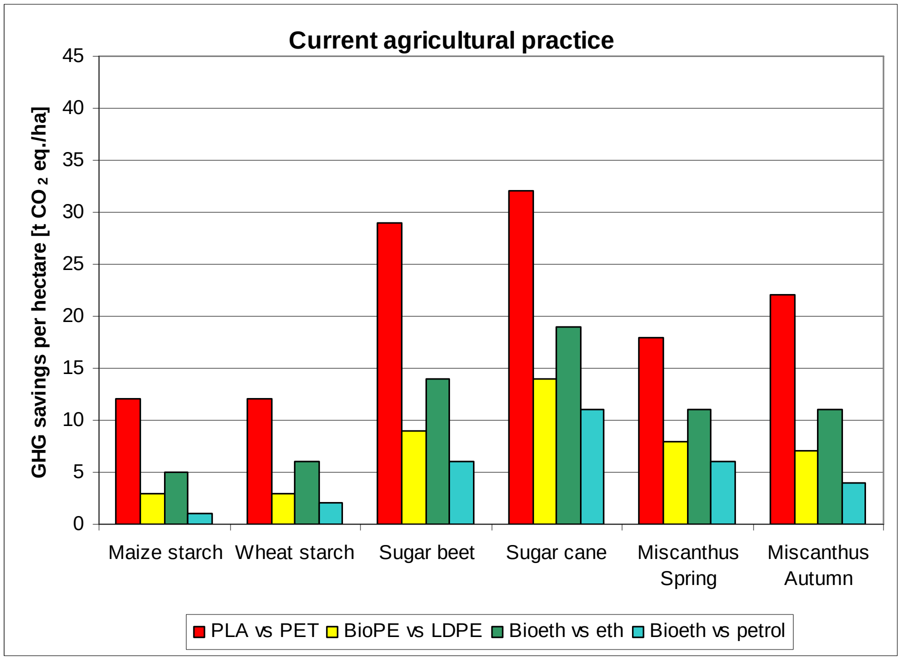

Fig. 7-3. Greenhouse gas savings per hectare for PLA, bioPE and bioethanol compared to their petrochemical counterparts, assuming current agricultural practice.

Following the same line of thought we can also express the greenhouse gas savings per hectare. This is presented in figure 7-3 and 7-4. Basically, the same conclusions can be drawn based on these graphs: the production of PLA saves most GHG per hectare, when all the applications are compared to their petrochemical counterpart, and the use of bioethanol for transport fuels is the least efficient in saving greenhouse gas per hectare, followed closely by bioPE. Also from these graphs we can conclude that for the Dutch situation sugar beet saves the highest amount of greenhouse gas per hectare, significantly more than the second generation crop Miscanthus.

We can conclude that the use of *all* co-products instead of the current practice offers potentials to further reduce the NREU and GHG emissions in the chains. Before putting this into practice it must, however, be studied which level of the use of the total amount of co-products would be detrimental for soil carbon levels and soil fertility and whether there are any other tradeoffs (e.g. with feed production). Any loss of carbon in the soil due to harvesting (all) co-products should be attributed to the GHG balance calculations and can result in substantial lower emission savings (Conijn & Corré, 2009).

The comparison with published data for PLA indicates that the choice of the "energy system expansion method" leads to lower NREU and GHG emissions in the chain than other methods

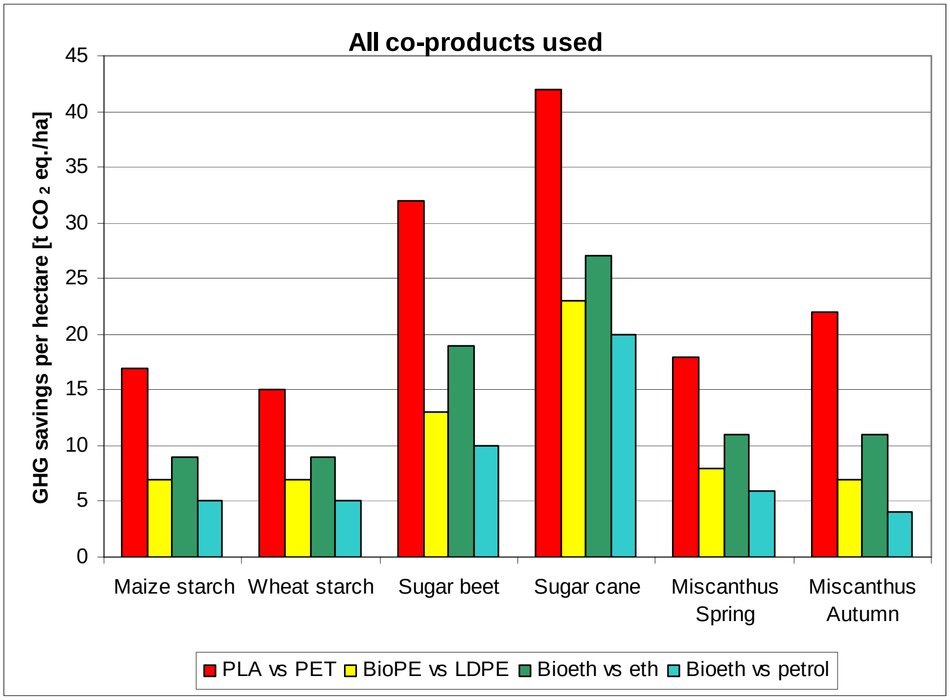

Fig. 7-4. Greenhouse gas savings per hectare for PLA, bioPE and bioethanol compared to their petrochemical counterparts, assuming all co-products are converted to energy.

for accounting for co-products. Further comparisons should be made to confirm this finding. If so, a subsequent question to be answered would be whether the use of *all* co-products instead of current practices would reduce the NREU and GHG emissions by a factor of two also when other methods for accounting for co-products are applied. Effects of these other methods on land use should be investigated as well. Discarding the use of the excess heat will result in lower savings comparable to the reduction in NREU use.
Based on the results for PLA, ethanol and PE made from crops that are typically cultivated in the Netherlands (i.e., wheat, maize and sugar beet) the results for NREU and GHG savings point to wheat and maize as preferred crops, provided that there is no lack of agricultural land; otherwise the preferred choice is sugar beet because it offers much larger savings per hectare of agricultural land.

None of the feedstocks studied resolves the problem related to the competition with agricultural land used for food purposes: wheat, maize and sugar beet are primarily food crops; this is not the case for Miscanthus but it is cultivated on agricultural land (which is typically used for food production).

Another issue not mentioned in this study is the competition with biodiversity. If land is not used primarily to provide goods for mankind it can be used by "nature". Depending on local conditions this will have a positive effect on biodiversity and the conservation of wild animals and plants. The effects of growing crops for the bio-based economy on biodiversity should also be taken into account.

Summarizing, the study leads to the following main conclusions:

- For the production of materials and fuels from biomass the reduction in GHG emissions and NREU, compared to the petrochemical alternatives, is positive in all cases studied (the effects of land-use change are not considered).
- If all co-products are used for energy-production, the difference between first and second generation crops becomes negligible (wheat and maize versus Miscanthus).
- Production of bioplastics leads to larger GHG emission reduction and NREU reduction than the production of bioethanol for fuels.
- Production of the bioplastic which retains most of the functional groups built-in in the biomass leads to the highest saving in NREU en GHG emission per hectare (PLA versus Bio-PE).
- Biobased products produced from sugar beet lead for the Dutch situation to the highest saving in NREU en GHG emission per hectare.

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Abbreviations and glossary

CHP	Combined Heat and Power
DDGS	Dried Distillers Grains and Solubles
Energy efficiency	For power generation, energy efficiency is given by the ratio of the power generated to primary energy used by the power plant
ERE	Energy requirements for energy; this is the energy required for the extraction, pretreatment and transportation of primary energy (e.g. natural gas)
GHG	Green House Gas
Gross power	Gross power generated in a power plant is equal to the total of Net power generated plus own power use in power plants
GWP	Global Warming Potential
HDPE	High Density Poly Ethylene
LDPE	Low Density Poly Ethylene
LLDPE	Linear Low Density Poly Ethylene
NREU	Non-renewable energy use
PE	Poly Ethylene
PET	
PLA	Poly Lactic Acid
Primary energy	Gas, oil, coal and uranium are primary energy carriers.
PS	Polystyrene
PUR	Poly Urethanes
PVC	Poly Vinyl Chloride
REU	Renewable energy use
Secondary energy	Power (electricity) and heat are secondary energy carriers. They are produced from primary energy carriers.

