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Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations

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ABSTRACT

With increasing use of biomass for energy, questions arise about the validity of bioenergy as a means to reduce greenhouse gas emissions and dependence on fossil fuels. Life Cycle Assessment (LCA) is a methodology able to reveal these environmental and energy performances, but results may differ even for apparently similar bioenergy systems. Differences are due to several reasons: type and management of raw materials, conversion technologies, end-use technologies, system boundaries and reference energy system with which the bioenergy chain is compared. Based on review of published papers and elaboration of software data concerning greenhouse gas and energy balances of bioenergy, other renewable and conventional fossil systems, this paper discusses key issues in bioenergy system LCA. These issues have a strong influence on the final results but are often overlooked or mishandled in most of the studies available in literature. The article addresses the following aspects: recognition of the biomass carbon cycle, including carbon stock changes in biomass and soil over time; inclusion of nitrous oxide and methane emissions from agricultural activities; selection of the appropriate fossil reference system; homogeneity of the input parameters in Life Cycle Inventories; influence of the allocation procedure when multiple products are involved; future trends in bioenergy (i.e. second-generation biofuels and biorefineries).

Because many key issues are site-specific, and many factors affect the outcome, it is not possible to give exact values for the amount of greenhouse gas emissions and fossil energy consumption saved by a certain bioenergy product, because too many uncertainties are involved. For these reasons, the results are here provided as a means of wide ranges. Despite this wide range of results, it has been possible to draw some important conclusions and devise recommendations concerning the existing bioenergy systems, and some emerging implications about the future deployment and trends of bioenergy products are pointed out.

1. Introduction and background

The potential environmental benefits that can be obtained from replacing petroleum fuels with biofuels and bioenergy derived from renewable biomass sources are the main driving forces for promoting the production and use of biofuels and bioenergy. There is a broad agreement in the scientific community that Life Cycle Assessment (LCA) is one of the best methodologies for the evaluation of the environmental burdens associated with biofuel production, by identifying energy and materials used as well as waste and emissions released to the environment; moreover it also allows an identification of opportunities for environmental improvement (Consoli et al., 1993; Lindfors et al., 1995).

Given the variety of processes leading to bioenergy, and the controversial discussion of their ‘net benefit’, several studies have

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[1] Bernhard Schlamadinger unexpectedly passed away on 28th August 2008 in his home town, Graz – Austria. Bernhard was a tireless champion of climate change mitigation through the use of land use and management changes, forestry and bioenergy. In addition to many other activities, he was the Lead Author of the IPCC Fourth Assessment Report, Working Group III, Energy Supply, and was part of the IPCC team which received the Nobel Prize for Peace in 2007 along with Al Gore. Bernhard's death is a huge loss for his family and for his extraordinary network of friends and colleagues worldwide. We cannot replace Bernhard. We can, however, work together to make Bernhard's vision of saving the world's forests and ecosystems a reality.

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already been undertaken using this methodology to analyse the processes in detail, in order to know which biofuels imply more or less environmental impacts (Heller et al., 2003; Blottnitz von and Curran, 2007; Gasol et al., 2007; Reinhardt et al., 2007; Quintero et al., 2008).

The energy and Greenhouse Gas (GHG) balances of bioenergy systems differ depending on the type of feedstock sources, conversion technologies, end-use technologies, system boundaries and reference energy system with which the bioenergy chain is compared. Regional differences can be also significant, especially with respect to land use, biomass production patterns and the reference energy system, and the Life Cycle Assessment results can change as technologies evolve. Furthermore, biofuel production usually results in the generation of co-products, which can replace conventional products providing further environmental benefits to the biofuel process chain.

With the exception of a few studies, most LCAs have found a significant net reduction in GHG emissions and fossil energy consumption when the most common transportation biofuels (bioethanol and biodiesel) are used to replace conventional diesel and gasoline (Punter et al., 2004; Kim and Dale, 2005; Blottnitz von and Curran, 2007). Several LCA studies have also examined life cycle impacts on other environmental aspects, including local air pollution, acidification, eutrophication, ozone depletion, land use, etc. (Reinhardt et al., 2004; Pimentel and Patzek, 2005; Farrell et al., 2006). These environmental burdens are even more affected by site-specific assumptions than GHG and energy balances, showing that it is not easy to draw simplified conclusions. Studies that have examined these other environmental issues have concluded that most, but not all, biofuels substituting fossil fuels will lead to increased negative impacts (Larson, 2005; Zah et al., 2007). This applies particularly to bioenergy crops where, among others, the intensive use of fertilizers (compounds based on N and P) and pesticides can cause contamination of water and soil resources. Therefore, it should always be acknowledged that the positive impacts on GHG emissions may carry a cost in other environmental areas, so that a much more careful analysis is needed to understand the trade-offs in any particular situation.

The aim of this paper is to summarize key LCA issues influencing LCA outcomes for bioenergy and to provide an overview of the GHG and energy balances of the most relevant bioenergy chains in comparison with their fossil competitors and other renewable energy systems.

2. Biomass supply

A wide range of biomass sources can be used to produce bioenergy in a variety of forms. For instance, process residues and energy crops can be utilized to generate electricity, heat, combined heat and power and gas/solid/liquid biofuels. Bioenergy provides today about 10% of the world's total primary energy supply and most of this is used in the residential sector for heating and cooking purposes (GBEP, 2007). Traditional bioenergy use (fuelwood and charcoal, often used with low efficiency) dominates in developing countries where up to 95% of national energy consumption relies on biomass. Contrarily, in developed countries, an efficient biomass use is becoming more important as a low carbon, distributed, renewable component of national energy systems. In fact, utilization of modern bioenergy applications is growing, especially cofiring of biomass with coal, gasification technologies and transportation biofuel generation (mainly bioethanol and biodiesel). A fundamental role is played by biomass supply, because the source of biomass has a big impact on LCA outcomes. Biomass for bioenergy purposes can be obtained in two ways: from residues and from dedicated energy crops, each of which is described below.

2.1. Biomass residues and wastes

Biomass residues and wastes are materials of biological origin arising as by-products and wastes from agriculture, forestry, forest or agricultural industries, and households (Hoogwijk et al., 2003). Unlike dedicated bioenergy crops, biowaste and residues are not produced specifically for use as an energy resource. They are the result of economic activity and production of goods in almost all sectors of the economy. As the production of biowaste occurs anyway, the diversion of biowaste to energy recovery options does not usually increase environmental pressures.

However, there are some exceptions:

- The removal of forestry or agricultural residues from land can reduce carbon storage in carbon pools like soil, dead wood or litter, and can deplete soil nutrients.
- The creation of a market for biomass residues or by-products, giving an additional income stream, can make the production of the main commodity (such as timber) economically more attractive, leading to expansion of this land use, which may have negative environmental impacts (for example, if native forests are replaced). However, increased production of wood products may also have positive climatic impacts through substitution of more emission intensive materials.

The diversion of biowaste away from landfill to energy recovery can also alleviate some of the environmental pressures associated with landfill, such as methane emissions from anaerobic decomposition of biomass in landfill.

2.2. Biomass from dedicated energy crops

Dedicated crops are grown first and foremost for energy, though they may also produce non-energy by-products. The ideal energy crop has efficient solar energy conversion resulting in high yields (C4 plants are more efficient converters in high light and high temperature conditions), needs low agrochemical inputs, has a low water requirement and has low moisture levels at harvest. While it is difficult to find a crop that meets all these criteria, perennial C4 grasses such as *Miscanthus* and switchgrass (*Panicum virgatum* L.) are particularly promising (Venturi and Venturi, 2003). Plants with perennial growth habits have the advantages of low establishment costs (when averaged across the rotation) and greater resilience in drought. When combustion is the end use of biomass, yield is probably the major decider between alternative crops, while for other end uses (e.g. ethanol production, biodiesel) quality and suitability of the crop are highly significant. The relative economic returns are likely to be the major driver in deciding the outcome of competition for land use between bioenergy and production of food, feed and fiber. The relative returns for bioenergy compared with other land uses will be influenced by relative yields and values, which are determined by market forces and market distortions (e.g. subsidies). The yield and value of by-products (e.g. fodder) will also be significant.

Another important aspect is the agronomic practices, which vary with intensity of production. In fact, increasing intensity of cultivation (i.e. the frequency of tillage, quantity of fertilizer, use of irrigation) increases yields, but also increases GHG emissions and can challenge the goal of a sustainable production. In any case, it is clear that, to be accepted, energy crops must fall within the parameters of sustainable agriculture.

Dedicated energy crops can have the added benefit of providing certain ecosystem services (e.g. C sequestration, biodiversity enhancement, salinity mitigation, enhancement of soil and water quality); the value of these services will depend on the particular bioenergy system in question and the reference land use that it displaces. For example, these benefits will be high for a mixed species woodland planted into a cropping district suffering dry-land salinity as a result of historical land clearing while, on the other hand, if native tropical forests are displaced by bioenergy crops, the value of ecosystem services may be reduced.

3. Biomass energy: CO_2 neutrality and its impact on carbon pools

Biomass use for energy generation is considered “carbon neutral” over its life cycle because combustion of biomass releases the same amount of CO_2 as was captured by the plant during its growth. By contrast, fossil fuels release CO_2 that has been locked up for millions of years. Bioenergy has an almost closed CO_2 cycle, but there are GHG emissions in its life cycle largely from the production stages: external fossil fuel inputs are required to produce and harvest the feedstocks, in processing and handling the biomass, in bioenergy plant operation and in transport of feedstocks and biofuels. Furthermore, the harvest of biomass may lead to a change in carbon stored above and below ground and in general these changes are not considered in the GHG balance of bioenergy systems, with few exceptions (Jungmeier and Schwaiger, 2000; Bradley, 2004; Cowie, 2004). Generally, C is stored in three different pools: vegetation (including roots), litter and soil. When changing land utilization, these storage pools can change until a new equilibrium is reached. For example, the additional use of forest residues for bioenergy purposes might lead to a decrease of C storage in forest litter and soil pools, since such residues are no longer left on the ground. This is a relevant aspect because of the large quantities of carbon in soil organic matter: soil contains around 50–300 t C/ha, compared with 2–20 t/ha in pasture or crop biomass. Globally, the soil carbon pool is estimated to hold 2500 Gt of carbon, compared with 560 Gt carbon in vegetation and 760 Gt in the atmosphere (Lal, 2008). Because the soil carbon pool is so large, even relatively small increases or decreases in its size can be of global significance. The potential to sequester carbon in soil is very site-specific and highly dependent on former and current agronomic practices, climate, and soil characteristics (Larson, 2005). Soil carbon stock at any one time reflects the balance between the inputs from plant residues and other organic matter, and losses due to decomposition, erosion and leaching. Intensive cultivation leads to loss of soil carbon, partly through the physical disturbance caused by tillage, which can stimulate decomposition. Another, sometimes more significant, cause of decline in soil carbon in cropping systems is the regular periods of minimal organic matter input during fallow periods. Therefore, converting from conventional annual row cropping to production of perennial grasses like switchgrass (for which tillage requirements are much lower, and soil carbon inputs are increased due to greater incorporation of leaf litter and fine root material) could result in substantial build-up of carbon in the soil. On the other hand, if woodlands or grasslands are converted to bioenergy crop production, there could be a decrease in soil organic carbon. The issue of carbon storage in soils is complicated by the fact that soil carbon depletion and build-up are relatively slow processes, so measuring changes is difficult (Heller et al., 2003). The few available experimental data (e.g. Tolbert et al., 2002; Hansen et al., 2004) and modelling studies (Grigal and Berguson, 1998) indicate that short rotation perennial bioenergy crops can increase soil C compared with intensive cropping. On the other hand, increasing intensity of harvest from existing agricultural and forest systems, and replacing pastures with short rotation energy crops may deplete soil carbon (Cowie et al., 2006).

Another factor which has a strong influence on soil carbon stocks of dedicated crops is the application of fertilizer. Results of a case study conducted to determine the response of switchgrass to fertilizers show that soil C increased at a rate of 2.4 t C/ha per year with NH_4NO_3 application and 4.0 t C/ha per year with manure (Lee et al., 2007). As a consequence, manure could be used as an alternative N source for bioenergy crop production on set-aside land with an added benefit of increased C sequestration. All the other implications related to land use change will be depicted in more details in a following section.

Biomass energy use can give rise to trade-offs and synergies with carbon sequestration mechanisms. In fact, the use of land for bioenergy production can compete with carbon sequestration objectives. Application of LCA reveals that bioenergy is the superior land use option delivering the greatest mitigation benefit where growth rates are high, biomass is used efficiently, initial carbon stocks are at low levels, and a long-term view is taken (Righelato and Spracklen, 2007). Conversely, bioenergy strategies based on increasing the harvesting levels in existing forests, or biofuel production that leads to deforestation, will deplete terrestrial carbon stocks, thus causing the trade-off between sequestration and renewable energy objectives. Fundamentally, a bioenergy system based on harvest levels that are not sustainable in the long-term is undesirable, and is not a renewable energy system.

However, bioenergy and carbon sequestration can also be synergistic. For example, afforestation, reforestation or revegetation of degraded land, in combination with future harvesting for biomass, is likely to increase carbon stocks while simultaneously generating feedstock for bioenergy.

4. Non-CO_2 GHG emissions in bioenergy systems

4.1. N_2O emissions

An important variable in LCA studies is the contribution to net GHG emissions of N_2O, which evolves from nitrogen fertilizer application and organic matter decomposition in soil (Stehfest and Bouwman, 2006). The application of fertilizer to agricultural land has an effect on the nutrient balance of the soil. Emissions from fields vary depending on soil type, climate, crop, tillage method, and fertilizer and manure application rates (Larson, 2005). The uncertainties in actual emissions are magnified by the high global warming potential of N_2O, 298 times greater than CO_2 (Forster et al., 2007). The impacts of N_2O emissions are especially significant for annual biofuel crops, since fertilization rates are larger for these than for perennial energy crops. Crops grown in high rainfall environments or under flood irrigation have the highest N_2O emissions, as denitrification, the major process leading to N_2O production, is favoured under moist soil conditions where oxygen availability is low (Wrage et al., 2005). Many LCA studies neglect N_2O emissions; those that include N_2O utilize default emission factors published by IPCC, which estimates emissions from several sources (IPCC, 2006):

- Volatilization of N as NH_3, at a rate of 10% of total N in the case of synthetic N application or 20% of total N in the case of manure application. Another study estimates these percentages much lower, around 2% (Van den Broek, 2000). 1% of the N in the NH_3 is then converted to N_2O.
- Direct soil emissions of N_2O, at 1% in case of synthetic N and 2% in case of manure (mean values).
- Runoff and leaching to groundwater as nitrate (30% of total N applied); 0.75% of it is converted to N_2O.

The resulting effect is that 1.325% of N in synthetic fertilizer is emitted as N in N_2O.

One recent study suggests that these default emission factors may underestimate nitrous oxide emissions three- to five-fold (Crutzen et al., 2007). As a consequence, this study is frequently cited as evidence against the use of biofuels as an effective means for mitigating global climate change; by contrast, other studies claim that Crutzen et al. apply an uncertain approach, questionable assumptions and inappropriate, selective comparisons to reach their conclusions (North Energy, 2008; RFA, 2008).

4.2. CH_4 emissions

Besides CO_2 and N_2O, the third most important GHG is CH_4. It is released in bioenergy process chain through combustion of fossil fuels, anaerobic decomposition of organic feedstocks and emissions from soil organic matter. In fact, cultivation of agricultural and lignocellulosic crops can reduce the oxidation of methane in aerobic soils, and thereby increase the concentration of methane in the atmosphere (Ojima et al., 1993; Thustos et al., 1998). The reduction in soil uptake (oxidation) of methane is related both to the use of nitrogen fertilizer and cultivation type; the reduction in methane uptake is equivalent to an emission of methane from cultivated soils. Such reduction is sensitive to a number of site-specific factors, such as soil temperature, soil moisture and the amount and kind of nitrogen fertilizer. As a consequence, measured effective emissions can range over orders of magnitude: CH_4 emissions related to fertilizer use can range from near zero to on the order of 100 g CH_4/kg N (Delucchi and Lipman, 2003). For instance, conversion of native grasslands and forests to managed pastures and cultivated crops reduces the oxidation of methane in the soil, due to N fertilization and soil disturbance, and, in general, cultivated soils show lower CH_4 uptake rates than soils under native conditions (Mosier et al., 1998). However, Delucchi and Lipman noted that a value of 10 g CH_4/kg N for CH_4 uptake reduction (which corresponds to a tantamount emission of CH_4) is reasonable for most circumstances and results in a relatively small contribution to life cycle GHG emissions of the bioenergy chain.

By contrast, CH_4 emissions may play a big role if tropical peat soils are involved: they represent a large storage of carbon and small losses may have a big influence on GHG balances. CH_4 emissions from peat soils to the atmosphere depend on the rates of methane production and consumption and the ability of the soil and plants to transport the gas to the surface (Hamelinck et al., 2008). The major environmental factors that control emission rates from peatland are water table position, temperature, substrate properties, drainage and N fertilization (Melling et al., 2005). The cultivation of tropical peatland primary forest to oil palm promoted CH_4 oxidation due to the lowering of water table by drainage which increased the thickness of aerobic soil layer. This improved CH_4 uptake can make the oil palm ecosystem a CH_4 sink (Hamelinck et al., 2008), though this may not override the substantial CO_2 emissions resulting from oxidation of soil organic matter after peatlands are drained.

5. Methodological concerns of bioenergy LCA

5.1. Land use change in bioenergy systems

The production of feedstock for bioenergy requires land that was previously used, and would otherwise be used, for a different purpose. This means that, besides a direct land use change which can have an influence on the GHG balance, there may also be further impact on GHG balance if the displacement of the previous land use leads to land use change elsewhere (Hamelinck et al., 2008). Therefore, both direct and indirect land use change must be considered. In the following paragraphs, these two effects are depicted and some technical indications for estimating the direct and indirect effect are provided with the help of recent scientific references.

5.1.1. Direct land use change

Direct land use change occurs when new agricultural land is taken into production and feedstock for biofuel purposes displaces a prior land use (e.g. conversion of forest land to sugarcane plantations), thereby generating possible changes to the carbon stock of that land. Depending on the previous use of the land and the crop to be established, this can be a benefit or a disadvantage: when a forest is converted to agricultural land for biofuel production there would be a loss of carbon stocks; on the other hand, when set-aside land is taken into production the carbon stock may increase. A study conducted on agricultural land converted from annual row crops to perennial grasses demonstrated an increase in carbon sequestration: up to 1.1 t C/ha were sequestered during the five years of monitoring (Gebhart et al., 1994). Other studies have also shown that switchgrass grown for biomass feedstock production has the potential to substantially increase soil C levels (Lal et al., 1998; Garten and Wullschleger, 2000; Conant et al., 2001; Zan et al., 2001; Franck et al., 2004). It can be summarized that converting cropland to grassland typically increases soil C at rates of 0.2–1.0 t C/ha per year for several decades. Therefore, beyond GHG emission savings coming from fossil fuel replacement, carbon sequestration strategies related to land use change might broaden the GHG mitigation benefits of bioenergy.

Altough GHG emissions from direct land use change have been included in LCA studies of biofuels only recently, some default values already exist. IPCC provides default values by which it is possible to estimate the annual effect of direct land use change (IPCC, 2006); an example of total soil carbon stock changes are reported in Table 1; through division by the plantation life time (IPCC default value: 20 years), the annual soil carbon stock change is found and can be converted to CO_2 emissions and accounted for in the GHG balance.

Besides soil carbon stocks, above ground carbon stocks may also be affected. For most bioenergy crops, the annual change in above ground carbon is equal to zero, since the whole crop is harvested annually. The change in above ground biomass is summarized in Table 2, where set-aside land, temperate and tropical grassland are assumed to contain negligible amounts of above ground biomass (Hamelinck et al., 2008).

However, drawing general figures for the quantification of direct land use change in GHG balances is difficult and each case study should be addressed autonomously. Several software tools able to model C stock changes are also available (Gabrielle and Kengni, 1996; Skjemstad et al., 2004; Easter et al., 2007).

5.1.2. Indirect land use change

Indirect land use change (or leakage) occurs when land currently used for feed or food crops is changed into bioenergy feedstock

Table 1
Soil C stock change in t C/ha (cold dry temperate conditions for set-aside, temperate grassland and forest). Source: Hamelinck et al. (2008).

From	To						
	Wheat	Sugar beet	Sugar cane	Maize	Palm oil	Rapeseed	Soy bean
Set-aside	−9	−9	n.a.	−9	n.a.	−9	−9
Temperate grassland	−9	−9	n.a.	−9	n.a.	−9	n.a.
Temperate forest	−13	−13	n.a.	−13	n.a.	−13	n.a.
Tropical grassland	n.a.	n.a.	n.a.	n.a.	−2	n.a.	n.a.
Tropical moist rain forest	n.a.	n.a.	−31	n.a.	−4	n.a.	−31

Table 2
Above ground carbon stock change in t C/ha (cold dry temperate conditions for set-aside, temperate grassland and forest). Source: Hamelinck et al. (2008).

From	To						
	Wheat	Sugar beet	Sugar cane	Maize	Palm oil	Rapeseed	Soy bean
Set-aside	0	0	n.a.	0	n.a.	0	0
Temperate grassland	0	0	n.a.	0	n.a.	0	n.a.
Temperate forest	−35	−35	n.a.	−35	n.a.	−35	n.a.
Tropical grassland	n.a.	n.a.	n.a.	n.a.	63	n.a.	n.a.
Tropical moist rain forest	n.a.	n.a.	−120	n.a.	−57	n.a.	−120

production and the demand for the previous land use (i.e. feed, food) remains, because the displaced agricultural production will move to other places where unfavourable land use change could occur (Fritsche, 2008a).

In order to meet a given demand of bioenergy a certain amount of feedstock is needed and, in general, these feedstock quantities can be obtained by (Gnansonou et al., 2008):

- biomass use substitution (i.e. destined to bioenergy production instead of food and feed purposes),
- crop area expansion,
- shortening the rotation length and
- yield increment in the same land.

Apart from the last option, all the other strategies may result in indirect land use effects. GHG emissions from indirect land use change are claimed to be even more important than emissions from direct land use change and, despite the high inaccuracy and calculation difficulties, some authors elaborated a range of values to show the magnitude of this effect (Farrell and O'Hare, 2008; Searchinger et al., 2008; Fritsche, 2008b; Fargione et al., 2008).

An example of one approach for calculating the indirect land use change and its influence on final results considers that use of arable land for additional biomass feedstock production will induce indirect land use change risks due to displacement, but that the risk is small and can be ignored for feedstock produced from wastes and on degraded land and also on set-aside and idle land, as well as biomass feedstock derived by increasing yields (Fritsche, 2008b; RFA, 2008). The indirect land use change (iLUC) factor is derived by considering the potential release of GHG from land use change caused by displacement to be a function of the land used to produce agricultural products for export purpose on the basis that only trade flows will be affected by displacement. An average CO_2 emission factor per hectare of displaced land is then derived, and discounted over a time horizon of 20 years. A "full" indirect land use change factor would have to be applied if the risk of displacement is 100%. Fritsche suggests that in practice the risk will be lower for feedstock produced on idle land, through intensification of existing cultivation schemes and use of marginal land. As a consequence, the indirect land use change factor can range from a "minimum" assuming 25% of all non-zero risk biofuels are subject to the iLUC factor, "medium" meaning a 50% share of non-zero risk feedstocks, and "maximum" for the 75% level of the iLUC factor (Fritsche, 2008b). In Table 3, the life cycle GHG emissions of biofuels, where the iLUC factor is included, are reported. Results suggest no net savings for biodiesel from rapeseed oil, and only small savings for ethanol from maize and wheat for the "minimum" iLUC factor. With a medium level of 50% risk of indirect land use change, rapeseed, wheat and maize will not be reducing GHG emissions. For a high level of the iLUC factor, only ethanol from sugarcane, and second-generation Biomass to Liquid (BtL) technologies would still provide a GHG reduction.

However, if bioenergy crops are cultivated on fallow, marginal or degraded land where previously no conventional crops were grown, and management strategies such as those proposed by Cerri and Cerri (2007) are implemented, no indirect GHG emissions occur and the GHG balance can be favourable, as in the case of perennial grasses discussed above.

5.2. Effects on GHG balance of crop residue removal

There is an ongoing debate about potential for crop residue removal from agricultural cropping systems (Wilhem et al., 2004; Lal, 2005). Current experimental evidence on the effect of straw removal on processes like soil organic matter turnover, soil erosion or crop yields are not consistent because of the strong influence of local conditions (climate, soil type and crop management). The use of straw as bioenergy source may influence environmental aspects like N_2O emissions, leaching of nitrate and changes in soil carbon pools. Except for nitrate leaching, there are few references on these effects in the scientific literature, and the patterns are not consistent between studies. However, removing crop residues for bioenergy production should occur only where environmental, economic and social benefits outweigh the direct and ancillary benefits of stover retention (such as soil quality).

A recent study modelled the effects of crop rotation and straw removal frequency on two different soil types (Gabrielle and Gagnaire, 2008). Results show that the differences between different rotations are generally more important than those related to straw management for a given rotation: the removal of straw implied limited consequences on field emissions.

The main GHG implications related to crop residue removal are the following:

- Crop productivity showed a decrease in yield of 0.05–0.15 t_{dry}/ha, because of a lower net mineralization of N in soils. This corresponds to a straw fertilizer value of 1.5–4.5 kg N/t dry straw, which is lower than the total N content of the straw (6 kg N/t dry straw). The implications for GHG balances of bioenergy systems arise from an increase of synthetic fertilizer application to balance the nutrient removed with the straw and the decrease in crop yields,

Table 3
Life cycle GHG emissions of biofuels, including indirect land use change. Source: Fritsche (2008b).

Biofuel route, location	Life cycle GHG emissions[a] (g CO_2-eq./MJ)		
	Maximum	Medium	Minimum
Rapeseed to FAME[b], EU	260	188	117
Palm oil to FAME[b], Indonesia	84	64	45
Soyoil to FAME[b], Brazil	101	76	51
Sugarcane to EtOH, Brazil	48	42	36
Maize to EtOH, USA	129	101	72
Wheat to EtOH, EU	144	110	77
SRC[c] to BtL[d], EU	109	75	42
SRC[c] to BtL[d], Brazil (tropical)	34	25	17
SRC[c] to BtL[d], Brazil (savannah)	59	42	25
Conventional gasoline		87–90	
Conventional diesel		85–90	

[a] Including cultivation, processing, by-products and indirect land use change.
[b] Fatty acid methyl ester.
[c] Short rotation crop.
[d] Biomass to liquid.

which must be addressed. This decrease will result in indirect land use change: the "missing" cereals will be produced somewhere else (by an expansion of agricultural land) or will be supplied by an increase of fertilization. The influence of these effects should be modelled and estimated by means of appropriate assumptions, and reported in the final GHG balances.

- N_2O emissions decreased slightly with increasing straw removal, at a rate of 0.1–0.25 kg N/t dry straw. The reason is that straw return to soil increases soil's denitrification potential and its capacity to produce N_2O (Cai et al., 2001). This effect should be accounted for in the GHG balance.
- Straw removal contributed to increase global warming due to the change of soil carbon stocks, in comparison with the case in which straw is left in the ground. Altough there is an increase in soil carbon stocks under all managements, the removal of straw causes a reduction in soil carbon increase of about 0.2 t C/ha per year with 50% of straw removed and 0.35 t C/ha per year with 100% straw removal (these figures already include the reduction in N_2O emissions).

Since all these aspects may influence the GHG balance, they should be addressed case by case or with suitable models and assumptions, because the impacts of residue retention are highly variable and depend on specific local factors.

5.3. Bioenergy system vs. fossil reference system

The energy and GHG balances of bioenergy systems should always be compared with fossil reference systems (Schlamadinger et al., 1997). In Fig. 1, the full fuel chains of a bioenergy (left side) and a fossil (right side) system producing electricity and heat are compared. The bioenergy chain starts at the top of the diagram with carbon fixation from the atmosphere via photosynthesis, or biomass carbon taken as biomass waste from the agricultural or forest product sector. At the end of the bioenergy fuel chain a certain amount of useful energy (electricity and heat) is supplied. All energy inputs and GHG emissions occurring along the fuel chain, for planting and harvesting the crops, processing the feedstock into biofuel, transporting and storing of feedstocks, distributing and final use of biofuels must be accounted for using a life cycle perspective. Non-energy utilization of by-products must also be considered; by-products can be used to displace other materials, having GHG and energy implications. The fossil fuel energy system is dealt with in a similar way, including all GHG emissions

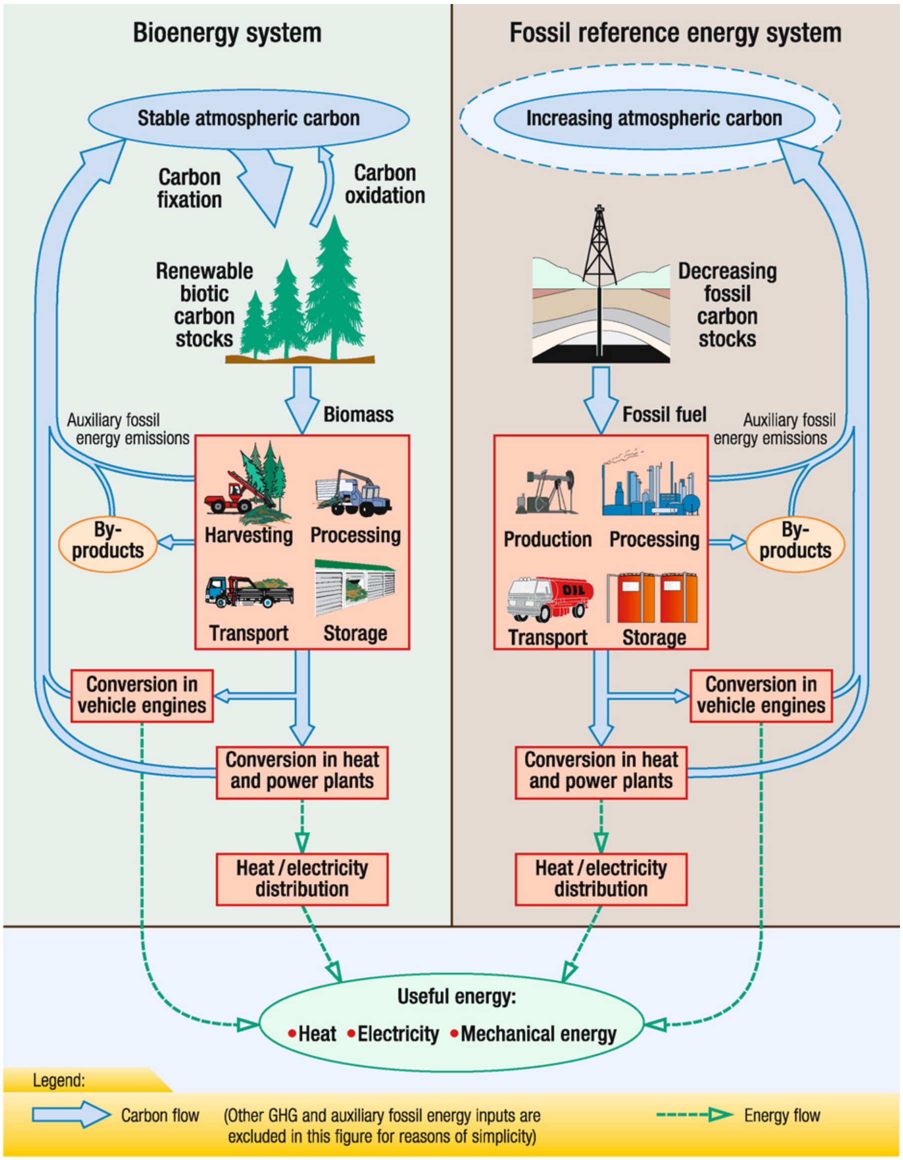

Fig. 1. Full fuel chains for comparison of bioenergy and fossil energy systems.

and energy consumption associated with the following life cycle stages: production of the raw fossil fuel, refining, storage, distribution and combustion. When production of feedstocks for bioenergy uses land previously dedicated to other purposes or when the same feedstock is used for another task (e.g. corn to bioethanol instead of animal feed), the reference system should include an alternative land use or an alternative biomass use, respectively. Similarly, when the bioenergy pathway delivers some co-products able to replace existing products (thus saving GHG emissions), the reference substituted products should be defined in the fossil reference system and emissions for their production accounted for in the GHG balance.

If presented in this manner, the differences between the two systems producing the same product/service can be compared.

5.4. *Functional unit*

One of the main purposes of the functional unit is to provide a reference to which the input and output process data are normalized and the basis on which the final results are shown.

Concerning LCA of bioenergy systems, results should be expressed in terms of the same functional unit, to ensure that the comparison is based on delivery of the same service. When assessing the efficiency of energy systems or their GHG impact the approach often practiced is to use measures such as input–output ratios or absolute emissions and primary energy requirements to be compared with conventional fossil fuel systems. Some studies carry the analysis further and express results on a per vehicle-km basis, which is the best way to show the LCA findings of transportation biofuel systems, in order to make them comparable with conventional diesel and gasoline. However, relatively few studies focus on the question of relative land use efficiency for different biofuel pathways, which should be the first parameter to take into account when dedicated energy crops compete against food, feed or fiber production under land-availability constraints, in order to use scarce land resources as efficiently as possible (Schlamadinger et al., 2005).

Therefore, the results of the energy and GHG balances of bioenergy from dedicated biomass crops should be expressed on a per hectare basis, since the available area for the production of biomass raw materials is the biggest limitation for the production of biofuels. On the other hand, for biomass residue feedstocks, the results should be expressed on a per unit output (kWh, km) basis, in order to be independent from the kind of biomass feedstock, or per unit input basis (kg, or J of feedstock) in order to be independent from the conversion process (this is usually the most relevant option when comparing alternative uses for a given residue).

Where the fossil fuel reference system differs strongly among bioenergy alternatives, or where there are bioenergy alternatives that use their own product in their production, it is important to show net emission reductions compared to the fossil reference system, rather than absolute emission levels without consideration of such reference systems.

5.5. *The origin of wide ranges*

The most striking feature when comparing LCAs reported by different authors and sources for the same biofuel and originating biomass source is the wide range of results in terms of energy balances and greenhouse gas emissions. For example, most studies have concluded that corn-based ethanol used as transportation biofuel to displace petroleum-derived fuels will reduce greenhouse gas emissions (Kim and Dale, 2002; Shapouri et al., 2002; Punter et al., 2004), while two studies by Pimentel have reported that the input energy for corn-based ethanol production is larger than the energy content of ethanol (Pimentel, 1991; Pimentel, 2002). This disagreement is attributable to differing data sets, including data sources and ages. In order to understand the wide variation between LCA results for apparently similar systems, investigation into numerical input assumptions is required as well as into the calculation methodologies that were used to generate the results. In fact, the most important aspects that give rise to wide ranges are input parameter values, system boundaries, allocation procedure, and fossil reference system. Different LCA studies are based on Life Cycle Inventories having different input values for an assessment of the same biofuel pathways. For instance, fertilizer requirements and crop yields vary widely, dependent on edaphic and climatic conditions: crop yield assumptions vary from 2.3 to 4.9 t/ha for wheat grown (Venturi and Venturi, 2003), while nitrogen fertilizer application ranges from 53 to 196 kg N/ha (Quirin et al., 2004). Less obviously, studies vary in the emission factors assumed: for example, primary energy input to make nitrogenous fertilizer vary from 42 to 70 MJ/kg N, depending on the fertilizer production process (Quirin et al., 2004). Wood and Cowie, in their review of emission factors for a variety of fertilizers, report wide ranges of emissions from production of nitrogenous fertilizers, from 3 to 9.6 kg CO_2-eq./kg N, and discuss the explanations, which include differences in processing technologies, energy sources and utilization of co-products (Wood and Cowie, 2004). Similarly, the choice of LCA system boundary can greatly impact the results, and should be clearly stated.

Furthermore, allocation rules are another reason for diverging results. Bioenergy systems often produce several energy products (e.g. electricity and/or heat) and may also produce material products such as DDGS (e.g. Distiller's Dried Grains with Solubles, from ethanol production) and compostable matter from biogas production; in such cases the emissions and offsets generated by the system must be estimated and allocated among products and co-products. In the scientific literature there are many papers which address the allocation issue in LCA and describe the alternative approaches to allocation (Frischknecht, 2000; Wang et al., 2004; Curran, 2007). Environmental impacts can be allocated according to economic value of co-products, their mass and energy content, or by system expansion (in which production of the product that is displaced by the co-product of the bioenergy system is also included in the system boundary).

The choice of allocation method can have a strong influence on the results. For instance, the importance for LCA results both of co-products and of the source/technology used for meeting the plant energy demand (natural gas or straw collected from the wheat field) clearly emerges in a case study where bioethanol is produced from wheat (Punter et al., 2004). Results are illustrated in Fig. 2: the

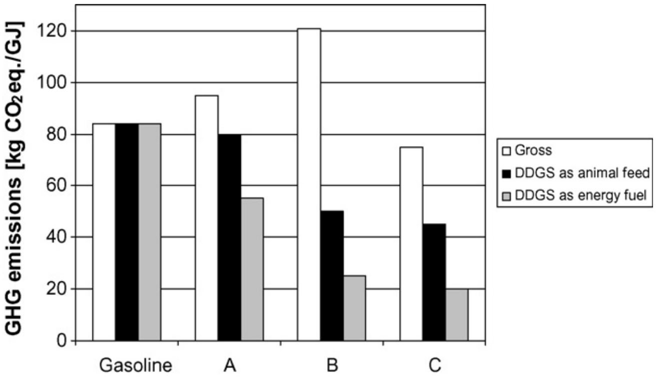

Fig. 2. Bioethanol from wheat: graphic showing the strong relation of final GHG emission results with by-product assumptions and energy providing systems; the cases A, B and C refer to different ways of energy provision to the fermentation plant: A = natural gas boiler for heat and electricity from the grid; B = natural gas turbine for heat and electricity generation (CHP); C = straw boiler for heat and electricity production from steam turbine (CHP). Source: Punter et al. (2004).

production of bioethanol from wheat implies the co-production of DDGS (the residue from the fermentation and distillation process), a protein rich product that has a high value as animal feed. If its use for this purpose replaces other animal feed material (mainly maize gluten feed), the energy used and GHG emitted for growing and processing maize will be saved; but DDGS could alternatively be used in power generation, and in this case substitution for conventional electricity provides a greater GHG saving (as shown in the figure).

In conclusion, LCA results based on selected default values and simple allocation may significantly increase the risk of drawing misleading conclusions. Some of the key parameters vary widely between different systems and locations, and many are subject to remarkable uncertainties. Thus, there is a high probability that the true energy balance and GHG emissions for a specific system will be substantially different from the 'default results'. Consequently, uncertainty and sensitivity analysis should be integrated into the final results, which should be presented with ranges that take into account all the different assumptions and variables.

6. Energy and GHG balances of bioenergy systems

6.1. Energy balance

Bioenergy systems usually require non-renewable energy for the production, transport and conversion to bioenergy, which must be included in the LCA. The same is true for the fossil reference system. Clearly, the more fossil fuel input a certain bioenergy system requires, the less energetically desirable it is. As a consequence, some production chains are more desirable than others, depending on the yield of the crop, the amount of fertilizers, pesticides and irrigation required, the feedstock processing requirements, energy conversion processes and the types of co-products. The energy balances of some representative bioenergy pathways and other renewable and fossil energy systems are reported in Table 4, with indices and indicators of system energy performance.

These results (and those in Table 5) should be considered carefully and used cautiously. The data are elaborated from the software tool GEMIS ("Global Emission Model for Integrated Systems") Version 4.42 (GEMIS, 2008). GEMIS is a life cycle analysis program and database for energy, material, and transport systems and includes the total life cycle in its calculation of impacts, i.e. fuel delivery, materials used for construction, waste treatment, and transports/auxiliaries. The GEMIS database covers for each process: efficiency, power, capacity factor, lifetime, direct air pollutants (SO_2, NO_x, halogens, particulates, CO, NMVOC), greenhouse gas emissions (CO_2, CH_4, N_2O, SF_6, all other Kyoto gases), solid wastes, liquid pollutants and land use. Results, given with wide ranges representing the typical span of performance for each system, are averages for European countries (generally Germany, Austria, France and Italy) except for bioethanol from sugar cane (set in Brazil). For electricity and heat, the range of the electric/thermal conversion efficiency (η) is also reported. These data are valid for systems that do not give rise to direct or indirect land use changes; since these effects are strictly dependent on specific factors (type of soil, climate, crop, rotation, etc.), it was not possible to draw general figures. However, if they occur in a particular case study, their related GHG implications can be estimated according to the guidelines depicted in the previous section and added to the findings of Table 5. The purpose of the tables is to present an overview of the primary energy demand and

Table 4
Table showing: the ratio non-renewable energy input/energy output ($E_{\text{non-ren-in}}/E_{\text{out}}$); the Cumulative primary Energy Requirement (CER), given by the sum of the Fossil Energy Requirement (FER) and the Renewable Energy Requirement (RER).

Transportation fuel	$E_{\text{non-ren-in}}/E_{\text{out}}$	Cumulative (CER) (MJ/km)	Fossil (FER) (MJ/km)	Renewable (RER) (MJ/km)
Bioethanol from sugar cane	0.15–0.25	12–13	0.2–0.3	11.8–12.8
Bioethanol from other crops (corn, sugar beet, wheat)	0.50–0.85	3.5–5.5	0.7–1.5	2.8–4
Biogas	0.15–0.40	3.5–4.5	0.3–1	3.0–4.0
Biodiesel (rapeseed, soy, sunflower)	0.40–0.70	3.5–4.5	0.8–1.8	2.5–3.3
FT-diesel from biomass[a]	0.15–0.40	4.4–4.8	0.1–0.2	4.2–4.6
Bioethanol from lignocellulose[a]	0.15–0.45	6.1–9.3	0.1–0.8	6.0–8.5
Gasoline	1.20	1.7–2.4	1.7–2.4	<0.001
Diesel	1.20	1.3–1.9	1.3–1.9	<0.001
Natural gas	1.05–1.20	2.5–2.8	2.5–2.8	<0.001
Electricity and cogeneration		CER (MJ/MJ_e)	FER (MJ/MJ_e)	RER (MJ/MJ_e)
Biomass (wood chips, pellets) (10% < η_e > 23%)		7.0–8.2	0.1–0.4	6.8–8–0
Biomass/coal cofiring[b] (20% < η_e > 30%)		6.0–7.0	1.0–2.0	5.4–6.5
Biogas (25% < η_e > 40%)		4.0–7.0	0.4–0.9	3.7–6.0
Wind		1.01–1.02	0.01–0.02	1
Geothermal		1.01–1.03	0.01–0.03	1
Hydro		1.0–1.01	0.0–0.01	1
Solar PV		1.1–1.4	0.1–0.4	1
Coal (25% < η_e > 40%)		2.5–4.2	2.5–4.2	<0.001
Oil (25% < η_e > 42.5%)		2.3–3.8	2.3–3.8	<0.001
Nuclear		2.8–3.3	2.8–3.3	<0.001
Natural gas (30% < η_e > 45%)		1.7–3.0	1.7–3.0	<0.001
Heat		CER (MJ/MJ_{th})	FER (MJ/MJ_{th})	RER (MJ/MJ_{th})
Biomass (wood chips, pellets) (70% < η_{th} > 85%)		1.1–1.2	0.01–0.05	1.1–1.2
Geothermal		1.01–1.02	0.01–0.02	1
Solar thermal		1.02–1.2	0.02–0.2	1
Coal (70% < η_{th} > 85%)		1.1–1.5	1.1–1.5	<0.001
Oil (70% < η_{th} > 90%)		1.1–1.4	1.1–1.4	<0.001
Natural gas (80% < η_{th} > 95%)		1.1–1.3	1.1–1.3	<0.001
Electricity—from natural gas (space heating)		1.4–1.7	1.4–1.7	<0.001
Electricity—from oil (space heating)		1.6–2.0	1.6–2.0	<0.001
Electricity—from coal (space heating)		1.9–2.1	1.9–2.1	<0.001

[a] Technologies under development.

[b] Biomass share in cofiring ranges between 5% and 15%.

Table 5
GHG emissions per unit of output.

Energy product	GHG emissions ($g\,CO_2$-eq./km)
Transportation fuel	
Bioethanol from sugar cane	50–75
Bioethanol from other crops (corn, sugar beet, wheat)	100–195
Biogas	25–100
Biodiesel (rapeseed, soy, sunflower)	80–140
FT-diesel from biomass[a]	15–55
Bioethanol from lignocellulose[a]	25–50
Gasoline[b]	210–220
Diesel[c]	185–220
Natural gas	155–185
	GHG emissions ($g\,CO_2$-eq./MJ)
Electricity and cogeneration	
Biomass (i.e. wood chips, pellets)	15–30
Biomass/coal cofiring[d]	20–100
Biogas	15–65
Wind	1–10
Geothermal	2–10
Hydro	0.5–10
Solar PV	15–40
Coal	300–500
Oil	200–300
Nuclear	5–30
Natural gas	100–200
Heat	
Biomass (i.e. wood chips, pellets)	5–20
Geothermal	1–5
Solar thermal	10–30
Coal	110–150
Oil	90–120
Natural gas	70–85
Electricity—from natural gas (space heating)	180–210
Electricity—from oil (space heating)	265–290
Electricity—from coal (space heating)	290–320

[a] Technologies under development.

[b] GHG from combustion already included: 75.92 $g\,CO_2$-eq./MJ (consumption: 2.45 MJ/km).

[c] GHG from combustion already included: 75.34 $g\,CO_2$-eq./MJ (consumption: 2.45 MJ/km).

[d] Biomass share in cofiring ranges between 5% and 15%.

GHG emissions for various energy products based on existing data, to allow broad comparison between energy chains. These results are very much in line with the results reported in other published LCA studies (WEC, 2004; EUCAR/CONCAWE/JRC, 2006).

The second column of Table 4 shows the input/output energy balance, calculated as “non-renewable energy consumption/energy output” ratio. This index reflects the non-renewable energy (mainly fossil) investment in the generation of one energy unit: if a biofuel has a value bigger than 1, it means that it consumes more non-renewable energy than it provides. For fossil fuels, the energy itself of the product is also included in the numerator, because it is not renewable.

Shown in the other columns are the Fossil Energy Requirement (FER), the Renewable Energy Requirement (RER, that is mainly made of biomass energy content used in the bioenergy chains), and the Cumulative primary Energy Requirement (CER, CER = FER + RER), which represents the total life cycle primary energy demand of the energy product. Bioenergy systems are affected by a larger CER than conventional energy systems and other renewables, but it is mainly constituted by the RER fraction while the FER is significantly smaller. In bioenergy systems, the FER is predominantly affected by fossil fuel energy inputs during cultivation or processing. In fact, the favourable energy balance for bioethanol from sugar cane and lignocellulosic ethanol are largely due to the fact that they are processed using the renewable energy of the biomass residues available at the processing plant. The fossil energy input is higher for biofuels from oil or starch crops, than for biomass-based electricity/heat generation, usually based on wood combustion. The reason is two-fold:

1. The agricultural phase is responsible for the largest percentage of energy inputs, due to the use of machines, fertilizers, pesticides (Zah et al., 2007). Oil and starch crops need higher cultivation inputs than woody crops.
2. While the production of heat and electricity from woody biomass or biomass residues requires few steps (collection, drying and combustion), the production of biofuels usually involves additional energy intensive stages (e.g. hydrolysis and fermentation for bioethanol, transesterification or hydrogenation for biodiesel).

It is important to note that Table 4 does not necessarily identify systems that deliver the greatest greenhouse gas mitigation benefit (see next paragraph for preferred measures).

6.2. *GHG balance*

Table 5 shows the GHG emissions per unit of output of bioenergy production chains, together with other renewable and fossil systems. Results for transportation fuels are related to 1 car-transportation-km. Results per 1 MJ of fuel are not reported because the utilization of such functional unit can be misleading, altough it is adopted by several case studies. In fact, the mechanical efficiency can vary from one fuel to another, so that one energy unit may allow different driving distances.

GHG emissions for the generation of electricity and heat are related to one energy output unit (MJ). Results demonstrate that most current and advanced bioenergy systems release lower GHG emissions than fossil energy systems, if a land use change (direct or indirect) is avoided. Findings of bioenergy systems with an attempt to include indirect land use change in the calculations have been reported in Table 3.

For some biomass systems, the entire chain from growing the feedstock to combustion can be close to carbon neutral. For example, net GHG emissions from generation of a unit of electricity from bioenergy are usually 5–10% of those from fossil fuel-based electricity generation. The ratio will be more favourable (lower), if biomass is produced with low energy input (or derived from residue streams), converted efficiently (ideally in CHP applications, where some of the residual heat after electricity generation is also utilized) and if the fossil fuel reference use is inefficient and based on a carbon-intensive fuel such as coal (rather than natural gas, which has lower carbon intensity and usually higher conversion efficiency). If compared with other renewable sources, electricity from biomass generally has higher emissions than hydro, wind and geothermal derived electricity, while it is comparable with photovoltaic power production systems.

Biodiesel achieves 40–65% of the GHG emissions of conventional diesel, while for bioethanol technologies the range of GHG reduction is wider: for some bioethanol production chains (e.g. for corn to ethanol in coal-fired process plants) the GHG emissions may be as high as 80–90% of their fossil fuel competitors, whereas they may be as low as 20–35% for bioethanol from sugar cane. The crucial factors are the amount and type of fossil fuel used (and non-CO_2 GHGs generated, such as N_2O) to produce, transport and process the feedstock, the efficiency in the conversion process, the degree to which biomass is used to fuel the process, and feedstock yields. The GHG and energy balance may also depend on the scale at which biomass is used. For instance, large-scale use may lead to significant land use changes, which can lead to increases or decreases in terrestrial carbon stocks, as discussed above.

Table 6

Energy and GHG savings per hectare per year (with replacement of inefficient coal or efficient natural gas) for fuels, electricity and heat generation from biomass. Data for fuels except for FT-diesel come from Quirin et al. (2004); data for heat, electricity and FT-diesel are from GEMIS, elaborated using lignocellulosic crop yields and heating values reported in Venturi and Venturi (2003).

Energy product	Energy and GHG savings	
	GJ saved/ha	t CO_2-eq. saved/ha
Fuel[a]		
Bioethanol from sugar cane	150–200	10–16
Bioethanol from other crops (corn, sugar beet, wheat)	15–150	0.5–11
Biogas	30–70	1.5–4.5
Biodiesel (rapeseed, soy, sunflower)	15–65	0.5–4
FT-diesel from biomass[b]	110–160	8–12
Bioethanol from lignocellulose[b]	25–95	2–7

Lignocellulose crops	Energy and GHG savings[c]	
	GJ saved/ha	t CO_2-eq. saved/ha
Electricity and cogeneration[d]		
Wood (chips and pellets)	55–125	0.5–14
Fiber sorghum	145–313	2–35
Sweet sorghum	115–250	2–29
Kenaf	85–180	1–20
Hemp	70–155	1–18
Miscanthus	135–290	2–33
Giant reed	145–315	2–33
Cardoon	65–145	1–17
Switchgrass	105–230	2–26
Heat[e]		
Wood (chips and pellets)	155–215	6–23
Fiber sorghum	150–515	18–58
Sweet sorghum	155–410	14–46
Kenaf	160–295	10–33
Hemp	160–255	9–28
Miscanthus	150–475	16–53
Giant reed	150–515	18–58
Cardoon	160–240	8–27
Switchgrass	155–380	13–43

[a] The savings are related to gasoline (for bioethanol), diesel (for biodiesel) and CNG for biogas.

[b] Technologies under development.

[c] Energy conversion efficiency assumed: 20% for electricity, 80% for heat; GHG emission: for wood 23 kg CO_2-eq./GJ_{fuel}, for other crops: 15 kg CO_2-eq./GJ_{fuel}; Fossil Energy Requirement: for wood 0.09 GJ/GJ_{fuel}, for other crops 0.053 GJ/GJ_{fuel}.

[d] Ranges from replacement of inefficient coal (500 kg CO_2-eq./GJ_e; 4 GJ_{fossil}/GJ_e) and efficient natural gas (100 kg CO_2-eq./GJ; 2 GJ_{fossil}/GJ_e).

[e] Ranges from replacement of inefficient coal (190 kg CO_2-eq./GJ_{th}; 1.6 GJ_{fossil}/GJ_{th}) and efficient natural gas (71 kg CO_2-eq./GJ_{th}; 1.2 GJ_{fossil}/GJ_{th}).

6.3. *Fossil energy and GHG savings per hectare*

Table 6 reports the fossil energy and GHG savings per hectare per year for several bioenergy chains, including biofuels and electricity and heat generation from combustion of different kinds of lignocellulosic crops having different yields. In general, electricity generation from biomass may achieve larger reductions of GHG and fossil energy consumption per unit of land area, particularly compared to some first-generation biofuels. The importance of the fossil fuel reference system is clearly visible in Table 6, where the energy and GHG savings of the different bioenergy options are related to the replacement of inefficient coal or more efficient natural gas, thus resulting in wide ranges. In fact, electricity generation provides larger climate change mitigation benefits per hectare of land than transportation biofuels if coal-electricity is displaced, but GHG impacts are comparable if lower-carbon electricity (e.g. natural gas) is replaced. Finally, uses of biomass for heating generally give greater GHG reductions per hectare than transportation biofuels or bioelectricity.

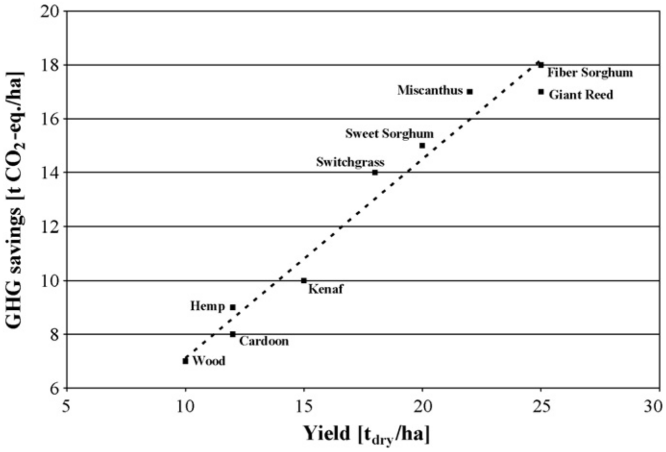

Fig. 3. GHG savings per hectare as a function of lignocellulosic crop yields. GHG savings come from central part of Table 6 (electricity and cogeneration). Mean values of yields and savings are used.

Among transportation biofuels, the largest GHG and fossil energy savings are achieved with bioethanol from sugar cane in Brazil, where there are high yields and use of bagasse for heat and power, on condition that the feedstock is produced without any significant land use change (either direct or indirect). The savings for technologies still under development (i.e. FT-diesel from biomass and bioethanol from lignocellulose) are more uncertain, but have been estimated to be 80–90% if residues are used as feedstock (see following section).

For dedicated bioenergy crops, crop yield affects GHG mitigation: as illustrated in Fig. 3, the higher the yield of the crop, the higher is the amount of GHG saved. In most European countries, yields are usually well known for rape, corn, wheat and other grain and seed crops and these values tend to be used as fixed inputs for LCA analyses. However, geographical position has significant impact on yield: yields are much lower and much more variable in places with low and erratic rainfall, such as Australia and central Africa. Regarding future trends of lignocellulosic crop yields, little analysis has been performed, especially concerning the impact on LCA results of different yield levels for a given biofuel pathway (e.g. how different switchgrass yields can affect the final results of ethanol production) (Greene et al., 2004; Smeets et al., 2009).

Energy and GHG balances of bioenergy systems can be made to look more attractive by using energy products from the bioenergy system for fuelling the processes involved. However, such conclusions of an improved GHG balance can be misleading: these energy products could alternatively be used for GHG mitigation outside the bioenergy system boundary, where they may generate greater GHG mitigation benefits, depending on the fossil-based system that is displaced. Biomass is a limited resource, even if produced on a sustainable basis, so selection of the optimal bioenergy system in a given situation should include assessment of the maximum GHG mitigation that can be achieved with that biomass.

Especially for bioenergy systems based on dedicated energy crops, it is important to consider the question of relative land use efficiency of different biofuel pathways. Where there is competition for land between energy, food, feed or fiber production, land resources should be used as efficiently as possible. To maximise GHG emission reduction per hectare of land one should:

- Grow biomass crops that have minimal processing requirements, on sites with high growth rates, while minimising external inputs such as fertilizers and pesticides.
- Use an efficient energy conversion system to replace a carbon-intensive fuel with low conversion efficiency.

- Increase efficiency of biomass use through ‘cascading’, i.e. multiple use of the same biomass, for example first for high-quality product (e.g. timber), then lower-quality product use (chipboard), and finally for energy.

7. Future trends in bioenergy

7.1. Second-generation biofuels

The first-generation of biofuels currently produced from sugars, starches and vegetable oils gives rise to several issues: these raw materials compete with food for their feedstock and fertile land, their potential availability is limited by soil fertility and per hectare yields and the effective savings of CO_2 emissions and fossil energy consumption are limited by the high energy input required for crop cultivation and conversion (Marris, 2006; Lange, 2007). These limitations can be partly overcome by the utilization of lignocellulosic materials, such as residues from agriculture, forestry and industry and dedicated lignocellulosic energy crops. In fact, results from Table 6 show that grain- and seed-based biofuels (first-generation biofuels) provide modest GHG mitigation benefits, when compared to petroleum-based fuels; they have rather high costs, and will be able to provide only modest level of fossil fuel displacement in the long-term due to high land requirements. The main reason for the relatively poor performance of grains and seeds is that the utilized fraction represents only a small portion of the above ground biomass (e.g. rapeseed grain yield is 3.4 t/ha but the oil content of the grain is only 40%, thus the ‘effective’ yield is reduced to 1.35 t/ha (Venturi and Venturi, 2003)). Among biofuels commercially available today, sugarcane bioethanol gives the highest land use efficiency for GHG mitigation, and is therefore an attractive biofuel from a GHG emission point of view.

The prospective ‘next’ (often called second) generation biofuels (i.e. FT-diesel from biomass and bioethanol from lignocellulosic feedstock) promise advantages over first-generation biofuels in terms of land use efficiency and environmental performance. The term second-generation shows wide variation in usage and can variably refer to feedstocks (lignocellulosic material), conversion routes (thermochemical, flash pyrolysis, enzymatic, etc.) and end products (gas or synthetic liquid biofuels); few LCA studies on second-generation biofuels are currently available (Baitz et al., 2004; Reinhardt et al., 2006; Jungbluth et al., 2007a,b,c). A recent LCA study, conducted on FT-fuel production from forest residues via gasification followed by FT-synthesis, estimates that such a bioenergy system can save up to 88% GHG emissions if compared with a fossil reference system (Jungmeier et al., 2007). Thanks to technology development, second-generation biofuel production could make use of high quantities of lignocellulosic residues and wastes which are already available: they can constitute the main raw material sources, which can be also supplemented with non-food crops such as perennial grasses, and short rotation forestry, grown on abandoned or marginal agricultural land. Many second-generation biofuels coming from biomass wastes and residues are at a pre-commercial stage, but could enter the market within 10–15 years if corresponding investments (R&D, infrastructure) and policy incentives and regulations (e.g. increase of biofuel share in conventional gasoline and diesel) are achieved. On the one side the raw material situation is optimum: widespread, relatively cheap and easily available; on the other side, their use could allow the co-production of valuable biofuels, chemical compounds as well as electricity and heat, leading to the development of biorefineries (see subsequent paragraph) (Kamm et al., 2006).

Since competition for biomass resources will be inevitable, it is important to make a selection of the best applications able to ensure the greatest GHG emission savings for the limited available biomass resources. The issue is whether biomass should be used as a biofuel in stationary energy systems for CHP or as a feedstock for transportation liquid biofuel production. Two independent studies analysed this topic by developing different energy economy models which arrived at diverging results (Azar et al., 2003; Gielen et al., 2003). Azar et al. reveal that it is more cost effective to use biomass as a replacement of fossil fuels in power and heat production, while Gielen et al. find that the most cost effective use of biomass is in the generation of transportation liquid biofuels (see Grahn et al., 2007, for discussion of the main differences between these two models).

7.2. Biorefinery

The term “biorefinery” is gaining prominence in the scientific community; the concept embraces a wide range of technologies able to separate biomass resources (wood, grasses, corn . . .) into their building blocks (carbohydrates, proteins, fats . . .) which can be converted to value added energy and material products. A definition of biorefinery was recently formulated by IEA Bioenergy Task 42 on Biorefineries (IEA, 2008):

> “Biorefining: the sustainable processing of biomass into a spectrum of marketable products and energy”.

Therefore, a biorefinery can be seen as a facility that integrates biomass conversion processes and equipment to produce biofuels, power, and chemicals from the all above ground biomass. The biorefinery concept is analogous to today’s petroleum refinery, which produces multiple fuels and products from petroleum. Unlike petroleum, biomass composition is not homogeneous, because feedstocks might be made of grains, wood, grasses, biological wastes and so on. This biomass compositional variety is both an advantage and a disadvantage. An advantage is that biorefineries can make more classes of products than can petroleum refineries and can rely on a wider range of raw materials. A disadvantage is that a relatively larger range of processing technologies is needed (Dale and Kim, 2006).

The main benefits which can be related to an extensive deployment of biorefineries in replace of oil refineries are based on the supply of renewable biomass. In fact, if this is managed with sustainable practices, biomass feedstocks are renewable resources that are locally available for many countries and their provision, together with an implementation and development of biorefinery industries, will decrease the dependence on fossil fuels, reduce GHG emissions and create a large number of jobs, especially in rural areas.

Therefore, biorefinery technologies should be widespread, compact and suitable for local installations. Biorefinery represents a change from the traditional refinery based on exploitation of natural resources and substantial waste production towards integrated systems in which all resources are used. An example of how the biorefinery of the future may evolve can be found in the history of the existing corn wet milling industry (Lasure and Ming, 2004). Initially the corn wet milling industry produced starch as the major product. As technology developed and the need for higher value products drove the growth of the industry, the product portfolio expanded from various starch derivatives such as glucose and maltose syrups to high fructose corn syrup, as well as fermentation derived products like ethanol, lactic acid, citric acid, glucanic acid and others. Many other by-products, such as corn gluten, corn oil, corn fiber and animal feed are now being produced. The final vision is the development of technical, commercial and political infrastructures for a biomass refinery (biorefinery) able to replace products of the current oil refinery. Over the next 10–15 years, it is expected that lower cost residue and waste sources of cellulosic biomass will provide the first influx of next-generation feedstocks, with cellulosic energy crops expected to begin supplying feedstocks for biofuel (and chemical) production towards the end of this time frame, then expanding substantially in the years beyond (Worldwatch Institute, 2006).

Altough no LCA studies of biorefinery systems have been published in the scientific literature, preliminary studies suggest that a lignocellulosic biorefinery system producing bioethanol, electricity, heat and phenols from forest wood residues can save up to 60% GHG emissions, if compared with its fossil reference system (including the decrease in forest carbon pools due to residue collection) (Cherubini and Jungmeier, 2008).

Despite of the limited scientific literature available, it can be argued that LCA of biorefineries will stress the importance of some key issues like the choice of the functional unit and allocation method. In fact, biorefinery systems are characterized by multiple high value products, both bioenergy carriers and materials. Therefore, particular attention is required in the choice of the functional unit and the allocation criterion. Concerning the functional unit, it cannot be related to the unit output, because the choice of one of the different high value products as main product is an arbitrary decision. Results can be expressed per unit of agricultural land (when feedstock is a dedicated crop) or per unit of biomass input (when residues are processed) or per reference year.

The allocation issue should also be handled with care. Even if ISO standards suggest to avoid allocation by expanding system boundaries (when possible), it is not recommended when a large number of high-quality outputs is produced (and even in this case the choice of a main product would be arbitrary). Alternative allocation criteria should be tested and the results compared in a sensitivity analysis.

8. Conclusions and recommendations

This paper explains that determination of energy balance and GHG emissions from bioenergy is complex, and different combinations of feedstocks, conversion routes, fuels, end-use applications and methodological assumptions lead to a wide range of results.

The main technical aspects emerging from this paper can be summarized as follows:

- Each bioenergy system (especially those based on dedicated energy crops) should avoid the depletion of carbon stocks or, at least, any decline in C stock of any pool should be taken into consideration in calculating the GHG mitigation benefits of the system.
- Perennial grasses like switchgrass and *Miscanthus* can enhance carbon sequestration in soils if established in set-aside and annual row crop land, thus increasing the GHG savings of bioenergy systems.
- LCA results of bioenergy from dedicated crops should be expressed on a per hectare basis, since the available land for production of biomass raw materials is the biggest bottleneck.
- LCA results of bioenergy system based on biomass residues should be expressed on a per unit output basis, if there is the need to be independent from the kind of biomass feedstock, or per unit input basis, in order to be independent from the final products and conversion processes.
- LCA results of transportation biofuel production should be expressed per km basis, in order to take into account engine mechanical efficiencies, type of fuel and emissions from combustion (which are relevant for fossil reference systems based on conventional fossil fuels).
- The production of liquid biofuels usually requires more fossil energy inputs than the generation of electricity and heat from biomass.
- As a consequence, electricity or heat generation from biomass may achieve larger GHG and fossil energy savings per hectare devoted to biomass production, than production of transportation biofuels.
- Bioenergy chains which have wastes and residues as raw materials show the best LCA performances, since they avoid both the high impacts of dedicated crop production, and the emissions from waste management.
- Given constraints in land resources and competition with food, feed and fiber production, high biomass yields are extremely important in achieving high GHG emission savings, although use of chemical fertilizers to enhance production can reduce the savings.
- Fossil energy savings and GHG mitigation will be increased if agricultural co-products (bagasse, straw . . .) and process residues (DDGS, lignin, char . . .) are also used for energy production to run the biomass conversion plants.
- However, when agricultural residues are collected from fields and used for bioenergy production, the effects of the removal on that particular soil type cannot be neglected and the GHG implications (i.e. lower yields, N_2O emissions from land and decline in soil carbon pools) should be accounted for when compiling the overall balance of the bioenergy system.
- High biomass conversion efficiency to energy products is fundamental for maximising GHG emission savings.
- A lower degree of savings is achieved when power from natural gas or cogeneration sources are displaced; high emission savings rate is achieved when coal-generated power, especially with low efficiency, is displaced.
- The initial use of biomass for products, followed by use for energy ('cascading'), especially in the case of wood, can further enhance GHG savings given scarce resources of biomass and/or land.

Biofuels can contribute to GHG mitigation strategies in transport sector only if significant emissions from land use change are avoided and appropriate production technologies are used.

All the key issues and methodological assumptions discussed in the paper prevent an exact quantification of the GHG emission savings or fossil energy consumption avoided through the use of bioenergy, because too many variables are involved. Some of the key parameters such as changes in soil carbon pools and nitrous oxide emissions from soils are not well known and uncertainties cannot be completely avoided. Therefore, the presentation of LCA comparing results by means of probable ranges is preferred.

The vast majority of biomass used worldwide falls into the category of traditional biomass fuels, characterised by often unsustainable production, and low conversion efficiencies. GHG mitigation strategies in this case must focus on efficiency improvements, and on the replacement with renewable (modern) biomass energy sources, as well as other renewables and high-efficiency use of fossil fuels, for example in cooking applications.

Even if a reduction of GHG emissions and fossil energy consumption from bioenergy compared to their fossil reference system can be achieved, it should be always kept in mind that the production of bioenergy can cause higher environmental impacts (local air pollution and eutrophication, among others) than fossil fuels. The evaluation of such trade-offs involves weighting greenhouse gas emissions in relation to other environmental impacts. Such judgements are often locally specific and go beyond the scope of this paper.

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