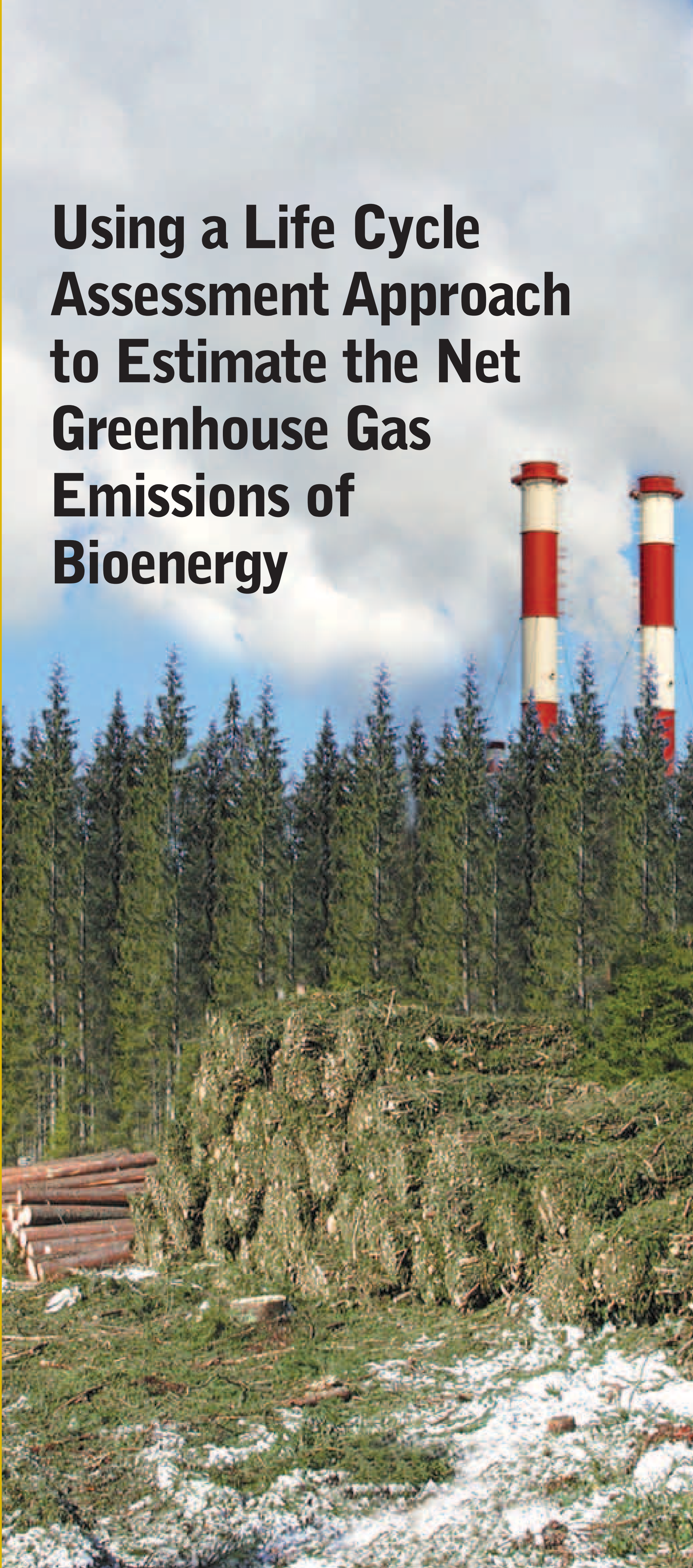
Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy



This strategic report was prepared by Mr Neil Bird, Joanneum Research, Austria; Professor Annette Cowie, The National Centre for Rural Greenhouse Gas Research, Australia; Dr Francesco Cherubini, Norwegian University of Science and Technology, Norway; and Dr Gerfried Jungmeier; Joanneum Research, Austria. The report addresses the key methodological aspects of life cycle assessment (LCA) with respect to greenhouse gas (GHG) balances of bioenergy systems. It includes results via case studies, for some important bioenergy supply chains in comparison to fossil energy systems. The purpose of the report is to produce an unbiased, authoritative statement aimed especially at practitioners, policy advisors, and policy makers.

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USING A LIFE CYCLE ASSESSMENT APPROACH TO ESTIMATE THE NET GREENHOUSE GAS EMISSIONS OF BIOENERGY

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KEY MESSAGES

1. Life Cycle Assessment (LCA) is used to quantify the environmental impacts of products or services. It includes all processes, from cradle-to-grave, along the supply chain of the product or service. When analysing the global warming impact of energy systems, greenhouse gas (GHG) emissions (particularly CO_2, CH_4, and N_2O) are of primary concern.

2. To determine the comparative GHG impacts of bioenergy, the bioenergy system being analysed should be compared with a reference energy system, e.g. a fossil energy system.

3. A reference energy system should be chosen that is realistically likely to be displaced by the bioenergy system. If this reference system is not certain, then one option is to use as the reference energy system the average fossil energy for that region. Another option is to make a conservative evaluation by comparing the bioenergy system with the best available fossil energy technology. Alternatively, a non-fossil option may be selected as the relevant reference energy system. Depending on the context of the study, this might be another renewable option or nuclear power.

4. The scope of the analysis (system boundary) should include all processes along the value chain with significant GHG emissions, including, where relevant, upstream processes of extraction or biomass production, and end-of-life processes.

5. The system boundary should be defined so that the bioenergy and reference fossil systems provide equivalent products and services. If it is not possible to achieve this through expansion of the system boundary then the GHGs can be allocated amongst energy and non-energy co-products of the bioenergy system (such as biodiesel and rapeseed cake, from processing of rapeseed oil), based on their share of physical (for example energy) or financial contributions.

6. Changes in carbon stocks in biomass, soil, and landfill can cause GHG emissions (or removals). These can be very important and should be included in the analysis.

7. In general, LCA is not concerned with the time at which the environmental impacts occur. However, in some cases bioenergy systems cause short-term GHG emissions due to the accelerated oxidation of carbon stocks through combustion as compared to natural decay. While this can affect short-term GHG targets, over a long-term perspective sustainable bioenergy causes less GHG emissions than comparable fossil energy systems.

8. Use of agricultural residues may affect GHG emissions through either changes in soil organic carbon (SOC) or land use changes that occur indirectly, in order to provide the equivalent services that the residues were providing. Exploitation leading to soil productivity losses may require compensating fertilisation (causing GHG emissions) to maintain yield levels and can also cause cropland expansion elsewhere to compensate for yield losses if these occur.

9. The type of technology, scale of plant, and co-products in both the bioenergy and reference energy system can influence the GHG mitigation benefits of the bioenergy system. Since small changes in methodological assumptions and input parameters can have large effects on the estimated environmental impacts, the bioenergy and reference systems should be described and assumptions listed in a transparent manner.

Cover Picture: *Harvesting sawlogs and forest residues in Finland. Thermal power station in background.*

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EXECUTIVE SUMMARY

Life cycle assessment (LCA) is a powerful tool that may be used to quantify the environmental impacts of products and services. It includes all processes, from cradle-to-grave, along the supply chain of the product. When analysing energy systems, greenhouse gas (GHG) emissions (primarily CO_2, CH_4 and N_2O) are the impact of primary concern. In using LCA to determine the climate change mitigation benefits of bioenergy, the life cycle emissions of the bioenergy system are compared with the emissions for a reference energy system. The selection of reference energy system can strongly affect the outcome.

When reviewing the literature one finds large ranges of GHG emissions per unit of energy from LCA studies of similar bioenergy systems. The differences occur for a multitude of reasons including differences in technologies, system boundaries, and reference systems. Some studies may be incomplete in that the bioenergy system and reference system provide different services. Others may omit some sources of emissions (e.g. land use change).

This paper discusses key criteria for comprehensive LCAs based on IEA Bioenergy Task 38 case studies. LCAs of the GHG balance of four different bioenergy systems and their counterpart reference system are highlighted using the case study examples.

The first example investigates heat production from woody biomass and grasses. This study shows that the emissions saved for the same type of service can vary due to the source of the biomass. The bioenergy systems studied reduce GHG emissions by 75-85% as compared to the counterpart reference systems.

In the second example, electricity is produced from woody biomass using two different technologies with different efficiencies. Depending on the technology, the biomass must be transported different distances. The example illustrates the importance of the efficiency of the system and the small impact of soil organic carbon (SOC) decline in comparison with emissions saved. Since the bioenergy systems include carbon sequestration, they reduce GHG emissions by 108-128% as compared to the counterpart reference systems.

A biogas plant providing combined heat and power is analysed in the third example, which illustrates the importance of finding a beneficial use for the heat produced, and of controlling fugitive emissions. In the optimal configuration of closed storage and maximised use of heat, the biogas system reduces emissions by 71% as compared to the counterpart reference system. This reduction decreases to 44% when the heat is not fully used and to only 27% if fugitive emissions are not controlled.

In the final example the bioenergy system provides biodiesel for transport. This example demonstrates the importance of the use of co-products, as the same bioenergy chain produces very different emissions savings per kilometre depending on whether the co-product is used as a material or combusted for energy. Compared to the reference system, the bioenergy systems reduce GHG emissions by 18% and 42% when the co-products are used for energy or materials respectively.

Similar to the case studies presented here, published studies find that GHG mitigation is greater where biomass is used for heat and electricity applications rather than for liquid transport fuels. Overall, the emissions savings from bioenergy systems tend to be similar to that of other renewable energy sources.

1. WHY COMPREHENSIVE LIFE CYCLE ASSESSMENTS ARE IMPORTANT

In the 21st century, climate change mitigation and energy security are important aspects of energy policy. The potential to reduce GHG emissions by replacing fossil fuels such as oil, gas and coal with fuels derived from renewable biomass sources is a significant driver for the promotion of bioenergy. The GHG balances of bioenergy systems should be compared with those of fossil and other renewable energy sources such as wind and solar to underpin decisions on energy policy, land use and utilisation of biomass resources.

LCA, which includes all processes from manufacture through to disposal, is used to quantify environmental impacts of products or processes. Prompted perhaps by the variety of processes for converting biomass resources to bioenergy for heat, electricity or transportation services, and the vigorous discussion of the 'net benefit' of bioenergy, many studies have been undertaken worldwide using LCA methodology to analyse the GHG and energy balance of various bioenergy systems. LCA studies have also been published for other renewable energy options such as wind and solar, and for fossil fuel (oil, gas, and coal) systems providing various energy services. It should be noted that energy systems modelling can also contribute important complementary information to LCA comparisons by evaluating bioenergy options in a broader context to depict development of the total energy system.

The GHG balances of bioenergy and other energy systems depend on a large number of factors, components and assumptions. There are numerous sources of biomass, with different yields and production practices. As well, the same biomass may be used in a myriad of conversion technologies, transportation and distribution processes and end-use technologies. For these reasons, it is very important that the LCA comparison clearly describes both the system being studied (hereafter referred to as the study system); and the system that the study system is being compared with (hereafter referred to as the reference system). Both systems should provide the same level of services and the analysis should include all relevant, significant sources of GHG emissions (and removals) and energy uses. Otherwise, the LCA may be comparing 'apples and oranges' and result in misleading conclusions.

The aim of this technical paper is to summarise and outline the key methodological aspects of LCA with respect to GHG balances of bioenergy systems and include results for some important bioenergy supply chains, in comparison to fossil energy systems. These methodological aspects will be highlighted using case studies conducted by Task 38.

2. METHODOLOGY OF LIFE CYCLE ASSESSMENT

2.1 Introduction

A LCA involves the investigation and evaluation of the environmental impacts of a given product or service, based on the identification of energy and materials inputs and emissions released to the environment. In LCA, the environmental impacts are calculated over the entire lifetime of the product 'from cradle-to-grave' – hence the name 'life cycle'.

Figure 1 shows, for the case of biofuel, the main stages in the life cycle of a product from resource extraction, processing and transport through use and disposal.

A more detailed diagram of the life cycle stages in energy systems is shown in Figure 2. In this diagram, the resource extraction phase is composed of two stages – land use change or facility construction and cultivation or collection or resource extraction. In addition, processes for the transportation of raw biomass or fossil resource to a conversion facility and the distribution of the processed energy carrier to the end user are included. The diagram is more complicated than Figure 1 because it includes co-products. Co-products are goods or services that are provided by the system, in addition to the main service or product. For example, straw used for silage or bedding is a co-product from a grain crop; dried distillers grains with solubles (DDGS), used as animal feed, is a co-product of ethanol production. Disposal of waste products from the conversion process (for example, sludge from biodigesters) is also included in LCA. Some wastes are used beneficially thereby displacing other products (for example, ash from a thermal process applied as fertiliser reduces the need for commercial fertilisers) illustrating that 'one man's trash is another man's treasure'.

The International Standards Organisation (ISO) has published a series of standards for LCA (ISO 14040, 14044). As defined in ISO 14040, a typical LCA study has the following structure:

1. ***Goal and scope definition:*** This phase is used to define and describe the object of the analysis, establish the context in which the assessment is developed, discuss assumptions and data quality, and identify system boundaries and the environmental effects to be assessed. While LCAs of goods and services may consider a range of environmental impacts, including for example, abiotic resource depletion*, acidification and eutrophication potential, and human toxicity potential, it is common for LCAs of energy products to consider solely the global warming impact and energy balance.

2. ***Life cycle inventory (LCI):*** This phase involves compilation of data on energy, material flows, and emissions to the environment in all phases of the life cycle. The result of this phase is an inventory of all inputs and outputs in the form of elementary flows to and from the environment for all the processes involved in the study (for example, inputs of fertiliser, pesticide, fossil fuels, and outputs of products, wastes, and emissions to air such as particulates and the GHGs; CO_2, CH_4, and N_2O).

3. ***Life cycle impact assessment (LCIA):*** Here the impacts associated with the service under study are evaluated in terms of impact categories. For example, the global warming impact is determined by summing the emissions of all GHGs, each expressed in carbon dioxide equivalents (CO_2-eq) calculated from their relative global warming

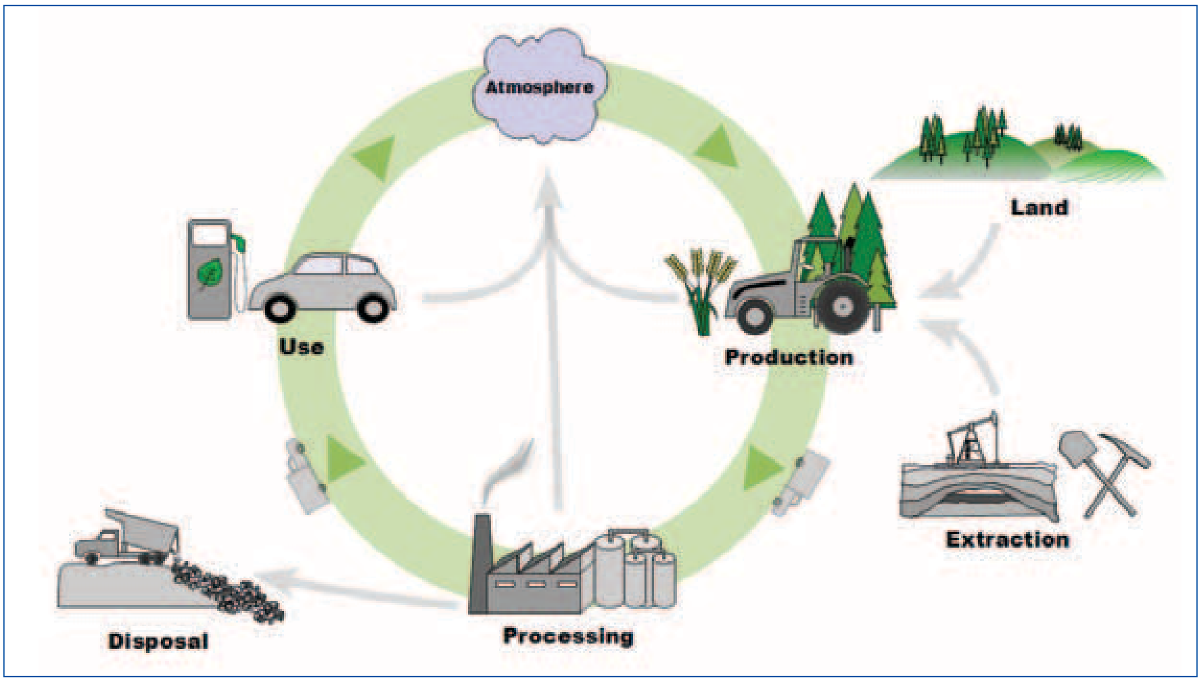

Figure 1. A simplified illustration of the main life cycle stages for a bioenergy system. The green circle represents the carbon cycle, the grey arrows show inputs and outputs from the bioenergy system. This simplified diagram does not attempt to show all carbon fluxes.

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*Abiotic depletion – Abiotic resources are natural resources such as iron ore and crude oil, which are regarded as non-living. Abiotic depletion is calculated based on estimates of reserves and rates of extraction of these resources to indicate the level of resource depletion.

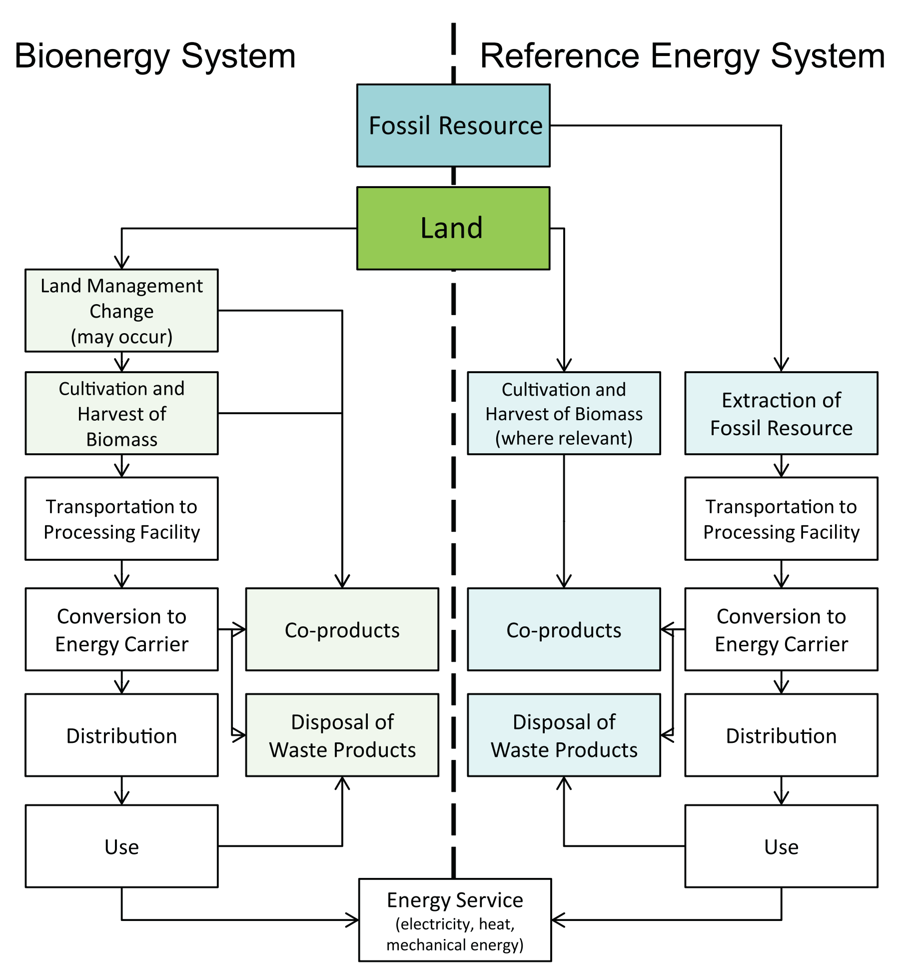

Figure 2. The life cycle stages of typical energy systems. The construction and dismantling of all facilities is not specifically shown in this diagram. However, the GHG emissions from these activities must be included.

potentials (GWP). Multiple impact categories can be combined using weighting to give an overall impact assessment (for example EcoIndicator 95, and ReCiPe). However, this is not considered further in this paper which focuses only on climate change impacts.

4. *Interpretation:* The final step is the interpretation of the results from the previous phases of the study in relation to the objectives of the study.

2.2 Comparing GHG emissions and energy usage of energy systems

Even though LCA can be used to analyse the environmental impacts of an individual product or service it is more commonly used to compare the impacts of two or more products or services. This is how LCA is used in Task 38 to compare bioenergy systems being studied to a reference fossil energy or bioenergy system. When comparing systems, one must take care that the comparison is valid. Otherwise, there is the risk that the comparison is between 'apples and oranges'.

2.2.1 Choice of reference system: The choice of the reference system to which the bioenergy system is compared is critical since the estimated benefits of bioenergy can differ widely depending on the assumed energy system replaced. For instance, fossil-derived electricity might be produced from oil, natural gas or coal, all of which have different GHG emissions per kWh of electricity generated. It would be misleading to calculate the GHG emissions caused by the bioenergy system and compare these to GHG emissions for an unrealistic fossil energy system. Ideally, in the most realistic evaluation, the bioenergy system should be evaluated against the energy system most likely to be displaced. However, in many real-life systems it is difficult to know which energy source will be replaced.

One option is to estimate the GHG emissions savings of the bioenergy system by comparing it to the average fossil energy system. Another option is to make a conservative evaluation by comparing the GHG emission of the bioenergy system with the GHG emissions for the best available fossil energy technology. For example, it could be assumed that electricity in the fossil fuel reference system is produced from natural gas (the lowest emission fossil technology), rather than coal. Since natural gas-generated electricity has a GHG emission factor of around 400 g CO_2-eq/kWh (110 g CO_2-eq/MJ) compared with 990 g CO_2-eq/kWh (240 g CO_2-eq/MJ) for coal-based electricity (see Figure 4, page 15, and *http://www.commodities-now.com/component/attachments/download/327.html*), assuming natural gas was being displaced would give a conservative estimate of emission reduction.

2.2.2 System boundary: In LCA, one must define the system boundary, outside which environmental impacts are ignored. The setting of the system boundary is very important and differences in system boundaries are often a major source of discrepancy between different analyses. The system boundary must include all life cycle stages, significant energy uses, material flows and GHG emissions in both the study and the reference system. In addition, for a valid comparison, the system boundaries should be set so that the same energy and product services are provided by both the bioenergy study and fossil energy reference systems.

As shown in Figure 2, both energy systems start with the same resources (land and fossil fuel) and both provide the same energy service. However, the paths from resource to service of the two systems are quite different.

The reference system includes the following process steps: construction of extraction facilities (optional); extraction of the resource; transportation of the resource to a conversion facility; conversion of the resource into an energy carrier that can be used by the user; distribution of the energy carrier; and use of the energy carrier to provide a service. If the fossil system is designed to provide a transportation service, then the fossil resource may be crude oil transported by pipeline or boat to a petroleum refinery that converts the crude oil to gasoline. The gasoline would then be distributed to gas stations for use in gasoline-powered vehicles to provide a transportation service.

The study system has process steps that are equivalent. Land use change should be included if the system requires a change in land management practices or a different biomass type than was originally on the land. This is equivalent to constructing the fossil extraction facility. The biomass that will be used as a feedstock must be cultivated and collected and transported to a conversion facility. Here it is converted into an energy carrier that is distributed to a user to be used to provide a service. Bioethanol derived from corn is an example of an energy carrier that is analogous to gasoline (the reference system). The land use change incurred could be pasture converted to cropland for the production of corn. Production of corn involves cultivation, using inputs such as diesel, fertilisers and pesticides. The corn is harvested and transported to the ethanol plant. At the plant, the corn is processed to ethanol, which is then distributed to gas stations and used in a vehicle.

Up to now, the paper has described two systems that provide the same energy service. In the bioenergy case, biomass is used to supply energy. To properly account for the differences between the study and reference systems one should consider what would have happened to that biomass in the reference case, when fossil fuel is the energy source. If the biomass for bioenergy is obtained from purpose-grown crops one should consider how that land would have been used in the reference system. This is why 'land' is included in both sides of Figure 2. For example in the reference system, the land may have originally been used as pasture for dairy cattle, producing dairy products. Thus dairy products are co-products of the reference system. In the bioenergy system, co-products should also be considered: the ethanol production process also produces dried distillers grains and solubles (DDGS), which can be used as feed for cattle. As such, the two systems are not strictly comparable.

In general, Task 38 (and ISO) considers it best practice to expand the system boundary of both the study and reference systems to include all significant sources of GHG emissions and energy uses, and assure equivalent services and co-products. This procedure is called system expansion. In the example above this would require consideration of an alternative source of feed for the dairy cattle. The DDGS could be a partial substitute

2.2.3 Comparing systems with different products:
If system expansion is not practical then the environmental impacts may be allocated between the main energy service and co-products in proportion to their functional or physical parameters (such as energy content of outputs) or to their economic value. For example, consider a bioenergy system producing 2 kg of rape cake with every 1 kg of biodiesel. If the energy content of rape cake is 52% of the total energy output then 52% of the GHG emissions associated with the system will be allocated to the rape cake and 48% to the biodiesel.

There are ongoing discussions about the 'best' allocation procedure and scientific publications show the benefits and disadvantages of alternative methods. The European Union's Renewable Energy Directive uses allocation by energy content to distribute emissions between co-products.

2.2.4 Units for comparison - functional units: Comparing the two systems requires some metric for the comparison. In LCA terminology, this is called the functional unit. It provides a reference to which the input and output process data are normalised. The results of the comparison are expressed in terms of the same functional unit, to ensure that the comparison of different systems is based on the delivery of the same service. There are two main types of functional units: input-related or output-related.

Input-related functional units: The question of relative land use efficiency for different biofuel pathways is often not addressed in LCAs. However, Task 38 recommends that the GHG emissions and energy balances of bioenergy systems are expressed on a per hectare basis, since the availability of land is the biggest bottleneck for the production of biofuels. Using input-related functional units answers the following questions:

- What amount of GHG emissions and fossil energy might be saved by using one biomass input unit (i.e. kg CO_2-eq saved/ kg biomass)?
- What amount of GHG emissions and fossil fuels can be saved per hectare by cultivating energy crops on agricultural land or harvesting forests for wood fuel (i.e. kg CO_2-eq saved/ha)?

Output-related functional units: Output-related functional units answer the question:

- What amount of GHG emissions and fossil energy might be saved by providing the same energy service from bioenergy?

Output-related functional units depend on the type of energy service provided by the bioenergy system. For example a typical functional unit for heat is g CO_2-eq saved / kWh_{heat}; for electricity it is g CO_2-eq saved/$kWh_{electricity}$; and for transportation g CO_2-eq saved / passenger-km.

The impact per unit of energy in the final energy carrier, e.g. per MJ of transportation biofuels, is not an adequate functional unit as it does not reflect the possible different efficiencies in the use of the energy carrier. For example, a car may travel further per MJ of gasoline than per MJ of ethanol because the internal combustion engine has been designed and calibrated for gasoline use; the fuel conversion efficiency may remain the same for lower ethanol blends such as E10 but may become lower for higher ethanol blends.

2.2.5 Changes in land management and use: Changes in land management and use can have significant impacts on GHG emissions associated with bioenergy supply chains. The new bioenergy land use may store a different amount of carbon than the original non-bioenergy land use. If there is a loss of carbon, in biomass or soil, then this is equivalent to a CO_2 emission. If instead there is a gain in biomass/soil organic carbon (SOC), then GHG savings are enhanced since CO_2 is removed from the atmosphere (sometimes designated 'negative emission'). A change in land use to produce biomass for bioenergy, for example, a shift from wheat to switchgrass cultivation, is a direct land use change (dLUC) and this is included within the system boundary of the LCA.

The term 'indirect land use change' (iLUC), refers to changes in land use that occur outside the system boundary due to the displacement of services (e.g. food production) that were previously provided on the land now used for bioenergy. Let's say Farmer A converts from growing wheat to growing switchgrass – an example of dLUC. This dLUC may result in iLUC since the reduced wheat availability drives up the wheat price, leading to somewhat reduced wheat demand and also increased wheat production elsewhere. If Farmer B converts his pasture to wheat cropping as a consequence of the action of Farmer A, CO_2 emissions may occur due to the ploughing of pasture land inducing SOC oxidation. This loss of SOC stock is referred to as an iLUC emission – it occurs at a site not directly affected by the biomass production, outside the control of Farmer A, and therefore outside the system boundary of the bioenergy system.

Most so-called attributional LCAs have up to now not considered iLUC and other indirect effects. As the dynamic effects of bioenergy expansion have become increasingly discussed, this omission has resulted in criticism of such bioenergy LCAs. In so-called consequential LCAs – that analyse bioenergy systems in the context of the economic interactions, chains of cause and effect in bioenergy production and use, and effects of policies/other initiatives that increase bioenergy production and use – attempts are made to consider indirect effects (primarily iLUC). However, quantifying emissions due to iLUC is very difficult because, as there is no direct link, it is not possible to identify which land use change is a result of a specific bioenergy system, nor which land use change is due to other causes, such as increased demand for food by the growing global population, or urban expansion. To determine emissions due to iLUC it is necessary to consider complex inter- and intra-sector interactions and trends, including regional and global deforestation, diets including responsiveness to food prices, cropland expansion and trade of food, feed, fibre and bioenergy, and so calculate iLUC on a regional or sectoral basis.

Measures can be taken to minimise iLUC associated with bioenergy, for example, by using biomass that is considered waste, or land that is not under agricultural production. Specific measures include:

a) lowering biomass demand through options such as stringent bioenergy efficiency requirements and efficient biomass-to-energy conversion;
b) using wastes/residues as biomass sources for bioenergy;
c) increasing biomass yield per hectare;
d) increasing intensity of production on other land remaining under agricultural use;
e) using co-products as animal feed;
f) using unproductive land (set-aside, fallow, degraded or otherwise marginal land) for energy production; and
g) integrating biomass production with agricultural land uses, such as through agroforestry.

Some of these measures are general requirements for optimising bioenergy systems but they may also mitigate food sector impacts resulting from the introduction of a bioenergy system. However, the consequences for land use change and the food sector will depend on the overall context, including existing policies. For instance, requirements for efficient biomass-to-energy conversion lower the biomass use per unit energy service provided, but also make biomass more valuable as bioenergy feedstock and this might instead increase the land pressure (and land price, and therefore food price) as biomass demand increases. If targets are set for specific bioenergy contributions then bioenergy efficiency requirements lower the volume of biomass needed to reach the target. If instead CO_2 targets or general renewable energy targets are used – and if more cost competitive bioenergy options become available – then more bioenergy will be used. In such a scenario, the GHG mitigation costs will be lower, but land use competition and pressures on valuable natural ecosystems may increase. In the absence of instruments discouraging conversion of carbon-rich land, the net effect may even be that land use change emissions increase.

It will be important that increased intensity of production (measures c and d above) do not result in unsustainable land use practices, or perverse outcomes such as increased net GHG emissions due to higher nitrous oxide emissions from additional nitrogen fertiliser inputs intended to increase biomass yields.

This paper has focused on iLUC in agriculture, but it can also be an issue with forestry. For example, the diversion of forest biomass from household heating to electricity production may cause iLUC to supply biomass for household heating, as the household will need to replace their fuel wood with another source. It is important to note that iLUC can also be an issue for other renewables. For example, the flooding of a river valley for a hydro-electricity project will cause iLUC to replace all services that the valley originally produced (agriculture, wood products).

For a more complete discussion of dLUC and iLUC, see the IEA Bioenergy publication (Berndes *et al.*, 2010) listed in Section 6 'Recommended Reading'.

2.2.6 Timing of emissions and removals: LCA is usually concerned with total environmental impacts over the entire lifetime of a process or service. Therefore, in conventional LCA it is commonly assumed that timing of emissions and removals is not important: the same weight is given to emissions that occur in the past, present and future. Thus, in LCA the total emissions from a process, including its establishment phase, are often amortised over the lifetime of the process. However, when operating a bioenergy system, there may be GHG emissions that occur primarily in the early stages (e.g. from combustion of living biomass, decay of soil organic matter, and accelerated oxidation of carbon stocks through combustion as compared to natural decay due to utilisation of harvest and wood processing residues), even when the land is being sustainably managed in the long run. Compensation for these emissions through carbon removals from the atmosphere may take some time; a new dynamic equilibrium will be reached, governed by dynamic ecosystem processes associated with the next rotation (e.g. forest growth and soil organic matter dynamics) and the energy and bio-based products that are harvested (i.e. the fate of products and wastes). During the transition to a new equilibrium carbon balance, there will either be a net emission of CO_2 if carbon stocks are lower in the new land use, or there will be a net removal of CO_2 from the atmosphere if carbon stocks increase to a higher level under the new land use.

There is agreement that over the long-term, bioenergy reduces GHG emissions when compared to fossil energy. However, the points made above regarding the timing of emissions and removals indicate that it may take several decades for atmospheric carbon removal by slow-growing forests to compensate for emissions that occur early in the life of a newly installed bioenergy scheme that utilises biomass from existing forests and wood products. Nevertheless, it is important to consider long-term climate objectives and encourage the establishment of bioenergy systems that can be demonstrated to provide a low carbon, GHG-friendly energy supply in the future.

2.3 Data requirements

The key data requirements for the calculation of the GHG and energy balance in the bioenergy system are listed in Table 1. Many parameters are system specific although some parameters such as the GHG emissions and energy balance for fertiliser, herbicide and pesticide production can be obtained from LCA databases such as ECOINVENT*, ELCD†, GEMIS‡ or US LCI§. Of course, similar information is also required for the fossil reference system (Table 2).

2.4 Quantifying environmental impacts

In LCA, all environmental impacts may be assessed. However, the work of Task 38 has typically focussed on two key assessment variables: GHG emissions and the primary energy usage. This report places principal focus on GHG balances and will report energy usage data in less detail.

GHG emissions: The most important GHGs in energy systems are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

Carbon dioxide (CO_2) is the main product of the combustion of fossil fuel and biomass. The amount of CO_2 emitted per energy unit depends – amongst other things – on the carbon content and heating value of the fuel. In the biosphere, CO_2 is removed from the atmosphere by growing plants, through photosynthetic production of carbon compounds and their subsequent accumulation in plant biomass. CO_2 is also produced by the aerobic degradation (decay) of biomass. Carbon stock changes that occur because of land use changes are converted to CO_2 by multiplying by the ratio of the molecular weights of CO_2 to C.

Table 1: Data requirements for the GHG and energy balance of bioenergy systems

Process step (see Figure 2)	Parameters to be collected or estimated	Variable calculated
Land management change	Carbon stocks in landfill, soil, and vegetation affected by the bioenergy system	Carbon stock change due to land use change
Cultivation and harvest of biomass	Biomass yield Residue amount and use Co-products amount and type Fertiliser amount and type Herbicides and pesticides use Fuel use by machines e.g. tractor operations, pumps GHG emissions for fertiliser, herbicide and pesticide production	GHG emissions and energy input from collection and cultivation
Transportation of feedstock	Transport distance and mode Fuel use per unit distance transported	GHG emissions and energy input from transportation
Conversion to energy carrier	Auxiliary materials input Co-products amount and type Energy and material efficiency of conversion process Energy demand of conversion facility GHG emissions for auxiliary materials production	GHG emissions and energy input from conversion
Distribution	Distribution distance and mode Distribution losses (e.g. electricity grid) Energy demand of distribution system (e.g. district heating system) Fugitive GHG emissions for the distribution system (e.g. natural gas grid)	GHG emissions and energy input from distribution
Use	Energy efficiency Auxiliary energy demand Auxiliary materials input	GHG emissions and energy input from use
Disposal	Quantity and type of waste	GHG emissions from end-of-life phase

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[*] *http://www.ecoinvent.org/database/* [†] *http://lct.jrc.ec.europa.eu/assessment/data* [‡] *http://www.oeko.de/service/gemis/en/index.htm* [§] *http://www.nrel.gov/lci/*

Table 2: Data requirements for the GHG and energy balance of reference systems

Process step (see Figure 2)	Parameters to be collected or estimated	Variable calculated
Cultivation and harvest of biomass (where relevant)	Biomass yield Residue amount and use Carbon stock of soil and vegetation Co-products amount and type Fertiliser amount and type Herbicides and pesticides use Water use Energy consumption by machines e.g. tractor operations GHG emissions and energy balance for fertiliser, herbicide and pesticide production	GHG emissions and energy input from reference land use
Extraction and transportation of fossil fuel	Energy requirement in fossil fuel extraction Transportation distance and mode Energy requirements by transportation	GHG emissions and energy input from extraction and transportation
Conversion to energy carrier	Energy and material efficiency of conversion process Energy demand of conversion facility GHG emissions and energy balance for auxiliary materials production	GHG emissions and energy input from conversion
Distribution	Distribution distance and mode Distribution losses (e.g. electricity grid) Energy demand of distribution system (e.g. district heating system) Fugitive GHG emissions from the distribution system (e.g. natural gas grid)	GHG emissions and energy input from distribution
Use	Energy efficiency Auxiliary energy demand Auxiliary materials input	GHG emissions and energy input from use
Disposal	Quantity and type of waste	GHG emissions from end-of-life phase

Methane (CH_4) is a flammable hydrocarbon-compound that is the main component of natural gas, but it is also a product of incomplete combustion processes. CH_4 is also emitted during coal mining and extraction of raw oil and natural gas. In the biosphere, the anaerobic degradation of biomass produces CH_4. This occurs mostly from the management of animal and human excrement, the landfilling of organic waste and rice production.

Nitrous oxide (N_2O) is formed in combustion processes under certain conditions. The amount of N_2O emitted depends on the nitrogen content of the fuel and the combustion temperature. N_2O is also emitted as a consequence of nitrification and de-nitrification processes controlling the fate of nitrogen applied as chemical fertiliser, manure or through fixation by legumes.

Other GHGs such as sulphur hexafluoride (SF_6) and chlorofluorocarbons (CFCs) are not so important for energy systems, though SF_6 is used to test oil and natural gas pipelines for leaks.

Global Warming Potential (GWP) is used to express the contribution of different GHGs to global warming. The impacts of the non-CO_2 GHGs are expressed in terms of the equivalent amount of CO_2 (CO_2-eq). The equivalency factors of the different gases are dependent on the time period over which the equivalency is calculated since different gases have different residence times in the atmosphere. Usually the 100-year GWP factors are used. For example, one gram of CH_4 has the equivalent global warming impact as 25 g of CO_2 when a 100-year time horizon is used. Using the same time horizon, one gram of N_2O has the equivalent global warming impact of 298 g of CO_2.

3. KEY FACTORS THAT INFLUENCE GREENHOUSE GAS EMISSIONS AND ENERGY USAGE

3.1 Feedstock procurement

Choice of biomass feedstock plays an important role in the GHG emissions of the bioenergy system. In general, the use of industrial and domestic residues for bioenergy has the lowest GHG emissions from the procurement stage. Energy crops grown specifically for bioenergy have the highest emissions, due to the energy and material input, e.g. tractor use, fertiliser. Bioenergy systems based on in-field crop and forestry residues generally have intermediate emissions. However, the use of the non-energy co-products of energy crops (such as soy meal for animal feed) and the reference use of the residues must be taken into account, as these factors can enhance or counteract the GHG savings from use of bioenergy.

3.1.1 Changes in biomass and soil carbon stocks: and use change may be the most important factor that affects the GHG balances of bioenergy systems. In extreme cases, the total emissions caused by land use change in order to create the bioenergy system may be more than a 100 times greater than the annual GHG savings obtained from displacing fossil fuel consumption. As previously discussed, both direct and indirect land use change are important and need to be considered when evaluating the GHG outcome of bioenergy implementation. Some LCA studies have included the direct emissions caused by the loss of above ground biomass. Seldom have LCA studies included the emissions from indirect land use change.

Soil organic carbon: A variable that many biofuel LCA studies neglect entirely is the change in soil organic carbon (SOC) due to change in land use or land management. The amount of SOC is very site-specific and highly dependent on former and current agronomic practices, climate, and soil characteristics. At any one time, the amount of SOC 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 SOC, partly through the physical disturbance caused by tillage, which can stimulate decomposition.

A key factor controlling the amount of SOC is the frequency and duration of pasture phases because these facilitate the build-up of organic matter in the soil. Pasture periods are a time of less physical disturbance by tillage. Similarly, converting from conventional tillage of an annual crop to production of a perennial energy crop like switchgrass could result in substantial build-up of SOC over time. On the other hand, if woodlands or grasslands are converted to croplands used for cultivation of annual bioenergy crops involving frequent ploughing and tilling, SOC is likely to decrease.

Measuring changes in SOC is difficult since SOC depletion and build-up are relatively slow processes and SOC stocks are spatially variable. The few available experimental data and modelling studies indicate that short rotation perennial bioenergy crops can increase SOC 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 reduce SOC. Conversely, changed management to increase the biomass output from forests, such as forest fertilisation, can result in increased SOC. If a land use change from forest ecosystems to a bioenergy crop occurs, then the loss of SOC may be very large. In an extreme case, the conversion of tropical peatland rainforest to oil palm for biodiesel may release ~800 t C per hectare converted, equivalent to 2900 t CO_2-eq.

Landfill: Landfills also store carbon and, as for SOC, the loss of biomass in landfills as a result of the use of residues is often ignored in LCAs. By diverting biomass from landfill to energy use, carbon that would otherwise have been stored in landfill is released to the atmosphere, and this 'avoided storage' counts as a negative contribution to the mitigation value of bioenergy. However, a fraction of biomass deposited in landfills decomposes to produce methane, which has 25 times higher GWP than CO_2 (100 year time horizon). Methane emissions avoided by using biomass from landfill for bioenergy enhance the climate benefit. Estimating the impact of avoided landfill is further complicated by the introduction of methane capture systems. In some cases, the methane is flared without use. In other situations, the methane is captured and itself used for energy. In this situation, the bioenergy system may or may not be preferable to a methane capture system on a landfill; this depends on the fossil fuel displacement effect of the bioenergy system vs. the landfill methane capture system and the effectiveness of recovery of landfill gas.

3.1.2 Environmental impact of agricultural residue removal: There is an ongoing debate about the desirability of utilising crop harvest residues from agricultural cropping systems for bioenergy production. There are generally two current uses of these harvest residues: (i) removal for use as fodder or bedding for animals; or (ii) soil management where the harvest residues are either left on the surface providing a mulch, or ploughed into the soil. In the first case, the straw is a valuable co-product that needs to be replaced if the straw is used for bioenergy. For example, an alternative source of animal feed should be provided in the bioenergy system and included in the analysis. If the residue is instead used for soil management in the reference system, the removal of crop residues could increase soil erosion, and reduce SOC and nutrient content, potentially leading to soil productivity losses and lower crop yields. The effects are strongly influenced by local conditions (climate, soil type and crop management). Direct GHG effects of this removal are a decline in SOC, and possibly changes in N_2O and CH_4 emissions from soil. In addition, if the soil fertility decreases, countervailing measures – e.g. increased fertilisation to keep up the yield levels or cropland expansion to compensate for the yield losses – will likely result in additional GHG emissions. To consider such consequences the system boundaries of the bioenergy system can be expanded to include this additional crop production elsewhere. Alternatively, if the system boundary is not expanded, the additional GHG emissions may be quantified in the same way as when quantifying the effects of indirect land use change.

In conclusion, removing crop residues for bioenergy should occur only if the environmental, economic and social benefits of this use are larger than the direct and ancillary benefits of residue retention. The effects of harvest residue use on the final GHG balance should be addressed case by case using suitable models and assumptions, as they are highly variable and depend on specific local factors.

3.1.3 N_2O and CH_4 emissions from agriculture: An important variable in LCA studies is the contribution to net GHG emissions of N_2O, which is produced by microbial processes in soil, from nitrogen supplied by fertiliser application or organic matter decomposition. Emissions from fields vary depending on soil type, climate, crop, tillage method, and fertiliser and manure application rates. The actual emissions may be small. Typically only 1.0-1.5% of N in synthetic fertiliser is emitted as N_2O*. However, as noted above, one gram of N_2O has the equivalent global warming impact of 298 g of CO_2 (100 year time horizon).

The impacts of N_2O emissions are especially significant for annual biofuel crops, because fertiliser application rates are higher 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 wet soil conditions where oxygen availability is low. For example, more than 6% of applied N can be released as N_2O from sugar cane fields, in warm, moist environments.

Most studies of CH_4 emissions from ecosystems have focused on wetlands, since these are the hotspots of CH_4 production. Until recently, biological CH_4 formation was assumed to arise exclusively from anoxic environments, but there is growing evidence that terrestrial plants can also emit small amounts of CH_4 under aerobic conditions. The drier upland ecosystems are, however, normally net sinks for atmospheric

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*In 2007, these factors were criticised as underestimating N_2O emissions 3-5 fold. However, since that time this claim has been refuted.

CH_4 since CH_4 consumption exceeds production. However, under water logged conditions, some forests may switch to become CH_4 sources. Pastures and cropland may also be net sources or sinks for CH_4. There are indications that higher temperatures and water stress enhance CH_4 emissions from commonly cultivated plants. Hence CH_4 emissions from plants may become higher due to the global climate change.

Conversion of land use from cropland or pasture to woody energy crops may reduce emissions of CH_4, while conversion of forests to annual energy crops is likely to increase net CH_4 emissions. Within a LCA study, soil CH_4 fluxes usually make a relatively small contribution to the total life cycle GHG emissions of the bioenergy chain.

As with quantification of the impacts of residue removal, these 'non-CO_2' GHG emissions should be estimated for each specific case, using suitable models and assumptions, as they are highly variable and depend on local factors.

3.2 Feedstock conversion

3.2.1 Energy service provided by bioenergy: The potential for bioenergy to reduce GHG emissions differs for the three different types of energy service – heat, electricity and transportation. It is mainly determined by the conversion efficiency from biomass to energy service. In general, the energy efficiency of converting biomass to heat (70% to 90%) is higher than to electricity (20% to 40%) and transportation fuel (about 20% to 50%), if there is no credit given for non-energy co-products. This means that for the same quantity of biomass, the GHG reduction is likely to be higher when producing heat than it is for electricity and transportation fuel.

3.2.2 Status of technology: Generally, new bioenergy technologies have higher energy efficiencies and lower GHG emissions. For example, new pellet boilers have efficiencies up to 90% and quite low CH_4 and N_2O emissions compared to a 10-year old pellet boiler. However, the state of technology of the substituted fossil energy system also strongly influences the possible GHG reduction by the bioenergy system. If a combination of old coal-fired heat generation and inefficient, coal-based condensing power generation is displaced by a high efficiency biomass-fired combined heat and power system, then the change in technology may have contributed as much to the environmental benefit as the change from fossil to bioenergy.

The reader should recognise that there are both mature and developing bioenergy systems. Mature systems are those that are currently commercially available (e.g. heating systems, combined heat and power production and so-called '1st generation' transportation biofuels). Developing bioenergy systems are generally not in commercial operation. These can include both developing technologies, for example synthetic biofuels, and new feedstocks, such as *Jatropha* or algae. The data – and hence the estimates of environmental impacts – are much more reliable for commercially available systems as compared to systems under development. Data are particularly limited for bioenergy systems based on new feedstocks, so only rough estimates of possible GHG savings can be made for these at present.

3.2.3 Fate of co-products: In general, when more co-products are created from the conversion process, fewer GHG emissions will be allocated to the energy service. The non-energy co-products linked to the bioenergy systems substitute for other products on the market. For example, rape cake from biodiesel production substitutes conventional animal feed. The GHG emissions associated with the substituted products are included in the system boundary for the reference system. These are an environmental benefit since in the study system these emissions are avoided.

4. CASE STUDIES OF GREENHOUSE GAS AND ENERGY BALANCES OF BIOENERGY SYSTEMS

Task 38 is a group of researchers from various countries that work on the specific theme: 'GHG Balances from Biomass and Bioenergy Systems'. In 1997, Task 38 published its standard methodology for GHG balances of bioenergy systems based on LCA. Since then members of the Task have used this methodology to analyse the GHG balances of more than 15 different bioenergy systems in participating countries. A few of these case studies are used in the next sections to illustrate the major factors affecting GHG savings from different bioenergy systems.

4.1 Heat

The energy balance and GHG emissions of a small-scale biomass heating system in the southwest of England have been studied (Task 38 UK Case Study: The Greenhouse Gas and Energy Benefits of a *Miscanthus* and a Wood-fuelled Heating System*). These examples show how the choice of biomass can affect the estimate of GHG emission benefits.

Example 1 - 150 kW wood versus oil-fired heating systems in Southern England

The first example investigates the GHG benefits of a wood heating system at Grascott Farm in southwest England.

Study system: The heating system was installed in January 2003 to heat a five bedroom farmhouse and a three bedroom holiday cottage. It was expanded to heat an additional cottage in 2008. The biomass comes from thinning the under-managed broadleaved woodland and fir plantation on the property (7.5 oven dry tonnes per year) and slab wood (22.5 oven dry tonnes per year) from a local sawmill 5 km away. All wood is air dried to 25% moisture (per unit dry biomass) before chipping.

Reference system: The heat is supplied by a single oil-fired boiler with storage tank. The woodland on the property is left unmanaged and the slab wood would be used in a board mill approximately 10 km further away from the sawmill.

Results: The results of the LCA for this example are shown in Table 3. It is assumed that the increased management intensity causes no loss of carbon stocks in the forest. However, the use of the slab wood for bioenergy means that the board mill needs to use wood from somewhere else. The analysis expanded the system boundary to include substitution of slab wood from a mill 10 km further away. The study did not consider the

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*Task 38 Case Study by Heaton, R and Matthews, R. *www.ieabioenergy-task38.org/projects/task38casestudies/index1.htm*

Table 3: GHG and energy balances of wood-fired heating assuming slab wood would have been incinerated without energy recovery in the reference case

Item	Units	Reference System	Study System
Fossil energy input	kWh/kWh_{heat}	1.20	0.12
Fossil energy saved	kWh/kWh_{heat}	1.08	
	kWh/t_{dry}	5,641	
Emissions			
Land management change	$g\ CO_2\text{-eq}/kWh_{heat}$	N/A	0
Cultivation and harvesting	$g\ CO_2\text{-eq}/kWh_{heat}$	N/A	6
All other emissions	$gCO_2\text{-eq}/kWh_{heat}$	379	46
Total	$g\ CO_2\text{-eq}/kWh_{heat}$	379	52
Emissions saved	$g\ CO_2\text{-eq}/kWh_{heat}$	327	
	$t\ CO_2\text{-eq}/\ t_{dry}$	1.71	

use of this biomass in the reference system. If one assumes that the additional biomass would have been incinerated without energy recovery in the reference case, then its use for bioenergy has no impact on carbon stocks. However, if it is assumed that the slab wood would have gone to landfill, then the loss of biomass in the landfill is estimated as 447 t over the 25 years of the project. This is roughly 79% of the biomass consumed.

If the slab wood had gone to landfill then the emissions from the study system would be 261 g CO_2-eq/kW_{heat}, including 209 g CO_2-eq/kW_{heat} from 'land management change' so the savings would be only 118 g CO_2-eq/kW_{heat}. The diversion of wood from the landfill for bioenergy use causes a decrease in the carbon stock in the landfill. The amount and rate of loss depends on the decay rate of the wood. This demonstrates the importance of accurate identification of the reference system.

Example 2: 70 kW Miscanthus versus oil-fired heating systems in West London
Study system: In the second example, a 70 kW *Miscanthus*-fired boiler was installed as a bioenergy demonstration project in a rural office complex in Hertfordshire, West London. The biomass is harvested annually from the 4.5 ha surrounding the complex. The emissions from cultivation and collection of the biomass are included in the estimate.

Reference system: The heat is supplied by a single oil-fired boiler with storage tank. The surrounding land would be left unused (set-aside*) but the grasses would be cut once annually and left on the ground.

Results: The results of the LCA for this example are shown in Table 4. This bioenergy causes little to no land use change since the biomass in grassland and in *Miscanthus* are roughly equal. The results are comparable to the earlier example. This system requires more energy specifically for cultivation and harvesting than the wood-based example.

Comparison with literature: Ranges for typical LCA studies for heat are given in Figure 3. The results from Example 1 are high when the loss of landfill biomass is considered, but compare reasonably otherwise. The values for Example 2 are somewhat higher than other studies but this can be expected given the large emissions from cultivation.

4.2 Electricity

This case study assessed the potential GHG emissions reduction from substituting electricity from coal with bioenergy based on *Eucalyptus* spp. plantation residues in northern New South Wales (Task 38 Case Study - GHG balance of bioenergy systems based on integrated plantation forestry in North East NSW, Australia#). The case study highlights the importance of the efficiency of the energy conversion process, and demonstrates the inclusion of SOC dynamics when there is a land use change.

Table 4: GHG and energy balances of *Miscanthus*-fired heating

Item	Units	Reference System	Study System
Fossil energy input	kWh/kWh_{heat}	1.22	0.52
Fossil energy saved	kWh/kWh_{heat}	0.70	
	kWh/t_{dry}	2,763	
Emissions			
Land management change	$g\ CO_2\text{-eq}/kWh_{heat}$	0	1
Cultivation and harvesting	$g\ CO_2\text{-eq}/kWh_{heat}$	16	56
All other emissions	$gCO_2\text{-eq}/kWh_{heat}$	380	45
Total	$g\ CO_2\text{-eq}/kWh_{heat}$	396	101
Emissions saved	$g\ CO_2\text{-eq}/kWh_{heat}$	295	
	$t\ CO_2\text{-eq}/\ t_{dry}$	1.17	

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*Set-aside land is land that does not produce a crop because it is not economically attractive. The land may still be managed (i.e. mowed, or tilled) to control weeds.
#Task 38 case study by Cowie, A. *www.ieabioenergy-task38.org/projects/task38casestudies/index1.htm*

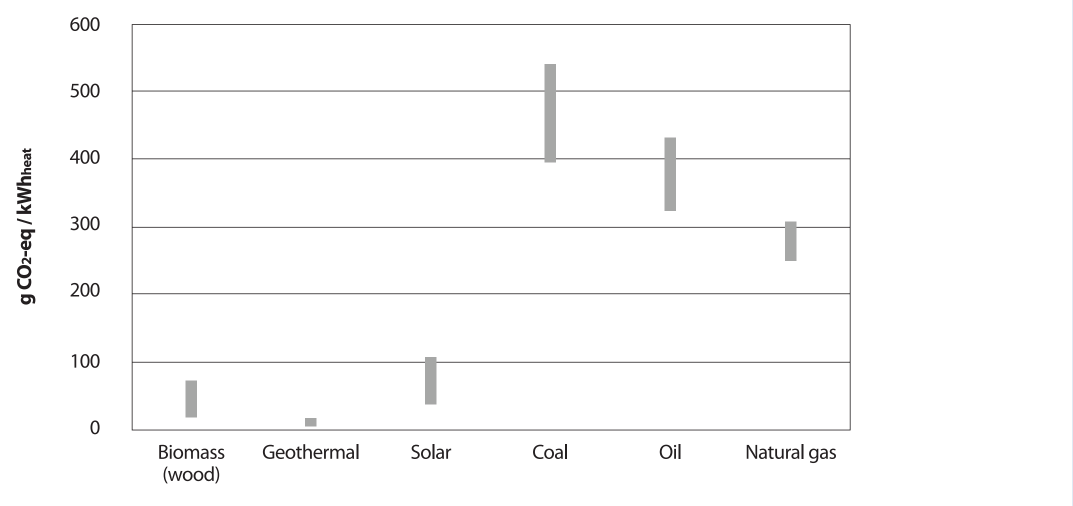

Figure 3. Ranges of GHG emissions for heat supply from different sources. Source: Cherubini *et al.* 2009. Energy- and GHG-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling. 53: 434-447.*

Example 1 – Firing of plantation residues in newly built 30 MW wood-fired generating stations in the plantation region

Study system: The study system is based on biomass production from conventional hardwood plantation forestry in northern New South Wales. Biomass is obtained from thinning, harvest and sawmill residues from 70,000 ha existing and 110,000 ha newly established hardwood plantations in the region. The biomass is fed into 30 MW wood-fired power stations newly constructed within the plantation region. There is no loss of timber production from the existing and newly planted plantations.

The 30 MW wood-fired generating stations use circulating fluidised bed boiler, steam turbine technology that has a 20% conversion efficiency. This value is low compared to most systems because it was assumed in the study that the biomass was not dried before combustion.

Reference system: The reference system to which the bioenergy system is compared represents current practice, in which electricity is generated from 500 MW black coal-fired power stations. In the reference system, thinning residues decay on the forest floor, harvest residues are windrowed and burned in the field, and sawmill residues that are not utilised in drying timber are burned to waste at the mill. Timber is obtained from 70,000 ha of existing plantations and 110,000 ha of newly established *Eucalyptus* spp. plantations.

The study and reference system boundaries include the power generation system, 70,000 ha of existing plantation, and 110,000 ha of grazing land newly converted to plantation. The same quantity of sawn timber is produced, and the same quantity of carbon is sequestered by the live trees. The carbon stock changes in the litter, deadwood, soil and landfill are estimated using a full carbon stock flow model (FullCAM). The calculation is made over 100 years to cover several plantation rotations.

Results: There is a decline in SOC predicted for the reference and bioenergy cases, for newly established forests (Table 5). Temporary loss of SOC commonly occurs where plantations replace pasture, because mineralisation exceeds input to the soil organic matter pool during the early stages of plantation growth, although large losses are limited to situations where high levels of fertilisation have built up a large pool of labile soil carbon in pasture. The rate of decline in soil C is greater under the study system than in the reference system. This is to be expected because biomass (thinning residues) is removed that would otherwise have entered the litter pool that interacts with the soil C pool. In addition, the combustion of the thinning material accelerates the return of carbon to the atmosphere as compared to the natural oxidisation. Nevertheless, changes in the soil C and litter pools are small compared with the accumulation of C in tree biomass over the first rotation, and the growing pools

Table 5: GHG balance and energy input of stand-alone 30 MW wood-fired electricity generation

Item	Units	Reference System	Study System
Fossil energy input	kWh/kWh$_{elec}$		0.25
Emissions			
Land management change	g CO_2-eq/kWh$_{elec}$	-313	-271
Cultivation and harvesting	g CO_2-eq/kWh$_{elec}$	40	59
All other emissions	gCO_2-eq/kWh$_{elec}$	981	12
Total	g CO_2-eq/kWh$_{elec}$	709	-201
Emissions saved	g CO_2-eq/kWh$_{elec}$	909	
	t CO_2-eq/ t$_{dry}$	0.949	

Table 6: GHG balance and energy input of 500 MW biomass co-fired electricity generation

Item	Units	Reference System	Study System
Fossil energy input	kWh/kWh$_{elec}$		0.45
Emissions			
Land management change	g CO_2-eq/kWh$_{elec}$	-235	-186
Cultivation and harvesting	g CO_2-eq/kWh$_{elec}$	28	40
All other emissions	gCO_2-eq/kWh$_{elec}$	981	88
Total	g CO_2-eq/kWh$_{elec}$	774	-59
Emissions saved	g CO_2-eq/kWh$_{elec}$	853	
	t CO_2-eq/ t$_{dry}$	1.30	

of products. Over several rotations, displaced fossil fuel carbon becomes the dominant pool.

The amount of biomass in tree growth, wood products, and hence 'products in landfill' do not differ between the bioenergy and reference cases.

Example 2 – Co-firing of plantation residues in existing 500 MW wood-fired generating station 360 km away from plantations.
Study system: In the second example, instead of going to newly built 30 MW facilities, the same amount of biomass is trucked 360 km and co-fired in an existing 500 MW generation station. The facility is a pulverised fuel black coal boiler, steam turbine in which biomass is co-fired 5% by weight. The efficiency of the system is 29%, which is lower than the efficiency of coal combustion due to the higher moisture content of the biomass

Reference system: The reference system is identical to Example 1.

Results: The results are shown in Table 6. Co-firing gives higher emissions reduction per unit of biomass than the stand-alone system due to the greater efficiency of energy conversion in the co-fired plant. (Note that the result for co-firing applies only to the electricity derived from biomass, not to the total electricity output of the plant). Due to the longer transportation distances, the emissions for co-fired bioelectricity are higher than those of the stand-alone system (Example 1, Table 5). In comparison, the emissions for electricity production from the reference coal power plant are 981 g CO_2-eq/kWh. The GHG emission savings per t of biomass for the co-firing option are higher than the stand-alone option, due to the higher efficiency of the co-firing system, even though there are higher transport emissions due to the longer transport distance to coal-fired power stations.

Comparison with literature: In Figure 4, the ranges of GHG emissions for electricity supply with different energy carriers are shown. The GHG emissions from hydro, solar and wind mainly arise from the construction and dismantling stage of the power plants. The bioenergy systems do not include direct changes in carbon stocks or indirect land use change. The GHG emissions from bioelectricity are 80% to 97% lower compared to fossil energy carriers, but similar to nuclear, hydro and wind power. Excluding land use change, the GHG emissions from Examples 1 and 2 are similar to those given in Figure 4.

4.3 Combined heat and power from biogas

This case study quantifies the GHG emissions savings of a biogas plant utilising dedicated energy crops, grass and manure as feedstock. In addition, the emissions of the bioenergy system were estimated with and without closed storage of the digested substrate (Task 38 Case Study - 'GHG benefits of a biogas plant in Austria', S. Woess-Gallasch, N. Bird, P. Enzinger, G. Jungmeier, N. Pena, R. Padinger and G. Zanchi).

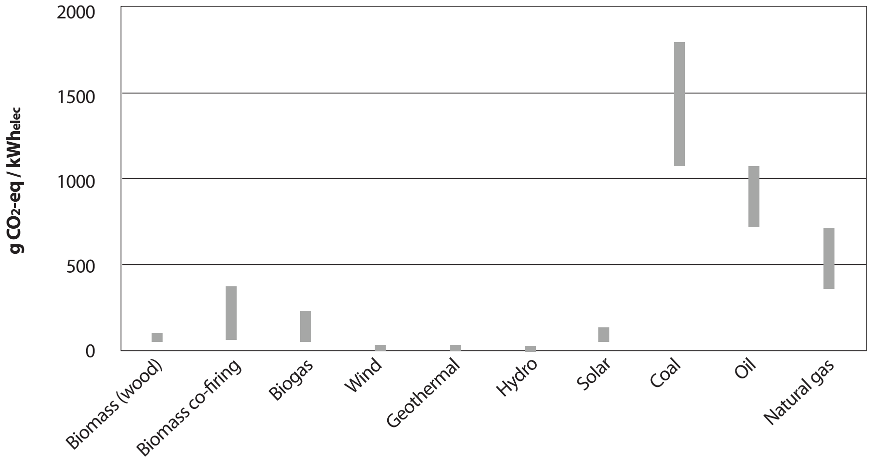

Figure 4. Ranges of GHG emissions for electricity and cogeneration from different sources. In biomass co-firing, biomass is assumed to provide between 5% and 15% of the energy. Source: Cherubini *et al.* 2009. Energy- and GHG-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling.* 53: 434-447.

The study shows the importance of finding a beneficial use for excess heat and preventing fugitive emissions from the biogas plant. In this example, land use change is not significant.

Study system: The biogas plant in Paldau, Austria, was analysed. The biomass used in the plant is derived from dedicated energy crops, animal manure and grass silage. The crops supply 3.12 kt per year of maize and 2.67 kt per year of maize silage. Animal manure (from pigs: 3040 m^3 per year; from cows: 300 m^3 per year) is supplied by five farmers situated close to the plant. In two cases, the manure is delivered by a pipeline (1,800 m^3 per year). The other three farmers deliver the manure by tractor in barrels (1,240 m^3 per year). Finally, the plant also consumes 740 t per year of grass silage.

The biomass goes through a two-stage digestion system, with a residence time of approximately 100 days. After digestion the digestate is stored in a closed storage tank for six months after which it is spread on pasture.

Approximately 270 m^3 per hour of biogas is collected from the digestion system (both stages) and from the storage tank. This is fed to two gas engines to produce electricity (4.03 GWh per year) and heat (7.2 GWh per year), but only 1.3 GWh per year heat is actually used. This results in an electricity conversion efficiency of 37% and an overall efficiency of 49%. If all the heat were used then the combined efficiency would reach 75%.

The maize used for biogas in the study system is, in the reference system, used for animal feed. Therefore, production of equivalent animal feed must be included in the study system. To supply this feed in the study system, additional fertiliser is applied to achieve increased yield of maize, and the remainder is supplied through imported soya feed.

Reference system: The reference system has two key differences to the study system. First, electricity is generated in a 500 MW natural gas closed cycle power plant and the heat is supplied by oil and wood boilers.

Secondly, in the reference system, the land used is set-aside land (20%) or used to produce maize for animal feed (80%). The set-aside land is mulched once per year to keep the soil properties suitable for future agricultural production. The maize crop residues are composted, and the animal manure is stored then used as fertiliser.

Results: The change in land use on 53 ha of set-aside land to cultivation of maize causes a small increase in SOC totalling 48 tonnes of CO_2 per year, reducing total GHG emissions by 3.4% (Table 7). The biogas plant reduced net GHG emissions by 44% compared with the reference system. Covering the stored digestate before spreading on pasture is important: emissions are 30% higher if the storage is not covered, and 1.9% less biogas is produced.

This study only reported the land use change emissions and the total emissions. To give the reader some idea of the relative contributions from the various stages, an estimate of emissions based on another study in Austria has been provided in Table 7. Typically, emissions from cultivation account for 64% of total emissions in the closed system.

In the case studied, only 17% of the heat generated was used. If the total available heat had been used, then emissions in the reference system would have increased to 930 g CO_2-eq per kWh_{total} and the emissions saved by the biogas plant with closed storage would be 664 grams per kWh_{total}. In this case the emissions from the biogas plant would be 70% less than the reference system. This demonstrates the importance of using as much of the produced heat as possible.

Comparison with literature: Figure 5 shows the typical emissions per total energy output for various energy sources. The results from this study are higher than typically found for biogas combined heat and power systems. The reasons for this difference may be two-fold:

a) in this study the majority of the heat produced is not used; and
b) in this study, most of the biomass comes from dedicated energy crops. This results in higher GHG emissions than biogas systems that use residues as the main feedstock.

This is an example where the timing problem referred to in Chapter 2.2.6 does not occur. Both the growth of dedicated crops (carbon uptake) and the decay of animal manure (avoided carbon emission) take place within roughly the same time span as the carbon emission from burning the 'biocarbon' in the biogas plant. Thus, the full credit of avoiding fossil carbon emission may be attributed to the bioenergy scheme.

4.4 Transportation biofuels

This study evaluated the GHG reduction potential of biodiesel use in Croatia (Task 38 Case Study: GHG Benefits of Biodiesel

Table 7: GHG balances of a biogas-fired combined heat and power system

Item	Units	Reference System	Study System Closed Storage	Study System Open Storage
Emissions				
Land management change	g CO_2-eq/kWh_{total}		-9	-9
Cultivation and harvesting	g CO_2-eq/kWh_{total}	Not calculated	*171*	*171*
All other emissions	g CO_2-eq/kWh_{total}	Not calculated	*105*	*182*
Total	**g CO_2-eq/kWh_{total}**	**473**	**266**	**344**
Emissions saved	**g CO_2-eq/kWh_{total}**		**207**	**129**
	t CO_2-eq/ t_{dry}		**0.29**	**0.18**

Note: values in italics are approximations based on other studies in Austria. They are given only for illustrative purposes.

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* *Task 38 case study by Fijan-Parlov, Liposcak, and Juric, Z. www.ieabioenergy-task38.org/projects/task38casestudies/index1.htm*

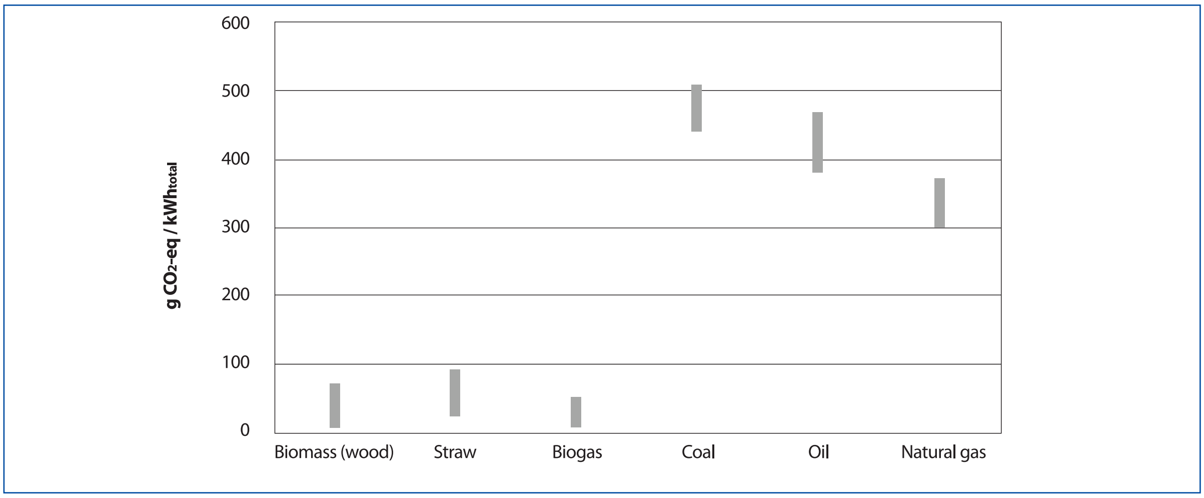

Figure 5. Ranges of GHG emissions for combined heat and power from different sources. Source: World Energy Council. 2004. Comparison of Energy Systems using Life Cycle Assessment, A Special Report of the World Energy Council, London and other sources.

Use in Croatia in the Context of Joint Implementation*). It illustrates that the use of co-products affects the environmental benefits.

Study system: The study system assumes that degraded and underutilised land that currently is set aside is converted to rape production for the production of biodiesel. The biodiesel will be used in public transportation (buses) or in private vehicles (cars) and displace fossil diesel use.

During the biodiesel production process co-products are created, such as rape cake in the process of pressing and glycerine in the process of esterification. The GHG emissions reduction depends strongly on how these co-products are used, and specifically whether they are used as material or energy sources. Two cases were analysed, where the bio-glycerine is used to substitute for either synthetically produced glycerine for material use (such as in the food or pharmaceutical sectors) or for fuel oil in a combined heat and power (CHP) facility.

Reference system: In the reference system, the land is left as set-aside and the buses are fuelled by fossil diesel.

Results: The GHG emission balances for the reference and study systems are shown in Table 8[‡]. No net change in carbon stock in soil is assumed to occur in the conversion of degraded set-aside land to rape production. In the study system, cultivation releases about 56 g CO_2-eq/km emissions from the use of machinery and fertilisers. Fossil fuel required to transport the rapeseed, process the rapeseed into biodiesel, create co-products (glycerine and rape cake), and distribute the biodiesel releases another 255 g CO_2-eq/km. The impact of co-product use is large. The glycerine can be used as an energy product, or as a material (for example, in the food or pharmaceutical sectors). In the former case, emissions saved from using the glycerine for energy amount to 154 g CO_2-eq/km whereas if the glycerine is used as a material there is a credit generated (-200 g CO_2-eq/km, Table 8).

Comparison with literature: Figure 6 shows the ranges of GHG emissions for transportation services for a passenger car fuelled with different energy carriers. The results from the study fit within these ranges. The analyses of bioenergy systems may or may not include direct changes in carbon stocks or indirect land use change. The estimates of GHG emissions from transportation biofuels vary substantially. This wide range is due to the variation in yields, inputs and emissions from agricultural systems in different locations, different feedstocks, and the different energy mixes used in biofuel production plants in different locations. The GHG emissions for 1st generation

Table 8: GHG balances of a rapeseed biodiesel-fuelled car system

Item	Units	Reference System	Study System Closed Storage	Study System Open Storage
Emissions				
Land management change	g CO_2-eq/km	Not applicable	0	0
Cultivation and harvesting	g CO_2-eq/km		56	
Co-products	g CO_2-eq/km		-154	-200
All other emissions	g CO_2-eq/km		255	255
Total	g CO_2-eq/km	**192**	**157**	**111**
Emissions saved	g CO_2-eq/km		**34**	**80**

[‡] *In the original Task 38 Case Study report (Fijan-Parlov et al.), the results are given for biodiesel used in buses only. The values shown in Table 8 have been converted using the relative fuel efficiency of buses and cars so that a comparison with Figure 6 can be made.*

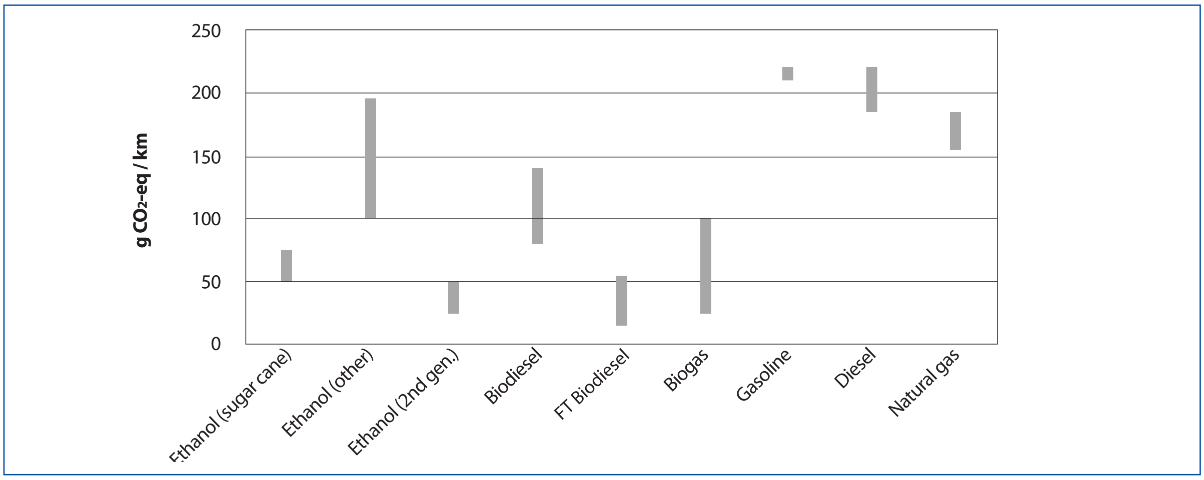

Figure 6. Ranges of GHG emissions for biofuels of different types from a variety of sources used in automobiles. FT = Fischer Tropsch. Values are for cars with average fuel efficiency. Source: Cherubini *et al.* 2009. Energy- and GHG-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*. 53: 434-447.

transportation biofuels are, in general, lower than gasoline and diesel. As shown in Figure 6, 2nd generation transportation biofuels made from wood and straw might reduce GHG emissions by more than 90%.

The IEA Implementing Agreement on Advanced Motor Fuels has commissioned a study *'A Non-Technical Comparison of Life Cycle Analysis Tools for Transportation Fuels'*. This study aims to provide guidance to decision makers on the appropriate uses of LCA , specifically for transportation fuels. The study should be available in the second half of 2011.

5. CONCLUSIONS

LCA is a powerful tool used to quantify the environmental impacts of products and services. It includes all processes from cradle-to-grave along the supply chain of the product or service. LCA can be used to quantify the GHG emission savings of bioenergy, by comparing the bioenergy system with a reference fossil energy system.

However, when reviewing the literature one finds large ranges of GHG emissions per functional unit and emissions saved per functional unit from LCA studies of similar bioenergy systems. The differences occur for a multitude of reasons. For example, the studies may use different technologies, different system boundaries, different reference systems or different methods of allocation or system expansion. Furthermore, some studies are inconsistent in that the bioenergy system and reference system provide different services. Others may not include some sources of emissions (for example, land use change). Since small changes in methodological assumptions and input parameters can have large effects on the estimated environmental impacts, the bioenergy and reference systems should be described and assumptions listed in a transparent manner.

In this paper, the various components of LCA have been discussed with a particular focus on bioenergy systems. The conclusion is that LCA is the tool of choice for quantifying the GHG emissions from, and emissions saved by bioenergy systems. However, to ensure that reliable comparisons are drawn, LCA should be conducted following standard procedures. Generic guidance is given in ISO 14040 and 14044. In this paper more specific guidance is provided on the critical aspects, particularly related to impacts of biomass production and utilisation, that must be considered in undertaking any LCA of bioenergy systems. It is important that the following are considered:

1. LCA is used to quantify the environmental impacts of products or services. It includes all processes, from cradle-to-grave, along the supply chain of the product or service. When analysing the global warming impact of energy systems, GHG emissions (particularly CO_2, CH_4 and N_2O) are of primary concern.
2. To determine the comparative GHG impacts of bioenergy, the bioenergy system being analysed should be compared with a reference energy system, which is usually – but not always – a fossil energy system.
3. A reference energy system should be chosen that is realistically likely to be displaced by the bioenergy system. If this reference system is not certain, then one option is to use as the reference energy system the average fossil energy for that region. Another option is to make a conservative evaluation by comparing the bioenergy system with the best available fossil energy technology. Alternatively, a non-fossil option may be selected as the relevant reference energy system. Depending on the context of the study, this might be another renewable option or nuclear power.
4. The scope of the analysis (system boundary) should include all processes along the value chain with significant GHG emissions, including, where relevant, upstream processes of extraction or biomass production, and end-of-life processes.
5. The system boundary should be defined so that the bioenergy and reference fossil systems provide equivalent products and services. If it is not possible to achieve this through expansion of the system boundary then the GHGs can be shared amongst energy and non-energy co-products of the bioenergy system (such as biodiesel and rapeseed cake, from processing of rapeseed oil), based on their share of physical (for example energy) or financial contributions.
6. Changes in carbon stocks in biomass, soil and landfill, can cause GHG emissions (or removals). These can be very important and should be included in the analysis.
7. In general, LCA is not concerned with the time at which the environmental impacts occur. However, in some cases bioenergy systems cause short-term GHG emissions due

to the accelerated oxidation of carbon stocks through combustion as compared to natural decay. While this can affect short-term GHG targets, over a long-term perspective sustainable bioenergy causes less GHG emissions than comparable fossil energy systems.

8. Use of agricultural residues may affect GHG emissions through either changes in SOC or land use changes that occur indirectly, in order to provide the equivalent services that the residues were providing. Exploitation leading to soil productivity losses may require compensating fertilisation (causing GHG emissions) to maintain yield levels and can also cause cropland expansion elsewhere to compensate for yield losses if these occur.
9. The type of technology, scale of plant, and co-products in both the bioenergy and reference energy system can influence the GHG mitigation benefits of the bioenergy system. Since small changes in methodological assumptions and input parameters can have large effects on the estimated environmental impacts, the bioenergy and reference systems should be described and assumptions listed in a transparent manner.

In the cited case studies, bioenergy systems reduce GHG emissions by between 18% and 128% compared to their counterpart fossil reference systems. Since these studies consider a range of bioenergy technologies and reference systems that have different types of land management change and a variety of uses for co-products, it is difficult to generalise. However, the cited case studies and published LCA studies find that GHG mitigation is greater where biomass is used for heat and electricity applications rather than for liquid transport fuels. The emissions savings from bioenergy systems tend to be similar to those of other renewable energy sources.

6. RECOMMENDED READING

LCA Methodology

Cherubini, F., Bird, N., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch S. 2009. Energy- and GHG-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. 2009. Resources, Conservation and Recycling 53: 434-447.

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Timing of Emissions from Land Use Change

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Soil Organic Carbon

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Crop Residues in Bioenergy

Blanco-Canqui, H. and Lal, R. 2007. Soil crop response to harvesting corn residues for biofuel production. Geoderma 355-362.

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Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J. and Whitmore, M.J. 2008. Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. Waste Management 28: 741–746.

CH_4 *and* N_2O *from Agriculture*

Stehfest, E. and Bouwman, L. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data modelling of global annual emissions, Nutrient Cycling in Agroecosystems, 74: 207-228.

IEA BIOENERGY TASK 38

The primary goal of Task 38 'Greenhouse Gas Balances of Biomass and Bioenergy Systems' is to investigate all processes involved in the use of bioenergy and carbon sequestration systems, with the aim of assessing overall GHG balances and supporting decision makers in selection of mitigation strategies. Participating countries in 2011 are Australia, Austria, Belgium, Brazil, Finland, Germany, the Netherlands, Norway, Sweden, and the USA. For more detailed information on the Task see: http://www.ieabioenergy-task38.org/

Case Studies

Australia	GHG balance of a co-firing system of biomass and a wood fired conversion facility, both based on conventional hardwood plantation forestry. Does soil carbon loss in biomass production systems negate the GHG benefits of bioenergy?
Austria	Greenhouse gas benefits of a biogas plant in Austria
Canada	GHG impacts of pellet production from woody biomass in BC, Canada, and transporting them to Europe, USA and Canada substituting fossil fuels. GHG balance of a small pyrolysis plant using both sawmill residues and thinnings from a juvenile spacing program to produce bio-oil, used either in a pulp mill limekiln or for export of biofuel
Croatia	Assessment of the GHG emissions-reduction potential of biodiesel production in the context of Joint Implementation
Finland	GHG balances of bioenergy and carbon sequestration projects with links between increased use of construction wood and the use of biomass-fired cogeneration plants, replacing fossil fuels
Ireland	GHG benefits of using municipal solid waste as a fuel in a thermal treatment plant. GHG balance of peat use for energy.
New Zealand	Assessment of the GHG balance of a bioenergy cogeneration plant based on the use of sawmill residues
Sweden	GHG balances of bioenergy and carbon sequestration projects with links between increased use of construction wood and the use of biomass-fired cogeneration plants, replacing fossil fuels
Netherlands	Import of wood pellets from Canada and of palm kernel shells from Malaysia to Netherlands for green energy production
UK	GHG balances of *Miscanthus* fuelled biomass projects
USA	GHG emission reduction potential associated with anaerobic digestion plant of organic wastes, California

ACKNOWLEDGEMENTS

For some time the Executive Committee has recognised the need for an unbiased, authoritative statement, on life cycle assessment of the greenhouse gas balance of bioenergy. Accordingly, this strategic report began with a proposal commissioned from the late Dr Bernhard Schlamadinger. He was succeeded as principle author firstly by Dr Gerfried Jungmeier, and then by Mr Neil Bird. The original editorial committee consisted of Dr J. Peter Hall, Dr Josef Spitzer, and the late Mr Larry Russo. This committee subsequently evolved to Dr Josef Spitzer (Convenor), Dr Tat Smith, and Mr Paul Grabowski. Associate Professor Göran Berndes provided some insightful comments during final editing. More recently Tat Smith was appointed Consultant Editor and provided valuable input in finalising the manuscript. The Secretary, John Tustin, organised final editing and publication. In addition, many colleagues made valuable contributions to this report through its various stages. All these contributors are gratefully acknowledged.

IEA Bioenergy

IEA Bioenergy is an international collaboration set up in 1978 by the IEA to improve international co-operation and information exchange between national RD&D bioenergy programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently IEA Bioenergy has 24 Members and is operating on the basis of 12 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

Further Information

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iea Energy Technology Network

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