



# SUNLIBB

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### Deliverable 8.5 “Sensitivity and comparative analysis report”

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# **Sustainable Liquid Biofuels from Biomass Biorefining (SUNLIBB)**

## **Work Package 8: Sustainability Assessment**

**Task 8.5: Sensitivity and Comparative Analysis**

**Deliverable D8.5: Sensitivity and Comparative Analysis Report**

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## Executive Summary

1. This report documents the application of quantitative and qualitative assessment to the sustainability of biorefineries within the context of the “Sustainable Liquid Biofuels from Biomass Refining” (SUNLIBB) Project. The SUNLIBB Project is funded by the European Commission (EC) under the 7th Framework Programme within the Energy Theme: Second Generation Biofuels and involves collaboration with the CeProBio Project in Brazil. The aims of the SUNLIBB Project are outlined and the rôle of Work Package 8 in addressing sustainability assessment is explained.
2. Sustainability assessment is introduced in relation to life cycle assessment as a means of quantifying environmental impacts. Different calculation methodologies are considered and the approaches used in other EC-funded biorefinery projects are discussed. The need for necessary functionality to address all technical and methodological options is established as a basis for the development of MS Excel workbooks for estimating primary energy inputs and prominent greenhouse gas (GHG) emissions associated with the production of ethanol from sugar cane/bagasse, corn stover and whole maize, and miscanthus.
3. The incorporation of biorefinery modelling into these workbooks is explained. Basic technological details are based on a conceptual biorefinery utilising the lignocellulosic conversion of corn stover into ethanol, as set out by the National Renewable Energy Laboratory. The modification of these details to represent the processing of sugar cane, bagasse, whole maize and miscanthus, as well as the effects of using supercritical carbon dioxide (CO<sub>2</sub>) extraction (SCE) and improved biomass feedstocks, as derived from results from WP6 and WP7, respectively, in the SUNLIBB Project, are summarised.
4. The capability of the workbooks, which form the main basis of Deliverables D8.2, D8.3 and D8.4 in the SUNLIBB Project, and their subsequent results are demonstrated through sensitivity and comparative analysis. In particular, the effects of choosing different calculation methodologies are presented. The importance of selecting appropriate technical options, especially regarding the integration of combined heat and power and capturing CO<sub>2</sub> from fermentation in biorefineries, is illustrated in terms of reducing associated GHG emissions.
5. Technical combinations are identified in biorefineries and their biomass feedstock pathways which achieve minimum net GHG emissions savings required by the EC’s Renewable Energy Directive after 2017 for ethanol used as a fuel, and net GHG emissions savings of ethanol used as a chemical over petro-ethanol. Reduced GHG emissions from using improved maize and miscanthus feedstocks are indicated. However, the disadvantages of SCE, with currently specified requirements and performance, are apparent.
6. The qualitative assessment of other environmental impacts summarises those which might cause possible problems for maize and miscanthus biorefineries, and those which are likely to be site-specific. Brief consideration of the socio-economics of biorefineries suggests potential benefits provided that they can compete economically through the development and implementation of technically-feasible and commercially-viable measures which do not compromise net GHG emissions savings.

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## 1. INTRODUCTION

The “Sustainable Liquid Biofuels from Biomass Refining” (SUNLIBB) Project is funded by the European Commission (EC) under the 7th Framework Programme within the Energy Theme: Second Generation Biofuels. Its support came about through the European Union (EU) – Brazil Co-ordinated Call and its activities involve collaboration with the CeProBio Project in Brazil. The aims of the SUNLIBB Project are:

- to use modern crop breeding approaches and cutting edge plant cell wall research to identify genes that will allow modification of cell wall composition so as to reduce costs associated with conversion processes,
- to upgrade residues and by-products, and to produce other value streams from biomass feedstocks so that the total energy output and profitability of second generation biofuels will be increased,
- to improve the process of converting sugars in biomass feedstocks into biofuels,
- to bring together improvements in biomass feedstocks and conversion processes in biorefineries so that the economic and environmental sustainability of second generation biofuels can be enhanced, and
- to review all pertinent guidelines, policies and regulatory frameworks for sustainable biofuels in both the EU and Brazil in order to take into account any influential developments that could affect the future potential for harnessing benefits from this work.

Within the SUNLIBB Project, Work Package (WP) 8 is concerned with “Sustainability Assessment”. Task 8.1 involves reviewing the policy and regulatory context at EU and Member State (MS) levels which have been reported in Deliverable D8.1 (Ref. 1). Specific environmental aspects of biorefineries supplied with sugar cane, maize and miscanthus feedstocks are addressed in Tasks 8.2 to 8.5. In particular, primary energy inputs, as indicators of energy resource depletion, and prominent greenhouse gas (GHG) emissions, in the form of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), as indicators of global climate change, are quantified by means of MS Excel workbooks for sugar cane biorefineries (Task 8.2), maize biorefineries (Task 8.3) and miscanthus biorefineries (Task 8.4). Sensitivity and comparative analysis are the main activities of Task 8.5. In addition to the quantification of specific environmental concerns, both Tasks 8.3 and 8.4 involve the qualitative assessment of other sustainability criteria for biofuels derived from biorefineries which process maize and miscanthus, respectively. This report covers sensitivity and comparative analysis, and subsequent results and conclusions.

## 2. SUSTAINABILITY ASSESSMENT

Quantitative sustainability criteria for biofuels and the biomass feedstocks from which they can be derived have evolved over a period of time in the EU. Officially, the initial consideration of sustainability criteria was raised in the EC's Renewable Energy Directive or RED (Ref. 2) and Fuel Quality Directive or FQD (Ref. 3), with subsequent elaboration for practical implementation (Ref. 4). Within the RED and FQD, the main focus for biofuels is the evaluation of total GHG emissions within the context of target net savings relative to fossil fuel comparators. The RED methodology provides one means, in a specifically-regulatory context, for assessing GHG emissions and subsequent net GHG emissions savings for fuels, such as ethanol, derived from biomass feedstocks. However, other GHG emissions calculation methodologies exist. For example, a widely-used approach for so-called "carbon footprinting" of goods and services is provided by the British Standards Institution's Publicly Available Standard (PAS) 2050 (Ref. 5). Given its intended broad application, this calculation methodology has sometimes been applied, specifically, to the production of goods such as chemicals.

There are some important differences between the RED and PAS 2050 methodologies, and these can be summarised, with particular respect to the sustainability assessment of biorefineries and their biomass feedstock pathways, as follows:

- The RED methodology classifies certain sources of biomass feedstocks as agricultural residues to which GHG emissions associated with cultivation and harvesting of the main crop are not allocated, whilst the PAS 2050 methodology treats main crops and their residues, if collected and used, as co-products that are subjected to GHG emissions allocation,
- The RED methodology bases co-product allocation on energy content, whereas the PAS 2050 methodology uses economic values (amount x price) for co-product allocation, if so-called "system expansion" cannot be adopted.
- The RED methodology applies a GHG emissions credit to any CO<sub>2</sub> captured from fermentation based on assumed displacement of CO<sub>2</sub> from fossil sources, whilst the PAS 2050 methodology regards any CO<sub>2</sub> captured and sold as a co-product which is subject to its stated allocation procedure,
- Although both the RED and PAS 2050 methodologies treat surplus electricity from cogeneration or a combined heat and power (CHP) unit in a facility such as a biorefinery by means of GHG emissions credits, instead of as co-products subjected to stated allocation procedures, the RED methodology bases this credit on the GHG emissions associated with power only generation using the fuel burnt in the CHP unit (referred to here as "replacement generation) and the PAS 2050 methodology adopts a credit which reflects the GHG emissions associated with grid electricity supply (referred to here as "gross grid electricity"), and

- The RED methodology excludes the GHG emissions associated with the manufacture of plant, equipment, machinery and vehicles, whereas the PAS 2050 methodology includes these GHG emissions provided that they make a substantive contribution (usually greater than 1%) to total GHG emissions.

There are other methodologies for the quantitative assessment of sustainability which are based, as are the RED and PAS 2050 methodologies, on the established principles of life cycle assessment (LCA). With specific relevance to the assessment of bioenergy, in general, and biorefineries, in particular, a number of relatively recent EC-supported projects have addressed the application of LCA and subsequent methodologies for quantifying a number of environmental impacts, including GHG emissions. The BIOSYENERGY Project, between 2007 and 2010, was concerned with “BIOmass for the market-competitive and environmentally-friendly SYNthesis of bio-products together with the production of secondary enERGY carriers through the biorefinery approach”. This project did address the environmental assessment of biorefineries (Ref. 6) but it did not propose a new comprehensive LCA methodology. The BEE, or “Biomass Energy Europe” Project was funded by the EC under the 7th Framework Programme and mainly addressed standardised methods for biomass resource assessment within the EU. This project incorporated the evaluation of environmental impacts into biomass resource assessment, mainly based on existing studies, (Ref. 7) but did not outline any new LCA methodological details.

In contrast, a thorough methodological basis for LCA applied to biorefineries is provided in the BIOCORE, or “BIOCommodity Refinery” Project which was funded by the 7th Framework Programme between 2010 and 2014. Crucially, the purpose of the LCA in the BIOCORE Project is established as assessment of “the environmental implications of the whole life cycle of a complete biorefinery including all its products instead of assessing individual products separately” (Ref. 8). This is addressed by means of consequential LCA which takes into account the global impacts of a technology. However, impacts related to the provision of infrastructure, which, though generally small, should, ideally, be included in a consequential LCA but they were excluded in the BIOCORE project. Other related projects funded by the EC include the SUPRABIO, or “SUstainable PRoducts from economic processing of BIOmass in highly-integrated biorefineries”, Project (Ref. 9), which focuses on novel product development biorefineries and refers to the LCA approach adopted by the BIOCORE Project in its networking activities, and the EUROBIOREF, or “EUROpean multilevel integrated BIOREFinery design for sustainable biomass processing”, Project (Ref. 10), which indicates adoption of the approach used in the European reference Life Cycle Database (ELCD) (formerly, the International reference Life Cycle Data system: ILCD) based on attributional LCA which assigns impacts, such as GHG emissions, to individual products. The BIOCORE, SUPRABIO and EUROBIOREF Projects, along with the co-ordinating STAR-COLIBRI Project, are sister activities on biorefineries supported by the EC. There have been discussions between relevant partners in the BIOCORE, SUPRABIO and EUROBIOREF Projects on harmonising LCA approaches but the outcomes, in terms of a unified methodology, are not yet publicly available (Ref. 10).

The fundamental point concerning selection of an appropriate LCA methodology is that it must be able to answer the specific question that has been posed on environmental impact. In LCA terminology, this means starting with a clearly stated “goal” which is further elaborated in the “scope”. These are basic requirements of an LCA but they are frequently overlooked altogether or addressed in a brief and perfunctory manner. It should always be appreciated that the “question” of any investigation determines the “answer”, and the same is true in LCA. Different goals and

scopes require different methodologies which generate different results. Unfortunately, too little effort is directed toward the goal and scope at the beginning of many LCAs so that too much time has to be spent later on trying to explain why results from one LCA differ from those of another. Since there is rarely agreement on the specific purpose of any given LCA, it was decided to adopt a flexible approach in the workbooks developed in WP8 of the SUNLIBB Project to address the major concerns of energy resource depletion and global climate change by quantifying primary energy inputs and prominent GHG emissions. This involved ensuring that these workbooks for sugar cane/bagasse, maize and miscanthus biorefineries incorporated a very high degree of functionality which enabled application of many different methodologies (see Sections 3 and 4).

Of course, there are other important environmental impacts and other important issues that need to be investigated as part of the sustainability assessment of biorefineries. However, given the stated coverage of WP8 in the SUNLIBB Project, these are addressed by means of qualitative assessment (see Section 5). These other environmental impacts include land use, soil changes, water use, emissions to air and water, and biodiversity. Other issues relate to socio-economic impacts consisting of changes in local, regional and national macroeconomics, and social aspects such as job creation. There are established techniques to evaluate these other environmental impacts, some quantitatively and others only qualitatively. However, large amounts of detailed data are often required to do this. There are also emerging approaches to socio-economic assessment but these also require extensive data and statistics which might or might not be available at the required scale. Hence, overall, qualitative assessment was applied to these other environmental and socio-economic impacts.

### **3. BIOREFINERY MODELLING**

In terms of WP7 and WP8, the SUNLIBB Project is focused on the production of ethanol by means of lignocellulosic conversion of maize (corn stover and whole maize but not maize grain) and miscanthus. The sister CeProBio Project addresses ethanol production from sugar cane and bagasse. Consequently, in the context of quantitative assessment, workbooks were needed to represent these biomass feedstock pathways and their subsequent biorefineries, to model relevant technical and methodological options, and to calculate primary energy inputs and prominent GHG emissions.

Although biorefinery design was not a major part of the SUNLIBB Project, it was necessary to agree common features on which to devise biorefinery models for WP7 and WP8. It was decided to base such biorefinery modelling on basic lignocellulosic processing data on details provided by the National Renewable Energy Laboratory (NREL) for the conversion of corn stover into ethanol (Ref. 11), adapted to the needs of the SUNLIBB Project in terms of other biomass feedstocks (sugar cane, bagasse, whole maize and miscanthus), the effects of genetic improvements in maize and miscanthus feedstocks (from SUNLIBB Project WP7) and novel biomass treatments which recover other products (from SUNLIBB Project WP6).

The NREL process uses dilute sulphuric acid for biomass pre-treatment. Considerable design and operating information is given on a conceptually commercial configuration for an integrated plant. This conceptual plant design includes:



- feedstock handling with corn stover milling;
- pre-treatment and conditioning with high temperature dilute acid and ammonia neutralisation;
- enzymatic hydrolysis and fermentation (with no heat requirement);
- cellulose enzyme production;
- ethanol separation and distillation;
- waste water treatment with anaerobic digestion for biogas production; chemical storage;
- CHP generation from lignin and waste solids (dewatered with pressure filtration rather than evaporation); and
- utilities (water management, cooling and general electricity supply within the plant).

The extent of the information for this conceptual design offers a sound basis for biorefinery specification in the SUNLIBB Project. The key parameters and values obtained from this particular source are summarised in Table 1. In order to use these data in the simulation of biorefineries using sugar cane bagasse and miscanthus as feedstocks, it was necessary to estimate recovery efficiencies for fermentable sugar and lignin from the relevant components of corn stover and apply these to those components in these other feedstocks. Using the NREL data for the conceptual plant for the conversion of corn stover into bioethanol, the following recovery efficiencies were estimated:

- recovery efficiency for fermentable sugars = 71%
- recovery efficiency for lignin = 83%

Using published characteristics for sugar cane bagasse (Ref. 12) and miscanthus (Ref. 13), the compositions of cellulose (for fermentable sugar recovery) and lignin were established. The relevant recovery efficiencies for the NREL conceptual plant were then applied to these compositions and unit outputs for fermentable sugar and lignin were extrapolated, as summarised in Table 2. It was assumed that all remaining material formed the waste solids output from the processing of these feedstocks.

Table 1 Key Parameters and Values for NREL Conversion of Corn Stover to Bioethanol

Parameter	Units	Value
Annual As Received (ar) Corn Stover Feed Rate Capacity	t (ar)/a	876,416
Corn Stover Moisture Content	% by weight	20.0
Annual Dry Corn Stover Feed Rate Capacity	t (dry)/a	701,133
Unit Electricity Requirement of Corn Stover Milling	kWh/t (ar feed)	7.90
Unit Heat Requirement of Pre-treatment <sup>(a)</sup>	MJ/t (dry feed)	151
Unit Electricity Requirement of Pre-treatment <sup>(b)</sup>	kWh/t (dry feed)	159
Unit Sulphuric Acid Requirement <sup>(a)</sup>	kg (93%)/t (dry feed)	23.8
Unit Ammonia Requirement <sup>(c)</sup>	kg/t (dry feed)	14.0
Unit Corn Steep Liquor Requirement <sup>(c)</sup>	kg/t (dry feed)	15.9
Unit Glucose Requirement <sup>(d)</sup>	kg/t (dry feed)	29.0
Unit Fermentable Sugar Output from Pre-treatment	t (dry)/t (dry feed)	0.291
Fermentable Sugar Concentration	% by weight	11.7
Unit Lignin Output from Pre-treatment	t (dry)/t (dry feed)	0.150
Lignin Moisture Content	% by weight	87.9
Unit Waste Solid Output from Pre-treatment	t (dry)/t (dry feed)	0.559
Waste Solids Moisture Content	% by weight	87.9
Unit Electricity Requirement of Fermentation	kWh/t ethanol	12.0
Unit Ethanol Output from Fermentation	g ethanol/g sugar	0.483
Unit Carbon Dioxide Output from Fermentation	t CO <sub>2</sub> /t ethanol	0.876
Unit Heat Requirement of Ethanol Recovery	MJ/t ethanol	7,437
Unit Electricity Requirement of Ethanol Recovery	kWh/t ethanol	93.4
Unit Electricity Requirement for Utilities	kWh/t ethanol	150
Annual Bioethanol (100% ethanol) Output Capacity	t/a	182,418

Notes

- (a) Pre-treatment only.
- (b) Pre-treatment, enzyme production and enzymatic hydrolysis.
- (c) Pre-treatment and enzyme production.
- (d) Enzyme production only.

Table 2 Basic Biomass Feedstock Composition and Extrapolated Process Outputs

Default Data	Sugar Cane Bagasse	Maize	Miscanthus
Feedstock Composition (dry matter):			
- Cellulose	46.4% <sup>(a)</sup>	41.0% <sup>(e)</sup>	38.2% <sup>(i)</sup>
- Hemicellulose	25.9% <sup>(b)</sup>	24.0% <sup>(f)</sup>	24.3% <sup>(j)</sup>
- Lignin	23.6% <sup>(c)</sup>	18.0% <sup>(g)</sup>	25.0% <sup>(k)</sup>
- Other	4.1% <sup>(d)</sup>	17.0% <sup>(h)</sup>	12.5% <sup>(l)</sup>
Process Output (dry matter output per dry matter feedstock input):			
- Fermentable Sugar	0.329 odt/odt <sup>(m)</sup>	0.291 odt/odt <sup>(p)</sup>	0.271 odt/odt <sup>(r)</sup>
- Lignin	0.196 odt/odt <sup>(n)</sup>	0.150 odt/odt <sup>(q)</sup>	0.207 odt/odt <sup>(s)</sup>
- Waste Solids	0.475 odt/odt <sup>(o)</sup>	0.559 odt/odt <sup>(o)</sup>	0.522 odt/odt <sup>(o)</sup>

Notes

- (a) Sugar cane bagasse composition for cellulose from Ref. 12.
- (b) Sugar cane bagasse composition for pentosans assumed to be hemicellulose from Ref. 12.
- (c) Sugar cane bagasse composition for lignin from Ref. 12.
- (d) Sugar cane bagasse composition remaining after accounting for cellulose, pentosans and lignin from Ref. 12.
- (e) Corn stover composition for hexoses (glucan, mannan and galactan) from Ref. 11.
- (f) Corn stover composition for pentoses (xylan and arabinan) from Ref. 11.
- (g) Corn stover composition for lignin from Ref. 11.
- (h) Corn stover composition remaining after accounting for hexoses, pentoses and lignin from Ref. 11.
- (i) Miscanthus composition for cellulose from Ref. 13.
- (j) Miscanthus composition for hemicellulose from Ref. 13.
- (k) Miscanthus composition for acid insoluble and acid soluble lignin from Ref. 13.
- (l) Miscanthus composition remaining after accounting for cellulose, hemicellulose and lignin from Ref. 13.
- (m) Estimated using sugar cane bagasse feedstock composition from Ref. 12 and assumed fermentable sugar recovery efficiency of 71% derived from Ref. 11.
- (n) Estimated using sugar cane bagasse feedstock composition from Ref. 12 and assumed lignin recovery efficiency of 83% derived from Ref. 11.
- (o) Remaining material assumed to be waste solids.
- (p) Estimated using corn stover feedstock composition from Ref. 11 and assumed fermentable sugar recovery efficiency of 71% derived from Ref. 11.
- (q) Estimated using corn stover feedstock composition from Ref. 11 and assumed lignin recovery efficiency of 83% derived from Ref. 11.
- (r) Estimated using miscanthus feedstock composition from Ref. 13 and assumed fermentable sugar recovery efficiency of 71% derived from Ref. 11.
- (s) Estimated using miscanthus feedstock composition from Ref. 13 and assumed lignin recovery efficiency of 83% derived from Ref. 11.

Using information summarised in Tables 1 and 2, supplemented with other relevant data for the NREL conceptual plant, earlier MS Excel workbooks for calculating primary energy inputs and greenhouse gas (GHG) emissions associated with sugar cane/bagasse, maize and miscanthus biorefineries, including biomass feedstock provision, were modified to accommodate biomass pre-treatment with dilute sulphuric acid. These workbooks were then modified further to simulate potential increases in the recovery of fermentable sugar by:

- applying supercritical carbon dioxide (CO<sub>2</sub>) extraction (SCE) during pre-treatment, and
- using genetically-improved maize and miscanthus.

The experimental data available from work conducted in SUNLIBB Project Work Package (WP) 6 on “Generating Added-Value from Biomass” and from the pilot scale trials in WP 7 on “Integrated Process Engineering to Obtain Full Value from Biomass Processing” provided the basis of these modifications. These modifications enabled the workbooks to address various aspects of the stated aims of the SUNLIBB Project, namely to:

- improve the feedstock quality of lignocellulose in biofuels crops to allow truly cost-effective ethanol production,
- add value to the overall process of conversion in biomass biorefining by upgrading residues and by-products and producing new value streams in addition to bioethanol,
- improve the conversion process by which we produce sugars,
- improve fermentation efficiency,
- develop integrated processes that capture maximum value from lignocellulosic biomass, and
- ensure that the new processes developed fulfil sustainability requirements by reducing GHG emissions, cutting other forms of air pollution, have minimal impacts on local environments and biodiversity, build sustainable rural industries, and do not impact on food production and prices.

From SUNLIBB Project WP6, data were available on the requirements needed to apply SCE to miscanthus and the subsequent recovery of wax (Refs. 14 and 15). These data consisted of the heat and electricity requirements of supercritical CO<sub>2</sub> extraction, as summarised in Table 3, and the capital costs of the necessary equipment for treating miscanthus. It was assumed that these data could also be adopted for the processing of maize. Additionally, data were available on the amounts of wax recovered from the SCE of maize (0.90%) and miscanthus (0.70%). Supplementary information was provided on the calorific value (approximately 40,000 MJ/t) and expected price of miscanthus wax (€10/kg) which was also assumed to apply to maize wax (Refs. 16 and 17).

Table 3 Summary of Data for Supercritical Carbon Dioxide Extraction

Parameter	Units	Value	Notes
Unit Heat Requirement	MJ/oven dry t biomass	1,819	Based on 64.88 kWh of heating for 0.1284 tonnes of miscanthus, assumed to be oven dry.
Unit Electricity Requirement	kWh/oven dry t biomass	1,947	Based on 20.27 kWh of refrigeration and 229.768 kWh of carbon dioxide pumping for 0.1284 tonnes of miscanthus, assumed to be oven dry.

In SUNLIBB Project WP7, trials were conducted on the pre-treatment of so-called generic maize and miscanthus, and two different genotypes of maize and miscanthus, referred to as low and high digestibility genotypes. Additionally, trials were also conducted on generic maize and miscanthus that had been subjected to SCE. Data were available on these trials from various documents (Refs. 18 and 19).

By combining these data together and extending it, where necessary, with supplementary information, it was possible to speculate on the recovery of fermentable sugar and lignin that could be achieved by using generic and genetically-improved maize and miscanthus, and by applying SCE. These results, in the form of arithmetic averages of trials with 3 samples which are presented in Table 4, were used to derive the changes in fermentable sugar and lignin recovery relative to the pre-treatment of generic maize and miscanthus without SCE, which are summarised in Table 5.

Table 4 Speculated Recovery of Fermentable Sugar and Lignin with Generic and Genetically-Improved Maize and Miscanthus and by Application of Supercritical Carbon Dioxide Extraction

Type of Biomass	Type of Pre-treatment	Sample Code	Average Unit Fermentable Sugar Output (dry t/dry t initial biomass input)	Average Unit Lignin Output (dry t/dry t initial biomass input)
Generic Maize	Without SCE	MA nE	0.141	0.182
Generic Maize	With SCE	MA E	0.144	0.180
Low Digestibility Genotype Maize	Without SCE	MA GeB	0.145	0.197
High Digestibility Genotype Maize	Without SCE	MA GeA	0.153	0.196
Generic Miscanthus	Without SCE	MI nE	0.087	0.233
Generic Miscanthus	With SCE	MI E	0.110	0.185
Low Digestibility Genotype Maize	Without SCE	MI GeB	0.112	0.258
High Digestibility Genotype Maize	Without SCE	MI GeA	0.117	0.256

Table 4 Relative Changes in Speculated Recovery of Fermentable Sugar and Lignin with Genetically-Improved Maize and Miscanthus and by Application of Supercritical Carbon Dioxide Extraction

Type of Biomass	Type of Pre-treatment	Sample Code	Relative Change in Fermentable Sugar Recovery (%)	Relative Change in Lignin Recovery (%)
Generic Maize	With SCE	MA E	+2.1	-1.1
Low Digestibility Genotype Maize	Without SCE	MA GeB	+2.8	+8.2
High Digestibility Genotype Maize	Without SCE	MA GeA	+8.5	+7.7
Generic Miscanthus	With SCE	MI E	+26.4	-20.6
Low Digestibility Genotype Maize	Without SCE	MI GeB	+28.7	+10.7
High Digestibility Genotype Maize	Without SCE	MI GeA	+34.5	+9.9

In the absence of other relevant information, the results shown in Table 5 were used to modify the MS Excel workbooks for the effects of using low and high digestibility genotypes, instead of generic maize and miscanthus, and of applying SCE in pre-treatment. It is, however, necessary to be aware of the following critical assumptions in adopting these results in this speculative manner:

- relative changes translate directly over to dilute sulphuric acid pre-treatment of maize and miscanthus, as incorporated into the NREL conceptual plant, from SUNLIBB WP 7 trials involving less aggressive pre-treatment using water, or sodium hydroxide and water, which resulted in low fermentation yields,
- relative changes for pre-treatment with SCE can be combined, multiplicatively, with relative changes due to the use of genetically-improved maize and miscanthus,
- cultivation practices and yields of genetically-improved maize and miscanthus are the same as conventionally grown maize and miscanthus, and
- unit ethanol output from fermentation, or fermentation yield, incorporated in the NREL conceptual plant can be adopted in biorefineries converting all types of maize and miscanthus to bioethanol.

The subsequent final versions of MS Excel workbooks for evaluating primary energy inputs and GHG emissions associated with biorefineries in the SUNLIBB Project consisted:

- SUNLIBB Sugar Cane Ethanol NREL Biorefinery v04.xls
- SUNLIBB Maize Ethanol Pilot Study Biorefinery v01.xls
- SUNLIBB Miscanthus Ethanol Pilot Study Biorefinery v02.xls

These workbooks consist of a common series of worksheets used on a standard basis by North Energy Associates Ltd to evaluate total primary energy inputs and total GHG emissions associated with any given technology in a transparent manner, incorporating modelling of key options and parameters. In general, this includes the following essential worksheets:

- an Input worksheet for entering values of specified options and parameters,
- a Unit Flow Chart worksheet for representing, visually, specific process stages of the technology,
- individual Process Stage worksheets for calculating primary energy inputs and CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions associated with each process stage in units relevant for that particular stage,
- a Reference worksheet for documenting all sources of data used in calculations, and
- Summary worksheets for presenting the main results of the evaluation, broken down by contribution, in tabular and graphical form.

Default values of parameters and options are provided in the Input worksheet and these can be changed (entries in Column F). For these particular workbooks, results are presented in terms of MJ of primary energy and kg of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and equivalent (eq.) CO<sub>2</sub> (combining CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions by means of selected Global Warming Potentials; GWPs) per t of ethanol produced and delivered. The necessary modelling capabilities of these workbooks are operated through the specified options and parameters. The most important options in these workbooks consist of:

- the choice of calculation methodology that determines which values are adopted for GWPs,
- the choice of whether to include primary energy inputs and GHG emissions associated with the manufacture of plant, equipment, machinery and vehicles,
- the choice of which credit value to adopt for any surplus electricity from the biorefinery,
- the choice of the type of biomass used as feedstock in the biorefinery (sugar cane or sugar cane and bagasse; corn stover or whole maize; and generic, low digestibility or high digestibility genotype maize or miscanthus),
- the choice of supplementary fuel used in the biorefinery (bagasse, lignin and/or waste solids),
- the choice of energy source used in the biorefinery (boiler with imported grid electricity or CHP),
- the choice of using SCE in the maize and miscanthus biorefineries, and
- the choice of capturing fermentation gases and whether a credit value is assigned to CO<sub>2</sub>.

In addition, databases are incorporated in these workbooks with primary energy multipliers and GHG emissions factors for different types and sources of nitrogen (N) fertilisers, phosphate (P) fertilisers, potash (K) fertilisers, and lime (ground limestone).

Generally, the parameters which can be altered in these workbooks include:

- biomass feedstock yield (assuming consistent changes in cultivation parameters),
- biomass feedstock transportation mode and round trip distance,
- unit heat requirements of the biorefinery (SCE, biomass processing, fermentation, ethanol recovery, and pressure filtration of lignin and waste solids),
- unit electricity requirements of the biorefinery (biomass milling, SCE, biomass processing, fermentation, ethanol recovery, pressure filtration of lignin and waste solids, and utilities),
- unit chemical requirements of biomass processing in the biorefinery,
- unit fermentable sugar and lignin production from biomass processing,
- unit ethanol output from fermentation,
- unit CO<sub>2</sub> output from fermentation,
- ethanol distribution modes and round trip distances, and
- net calorific values, prices and substitution credits for co-product allocation.

## **4. QUANTITATIVE RESULTS**

### **4.1 Sensitivity Analysis**

Given the considerable functionality summarised previously (see Section 3), a very large range of sensitivities can be explored using these workbooks. In order to ensure that sensitivity analysis is manageable and subsequent outcomes understandable, it was necessary to restrict the exploration reported here to the most significant sensitivities. From previous work, it is well-known that the calculation methodology has a very fundamental impact on results, especially in terms of GHG emissions. Additionally, for biorefineries based on fermentation, the choice of capturing CO<sub>2</sub>, is very influential. It is also known that the source of energy in the biorefinery can affect results substantially. However, since this affect is considered later (see Section 4.2), it has been assumed that this source of energy is CHP, primarily fired by natural gas supplemented by lignin, waste solids and biogas recovered from waste water treatment. This reflects the configuration frequently adopted in proposed designs for biorefineries.



For this sensitivity analysis, the following four different calculation methodologies were considered:

- RED methodology (excluding GHG emissions associated with the manufacture of plant, equipment, machinery and vehicles; credit for any surplus electricity from the biorefinery based on replacement generation; credit for any CO<sub>2</sub> captured from fermentation based on displaced fossil CO<sub>2</sub>; and co-product allocation based on energy content),
- Mass allocation methodology (as RED methodology but with all co-product allocation based on mass),
- PAS 2050 methodology (including GHG emissions associated with the manufacture of plant, equipment, machinery and vehicles; credit for any surplus electricity from the biorefinery based on displaced gross grid electricity; any CO<sub>2</sub> captured treated as a co-product; and all co-product allocation based on economic value or price), and
- Substitution credit methodology or consequential LCA (as PAS 2050 methodology but with all co-products evaluated by substitution credits for displaced alternative products).

#### 4.1.1 Sugar Cane/Bagasse Biorefinery

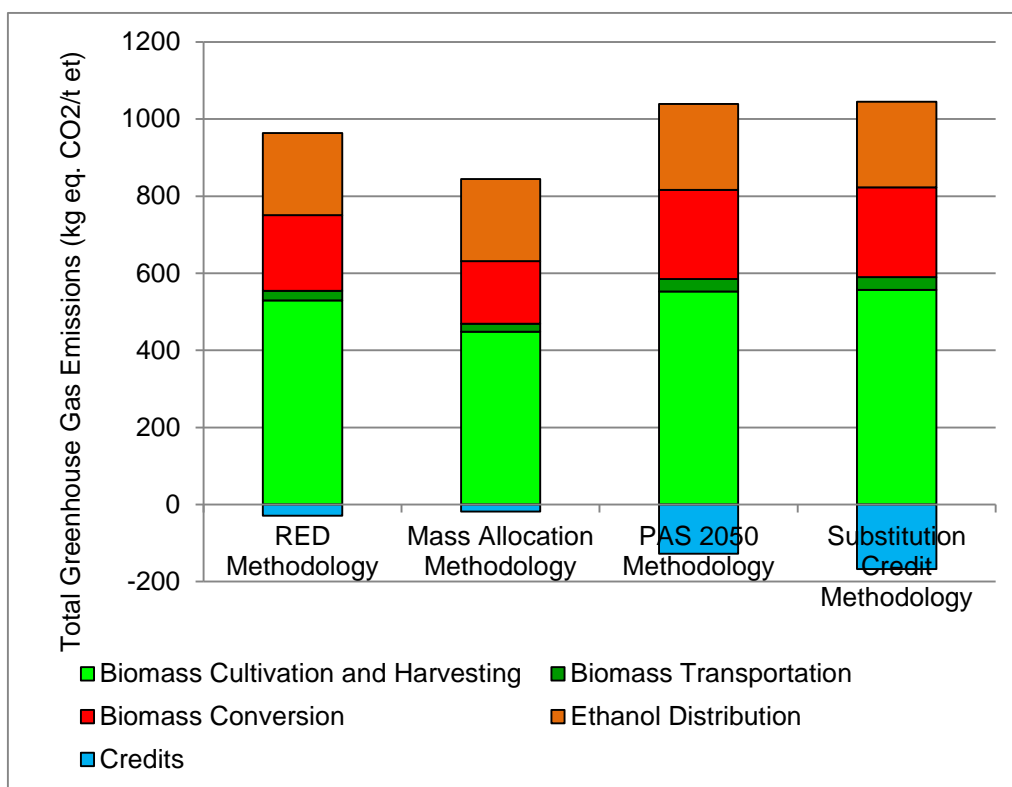
As an effective baseline for biorefineries, the total GHG emissions associated with the production of ethanol from sugar cane using bagasse as a fuel were determined for each of these methodologies. The results are shown in Figure 1 which indicates that total GHG emissions range from 826 kg eq. CO<sub>2</sub>/t (mass allocation methodology) to 934 kg eq. CO<sub>2</sub>/t (RED methodology). The result with the mass allocation methodology is lower than that for the RED methodology, which uses energy content allocation, because of the relatively high masses of co-products which, effectively, reduced the allocation of GHG emissions to ethanol. Leaving aside the credits which introduce negative contributions to GHG emissions, the GHG emissions under the PAS 2050 and substitution credit methodologies are higher mainly because GHG emissions from the manufacture of plant, equipment, machinery and vehicles are included. The credits shown in Figure 1 are due to the export of surplus electricity. The credit with the PAS 2050 methodology is higher than those of the RED and mass allocation methodologies due to the use of a credit based on the displacement of gross grid electricity rather than displaced generation<sup>1</sup>. The credit with the substitution credit methodology is the highest because this includes credits for all co-products as well as that for surplus electricity from the CHP unit in the biorefinery.

With all the methodologies, the largest contribution to total GHG emissions is from sugar cane cultivation and harvesting. The next most significant contributions are from biomass conversion and ethanol distribution. This later contribution is significant because it assumes ethanol production in Brazil and subsequent transport to the EU. The contribution from biomass transportation is very low due to the relative proximity of the biorefinery to areas where sugar cane is grown.

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<sup>1</sup> GHG emissions credits derived from displaced generation are based on the assumption that the fuel used in the CHP unit of the biorefinery are used to generate electricity only. If a large proportion of CHP fuel is biomass then a credit based on displaced generation is lower than a credit for grid electricity that has been generated with a large proportion of fossil fuels.

Figure 1 Total Greenhouse Gas Emissions Associated with Ethanol Production from Sugar Cane with Bagasse as Fuel, without Carbon Dioxide Capture from Fermentation



The effect on total GHG emissions of using bagasse as a feedstock, in addition to sugar cane, for ethanol production can be seen in Figure 2. The range of results with the different methodologies is now between 763 kg eq. CO<sub>2</sub>/t (mass allocation methodology) and 877 kg eq. CO<sub>2</sub>/t (PAS 2050 methodology). Overall, there is a noticeable reduction in the total GHG emissions associated with ethanol production. Additionally, the amount of ethanol produced per unit area of land increases from 5.04 t/ha with sugar cane only as a feedstock to 7.41 t/ha with sugar cane and bagasse as feedstocks. These estimates are based on the default values adopted in the sugar cane/bagasse biorefinery workbook. The reductions in total GHG emissions for ethanol are mainly due to a decrease in the contributions from biomass cultivation and harvesting, for all methodologies. This is because more ethanol can be obtained from the same area of land which requires a given amount of inputs, in the form of diesel fuel for machinery, fertilisers, etc. There is an increase in the contributions to total GHG emissions from biomass conversion which is mainly due to the higher use of natural gas in the CHP unit of the biorefinery caused by reliance on only lignin and waste solids, and not also bagasse, as supplementary fuels.

The impact of capturing CO<sub>2</sub> from fermentation on total GHG emissions of ethanol production from sugar cane with bagasse as a CHP fuel is demonstrated in Figure 3. This indicates very different outcomes for the different methodologies. In general, the range of total GHG emissions is from - 2,587 kg eq. CO<sub>2</sub>/t (substitution credit methodology) to 863 kg eq. CO<sub>2</sub>/t (PAS 2050 methodology). These large differences are due to the way that the captured CO<sub>2</sub> is treated in calculations performed under each methodology. With the RED methodology, CO<sub>2</sub> captured from fermentation is regarded as biogenic (which, overall, does not increase the amount of CO<sub>2</sub> in the

Figure 2 Total Greenhouse Gas Emissions Associated with Ethanol Production from Sugar Cane and Bagasse, without Carbon Dioxide Capture from Fermentation

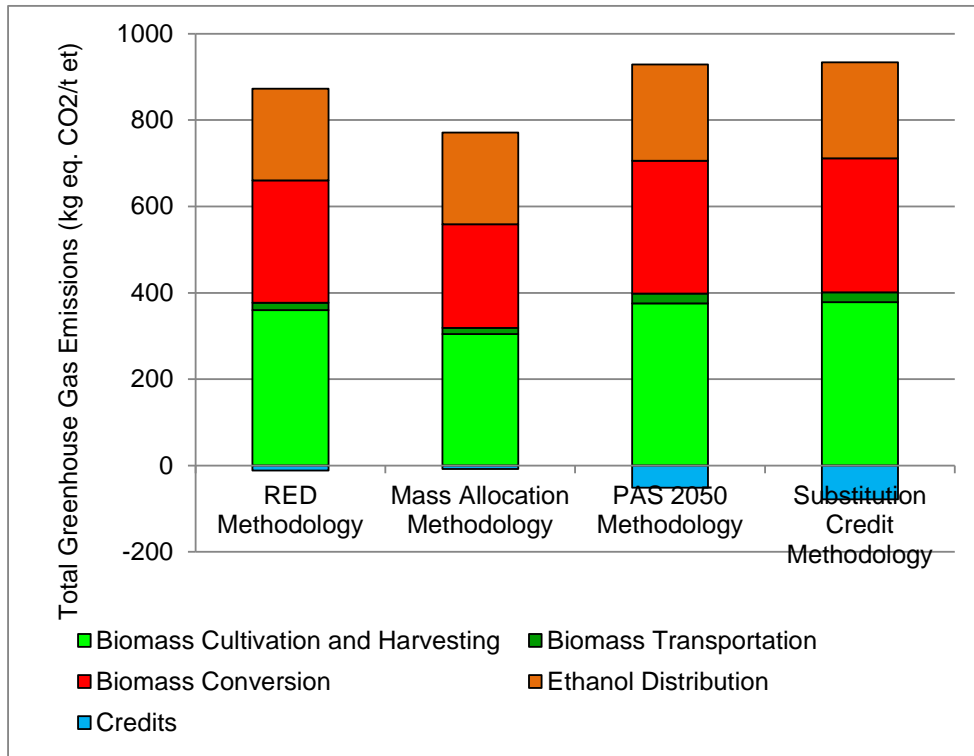
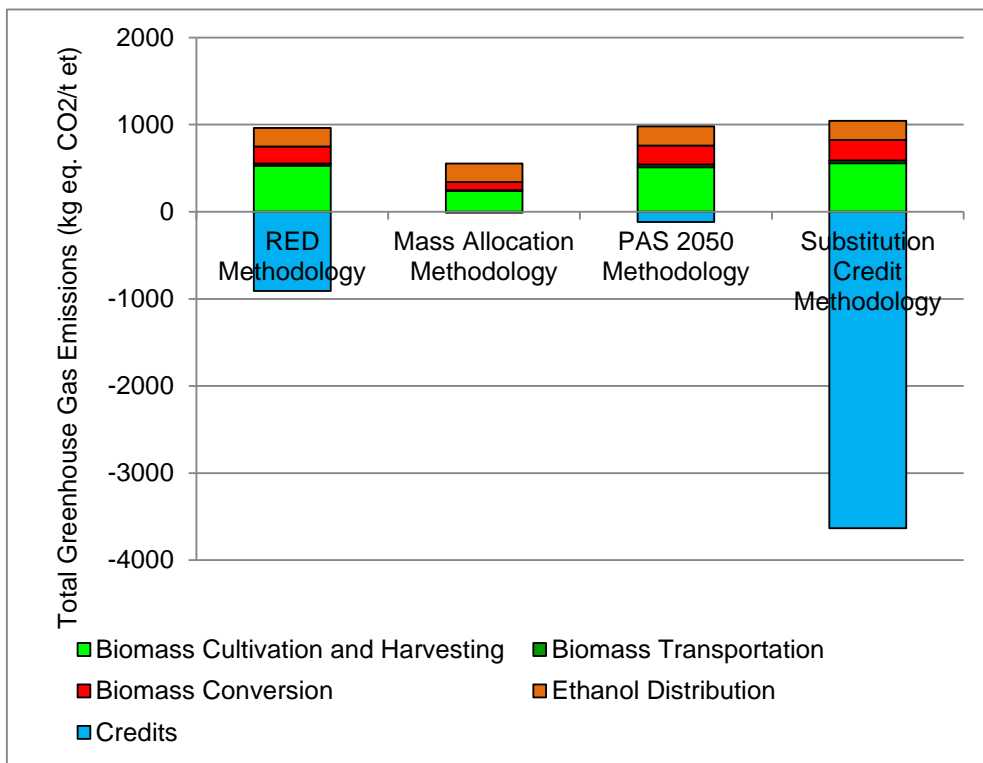
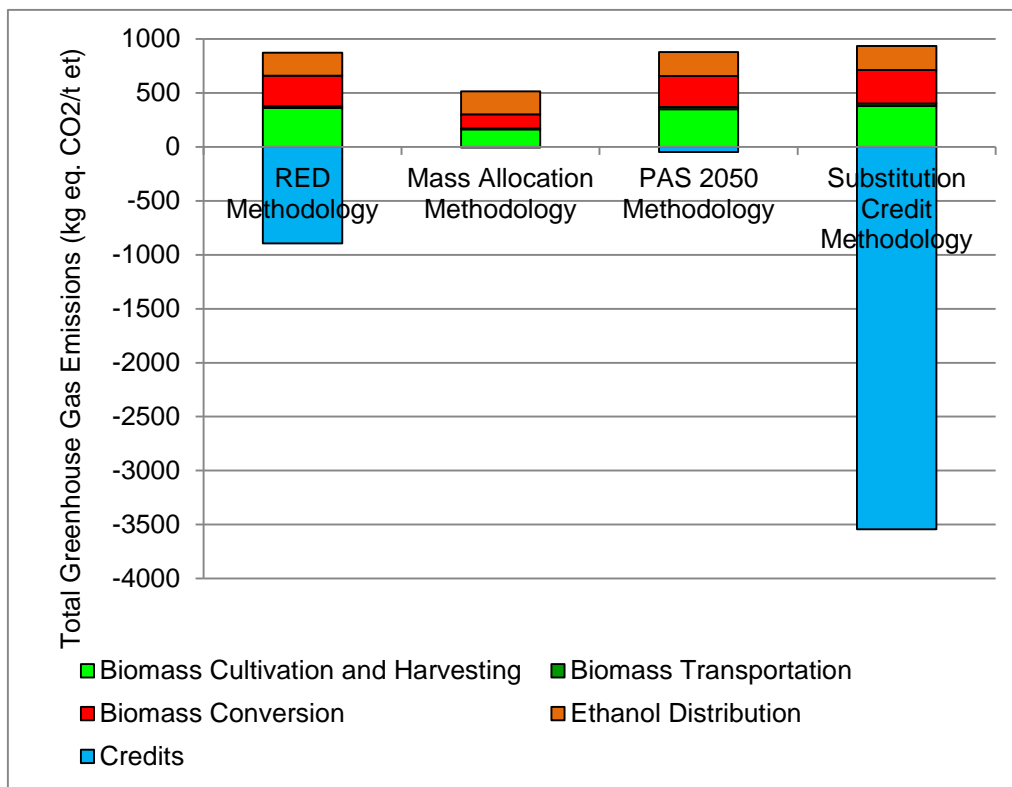


Figure 3 Total Greenhouse Gas Emissions Associated with Ethanol Production from Sugar Cane with Bagasse as Fuel, with Carbon Dioxide Capture from Fermentation



atmosphere) and it displaces fossil CO<sub>2</sub> (which does increase the amount of CO<sub>2</sub> in the atmosphere). Hence, the credit applied in the RED methodology is 1,000 kg eq. CO<sub>2</sub>/t CO<sub>2</sub>. With the mass allocation methodology, there is no credit for the captured CO<sub>2</sub> and the only impact on total GHG emissions is that the CO<sub>2</sub> forms an additional co-product from ethanol production in the biorefinery. Likewise, there is no credit for the captured CO<sub>2</sub> with the PAS 2050 methodology as it is classed as another co-product and allocated GHG emissions via its price, which is low compared to that of ethanol. A much more dramatic impact is generated with the captured CO<sub>2</sub> under the substitution credit methodology. This is because a substitution credit of 3,932 kg eq. CO<sub>2</sub>/t has been applied to the CO<sub>2</sub> captured from fermentation since it has been assumed that it displaces CO<sub>2</sub> that would have been produced from crude oil with all related processing activities (Ref. 20). Similar outcomes can be found in Figure 4 which presents total GHG emissions associated with the production of ethanol from sugar cane and bagasse with capture of fermentation CO<sub>2</sub>. In this case, total GHG emissions are reduced further and range from -2,609 kg eq. CO<sub>2</sub>/t (substitution credit methodology) to 831 kg eq. CO<sub>2</sub>/t (PAS 2050 methodology).

Figure 4 Total Greenhouse Gas Emissions Associated with Ethanol Production from Sugar Cane and Bagasse, with Carbon Dioxide Capture from Fermentation



As discussed previously (see Section 2), the RED methodology is the official means of assessing biofuels for regulatory purposes in the EU. Consequently, it is instructive to examine the results for ethanol as a biofuel produced from sugar cane or sugar cane and bagasse using the relevant workbook. In this context, results can be converted into net GHG emissions savings, based on a net calorific value for ethanol of 26,700 MJ/t and a gasoline comparator of 0.0838 kg eq. CO<sub>2</sub>/MJ. Such results can be compared with minimum net GHG emissions saving of 60% which apply after 2017 under the RED. Subsequent results are given in Table 5 which considers the effects using

bagasse as a fuel or feedstock, using a boiler and imported electricity or a CHP unit, and releasing or capturing fermentation CO<sub>2</sub> in the biorefinery.

Table 5 Total Greenhouse Gas Emissions Associated with Sugar Cane and Bagasse Conversion to Ethanol as a Fuel

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions		Net Greenhouse Gas Emissions Savings (%)
		kg eq. CO <sub>2</sub> /t	kg eq. CO <sub>2</sub> /MJ	
Bagasse used as fuel, boiler and imported electricity, and carbon dioxide from fermentation released	5.04	1,046	0.0392	53
Bagasse used as fuel, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation released	5.04	934	0.0350	58
Bagasse used as fuel, boiler and imported electricity, and carbon dioxide from fermentation captured	5.04	165	0.0062	93
Bagasse used as fuel, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation captured	5.04	53	0.0020	98
Bagasse used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	7.41	941	0.0352	58
Bagasse used as feedstock, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation released	7.41	861	0.0322	62
Bagasse used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	7.41	60	0.0022	97
Bagasse used as feedstock, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation captured	7.41	-21	-0.0008	101

Note

\* All other parameters set at default values.

To assist with the interpretation of results, a “traffic light” system is applied in Table 5 to indicate those results which do not meet the minimum net GHG emissions savings (red), those which clearly exceed this minimum (green) and those which are very close to the minimum and should be treated with caution as small changes in other parameters could cause them to fall below the minimum (amber). Although all the design configurations considered here achieve net GHG emissions savings only those combinations which incorporate fermentation CO<sub>2</sub> capture definitely exceed the minimum of 60%.

Unlike biofuels, there is no mandatory minimum net greenhouse gas emissions savings for biochemicals. However, it is reasonable to assume that total GHG emissions associated with biochemicals should be lower than those for their fossil fuel-derived equivalents. Additionally, there is no mandatory methodology for calculating total GHG emissions for biochemicals. However, the PAS 2050 methodology is widely used in the carbon footprinting of products and services and, hence, it would seem appropriate to apply it here as it is evaluating the total GHG emissions associated with the production of ethanol used as a chemical. In this context, a comparator for petro-ethanol of 1,247 kg eq. CO<sub>2</sub>/t (Ref. 21) has been used to determine the net GHG emissions savings of ethanol derived from biomass and used as a chemical. Subsequent results are given in Table 6 which considers the effects using bagasse as a fuel or feedstock, using a boiler and imported electricity or a CHP unit, and releasing or capturing fermentation CO<sub>2</sub> in the biorefinery. This shows that, for all the combinations of design configurations examined here for the production of ethanol from sugar cane or sugar cane and bagasse, there are net GHG emissions savings over petro-ethanol. It is, however, apparent that some of these net GHG emissions savings are relatively small.

It should be noted that this evaluation only addresses production and that a key consideration concerns the ultimate fate of products derived from ethanol used as a chemical. The reason why this is a key consideration depends on whether the carbon in the product is ever released into the atmosphere. In particular, for ethanol derived from sugar cane/bagasse, the carbon is biogenic. Consequently, if it is eventually released, say, by incineration as a means of waste disposal, then this will be balanced by the carbon which was originally absorbed, in the form of CO<sub>2</sub>, by the sugar cane plants. As a result, there is no overall impact. In contrast, if waste disposal involves burial in landfill with no subsequent breakdown of the product, then the carbon will be “locked away” from the atmosphere. In this case, the overall impact will be that carbon will, in effect, have been removed from the atmosphere. These outcomes can be compared with the impacts of the waste disposal of products incorporating petro-ethanol. Since this contains fossil carbon which was originally extracted from the ground, if it is released by incineration, it will lead to an increase of CO<sub>2</sub> in the atmosphere. Burial in landfill without subsequent degradation will ensure that the fossil carbon is not allowed to enter the atmosphere. Given that ethanol has the potential to release 957 kg CO<sub>2</sub>/t into the atmosphere or, indeed, store it away from the atmosphere, the end-of-life fate of any given product containing this chemical has a fundamental influence on its total “cradle-to-grave” GHG emissions. Unfortunately, most manufacturers cannot dictate the eventual fates of their products so that such outcomes cannot be determined with certainty. Hence, in this analysis, attention is focused primarily on GHG emissions associated with ethanol production.

Table 6 Total Greenhouse Gas Emissions Associated with Sugar Cane and Bagasse Conversion to Ethanol as a Chemical

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions kg eq. CO <sub>2</sub> /t	Net GHG Emissions Savings Over Petro-ethanol (%)
Bagasse used as fuel, boiler and imported electricity, and carbon dioxide from fermentation released	5.04	1,122	10
Bagasse used as fuel, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation released	5.04	911	27
Bagasse used as fuel, boiler and imported electricity, and carbon dioxide from fermentation captured	5.04	1,059	15
Bagasse used as fuel, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation captured	5.04	863	31
Bagasse used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	7.41	997	20
Bagasse used as feedstock, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation released	7.41	877	30
Bagasse used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	7.41	943	24
Bagasse used as feedstock, combined heat and power (5.7:1 heat to power ratio), and carbon dioxide from fermentation captured	7.41	831	33

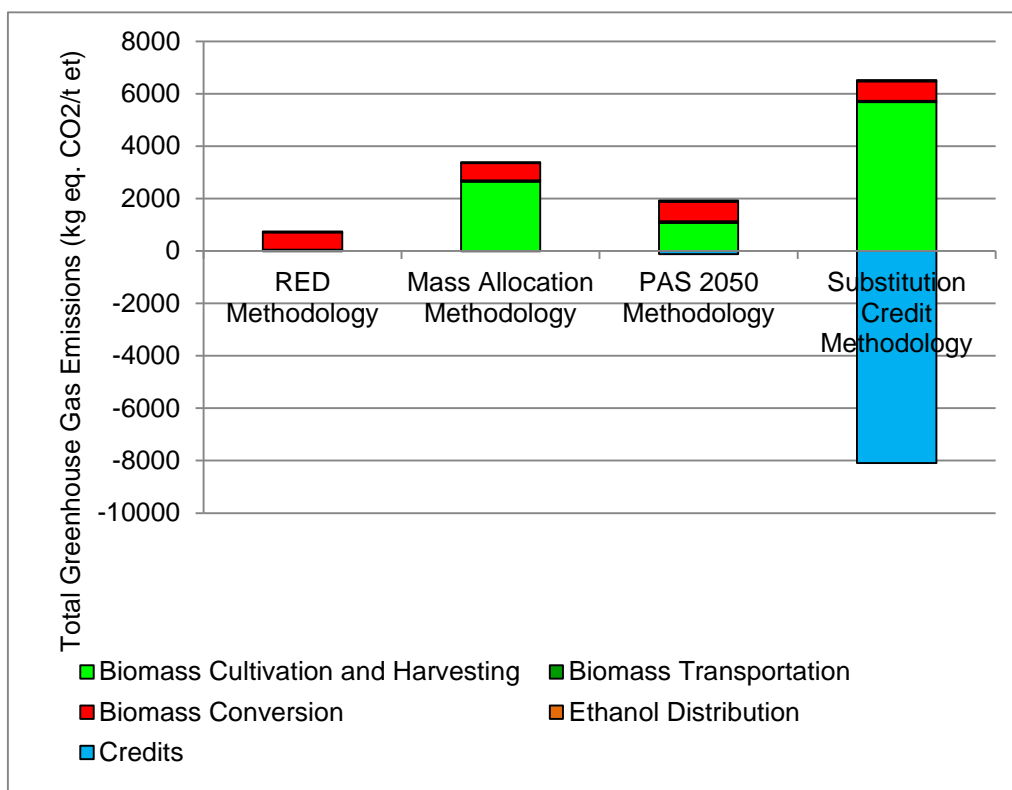
Note

\* All other parameters set at default values.

4.1.2 Maize Biorefinery

Total GHG emissions associated with the production of ethanol from corn stover and whole maize were estimated with the four calculation methodologies under consideration here. Figure 5 shows the results for corn stover with a CHP unit in the biorefinery fired by a combination of lignin and waste solids from biomass processing but without fermentation CO<sub>2</sub> capture. It is apparent that there is a very considerable range of total GHG emissions across the different methodologies, between

Figure 5 Total Greenhouse Gas Emissions Associated with Ethanol Production from Corn Stover, without Carbon Dioxide Capture from Fermentation



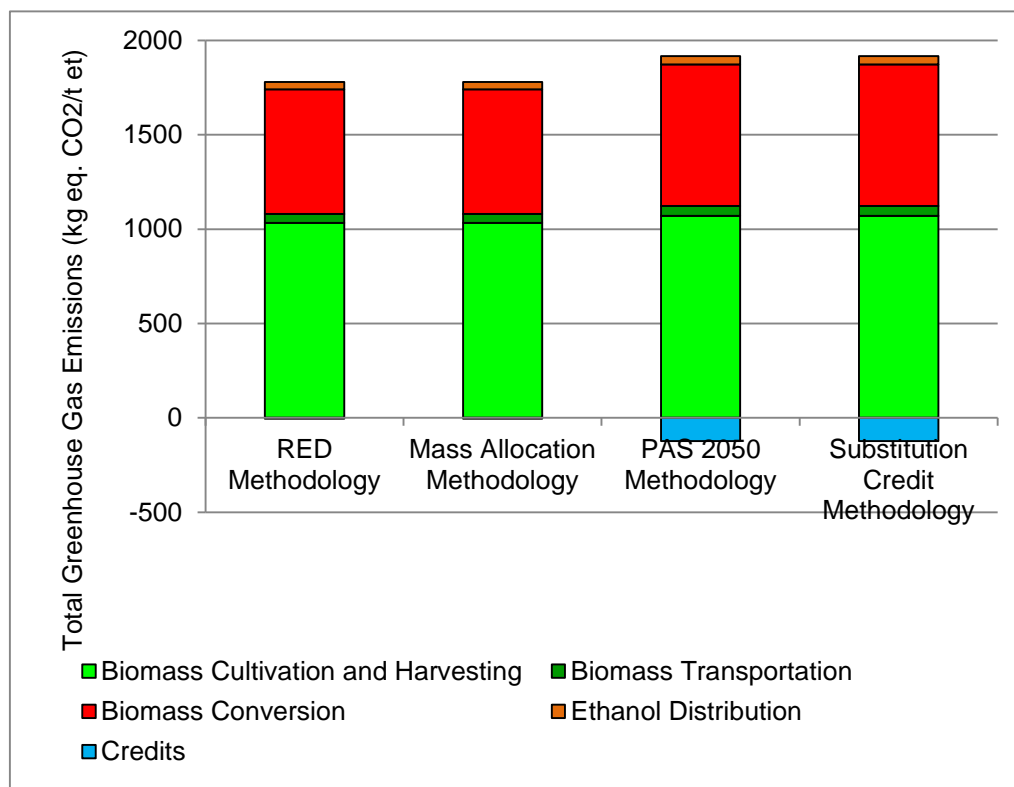
– 1,566 kg eq. CO<sub>2</sub>/t (substitution credit methodology) and 3,387 kg eq. CO<sub>2</sub>/t (mass allocation methodology). The specific details of these calculation methodologies are basically responsible for this large range in results. Total GHG emissions associated with ethanol production from corn stover under the Red methodology are comparatively low at 742 kg eq. CO<sub>2</sub>/t. This is due to the requirements of the RED methodology which means that corn stover is regarded as an agricultural residue with no GHG emissions associated with the cultivation and harvesting of maize grain. Total GHG emissions with the mass allocation methodology are higher because there is attribution of cultivation and harvesting GHG emissions on a mass basis between corn stover and maize grain. Similarly, there is a contribution from cultivation and harvesting to total GHG emissions of 1,800 kg eq. CO<sub>2</sub>/t under the PAS 2050 methodology although this is relatively lower due to the assumed price of corn relative to the price of maize grain. With the substitution credit methodology, GHG emissions from maize cultivation are much higher since they are all accounted. However, these are more than counter-balanced by a large credit for maize grain.

Results are quite different for ethanol production from whole maize without fermentation CO<sub>2</sub> capture, as indicated in Figure 6. The range of total GHG emissions is very narrow, from 1,775 kg eq. CO<sub>2</sub>/t (RED and mass allocation methodologies) to 1,793 kg eq. CO<sub>2</sub>/t (PAS 2050 and substitution credit methodologies). This is due to the fact that, with a single biomass feedstock crop such, as whole maize, and biomass processing with only one product, such as ethanol, there is no co-product allocation. Hence, results under the RED and mass allocation methodologies are the same. For the same reason, the results with the PAS 2050 and substitution credit



methodologies are also the same but higher than with the RED and mass allocation methodologies due to the inclusion of GHG emissions from the manufacture of plant, equipment, machinery, etc.

Figure 6 Total Greenhouse Gas Emissions Associated with Ethanol Production from Whole Maize, without Carbon Dioxide Capture from Fermentation



Similar patterns of results are obtained for total GHG emissions associated with ethanol production from corn stover and whole maize with fermentation CO<sub>2</sub> capture, as illustrated in Figures 7 and 8. However, the results for all methodologies are lower than those in Figures 5 and 6 due to the benefits, in terms of GHG emissions, of capturing CO<sub>2</sub> from fermentation. The range of total GHG emissions associated with ethanol production from corn stover, with fermentation CO<sub>2</sub> capture, is from -5,032 kg eq. CO<sub>2</sub>/t (substitution credit methodology) to 1,826 kg eq. CO<sub>2</sub>/t (mass allocation methodology). Similarly, the results with the RED and PAS 2050 methodologies are lower at -139 kg eq. CO<sub>2</sub>/t and 1,794 kg eq. CO<sub>2</sub>/t, respectively. The range of total GHG emissions associated with ethanol production from whole maize, with fermentation CO<sub>2</sub> capture, is from -1,672 kg eq. CO<sub>2</sub>/t (substitution credit methodology) to 1,787 kg eq. CO<sub>2</sub>/t (PAS 2050 methodology). Likewise, the results with the RED and mass allocation methodologies are lower at 894 kg eq. CO<sub>2</sub>/t and 966 kg eq. CO<sub>2</sub>/t, respectively.

Estimated net GHG emissions savings of ethanol, as a fuel, derived from corn stover and whole maize, under the RED methodology, are presented in Table 7 for biorefineries using a boiler and imported electricity or a CHP unit, and releasing or capturing fermentation CO<sub>2</sub>. The traffic light system is again deployed to indicate which combinations clearly achieve net GHG emissions savings higher than the required minimum of 60% after 2017. This shows that minimum net GHG emissions savings for ethanol from corn stover are possible provided that the use of a boiler and imported grid electricity, and fermentation CO<sub>2</sub> release to the atmosphere, is avoided. In contrast,

all combinations of the technological options considered here for the production of ethanol, as a fuel, from whole maize fail to achieve, minimum net GHG emissions savings clearly.

Figure 7 Total Greenhouse Gas Emissions Associated with Ethanol Production from Corn Stover, with Carbon Dioxide Capture from Fermentation

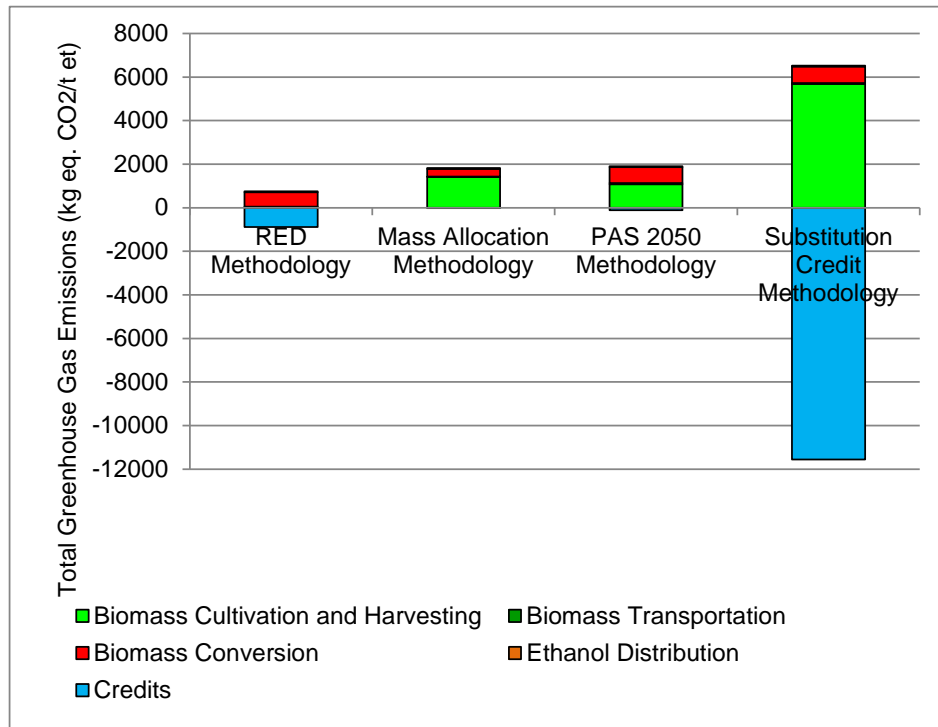


Figure 8 Total Greenhouse Gas Emissions Associated with Ethanol Production from Whole Maize, with Carbon Dioxide Capture from Fermentation

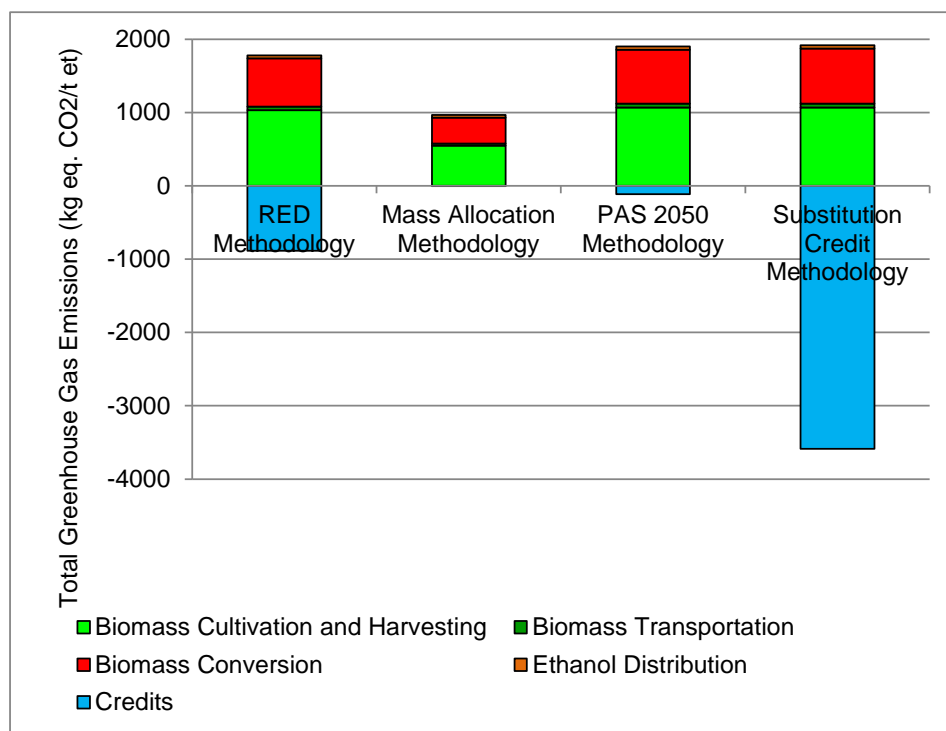


Table 7 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Fuel

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions		Net Greenhouse Gas Emissions Savings (%)
		kg eq. CO <sub>2</sub> /t	kg eq. CO <sub>2</sub> /MJ	
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	0.36	1,480	0.0554	34
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	0.36	742	0.0278	67
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	0.36	598	0.0224	73
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	0.36	-139	-0.0052	106
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	1.82	2,512	0.0941	-12
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	1.82	1,775	0.0665	21
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	1.82	1,631	0.0611	27
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	1.82	894	0.0335	60

Note

\* All other parameters set at default values.

As shown in Table 8, total GHG emissions associated with the production of ethanol, as a chemical, with all the technological options considered here, are higher than those of 1,247 kg eq. CO<sub>2</sub>/t for the production of petro-ethanol. As discussed previously (see Section 4.1.1), these results only refer to GHG emissions of production and they exclude the effects of any CO<sub>2</sub> released or “locked away”, depending on the chosen waste disposal option, at the end-of-life of the product that incorporates the ethanol. Taking the potential avoidance of 957 kg CO<sub>2</sub>/t released into the atmosphere, certain options represented in Table 8 would result in net GHG emissions lower than petro-ethanol. These options consist of ethanol, as a chemical, produced from either corn stover or whole maize in a biorefinery with a CHP unit, and with or without fermentation CO<sub>2</sub> capture.

#### 4.1.3 Miscanthus Biorefinery

Based on the four calculation methodologies considered here, the estimated total GHG emissions associated with the production of ethanol from miscanthus were estimated. Figure 9 provides the results for miscanthus with a CHP unit in the biorefinery fired by a combination lignin and waste solids from biomass processing but without fermentation CO<sub>2</sub> capture. The results range from 807 kg eq. CO<sub>2</sub>/t (PAS 2050 and substitution credit methodologies) to 892 kg eq. CO<sub>2</sub>/t (RED and mass allocation methodologies). This particular pattern of results is due to the fact that there are no co-products involved in the production of ethanol from miscanthus when fermentation CO<sub>2</sub> is not captured. The only differences between results are that, for the RED and mass allocation methodologies, GHG emissions for the manufacture of plant, equipment, machinery and vehicles are excluded and the credit for surplus electricity is based on replacement generation, whilst for the PAS 2050 and substitution credit methodologies, the GHG emissions of plant, etc., manufacture are included and the credit for surplus electricity is based on gross grid electricity.

The results for ethanol production from miscanthus with fermentation CO<sub>2</sub> capture with the four different methodologies are illustrated in Figure 10. These results are quite different, ranging from - 2,658 kg eq. CO<sub>2</sub>/t (substitution credit methodology) to 753 kg eq. CO<sub>2</sub>/t (PAS 2050 methodology). With the RED methodology, the total GHG emissions for ethanol production are 10 kg eq. CO<sub>2</sub>/t and, with the mass allocation methodology, they are 496 kg eq. CO<sub>2</sub>/t. The most significant cause of these differences is the capture of fermentation CO<sub>2</sub>. In the case of the RED methodology, a credit of 1,000 kg eq. CO<sub>2</sub>/t CO<sub>2</sub> is adopted compared with a credit of 3,932 kg eq. CO<sub>2</sub>/t CO<sub>2</sub> with the substitution credit methodology. With the mass allocation methodology and the PAS 2050, the effect of fermentation CO<sub>2</sub> capture is applied via allocation based on mass, and on economic value derived from the product of mass and price, respectively.

Estimated net GHG emissions savings for ethanol used as a fuel, under the RED methodology, are presented in Table 9 for biorefineries using a boiler and imported electricity or a CHP unit, and releasing or capturing fermentation CO<sub>2</sub>. These results show that minimum net GHG emissions savings of 60% are only achieved clearly when fermentation CO<sub>2</sub> is captured from the biorefinery. Net GHG emissions savings of 60% are estimated for ethanol production from miscanthus in a biorefinery with a CHP unit and without fermentation CO<sub>2</sub> capture. However, this should be considered as a marginal achievement of the minimum required since an adverse change in other parameters, such as a reduction in miscanthus yield or an increase in transport distance, could cause a net GHG emissions savings to fall below this level.

Table 8 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Chemical

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions kg eq. CO <sub>2</sub> /t	Net Savings GHG Over Petro-ethanol (%)
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	0.36	2,659	-113
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	0.36	1,800	-44
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	0.36	2,629	-111
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	0.36	1,794	-44
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	1.82	2,652	-113
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	1.82	1,793	-44
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	1.82	2,622	-110
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	1.82	1,787	-43

Note

\* All other parameters set at default values.

Figure 9 Total Greenhouse Gas Emissions Associated with Ethanol Production from Miscanthus, without Carbon Dioxide Capture from Fermentation

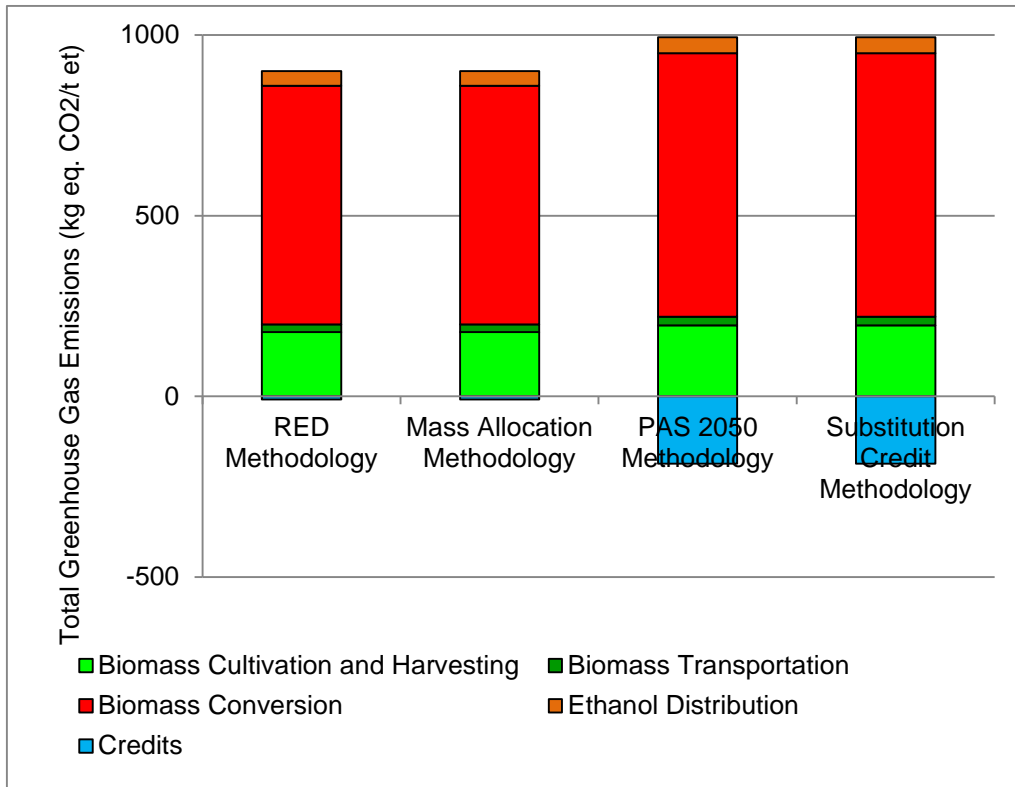


Figure 10 Total Greenhouse Gas Emissions Associated with Ethanol Production from Miscanthus, with Carbon Dioxide Capture from Fermentation

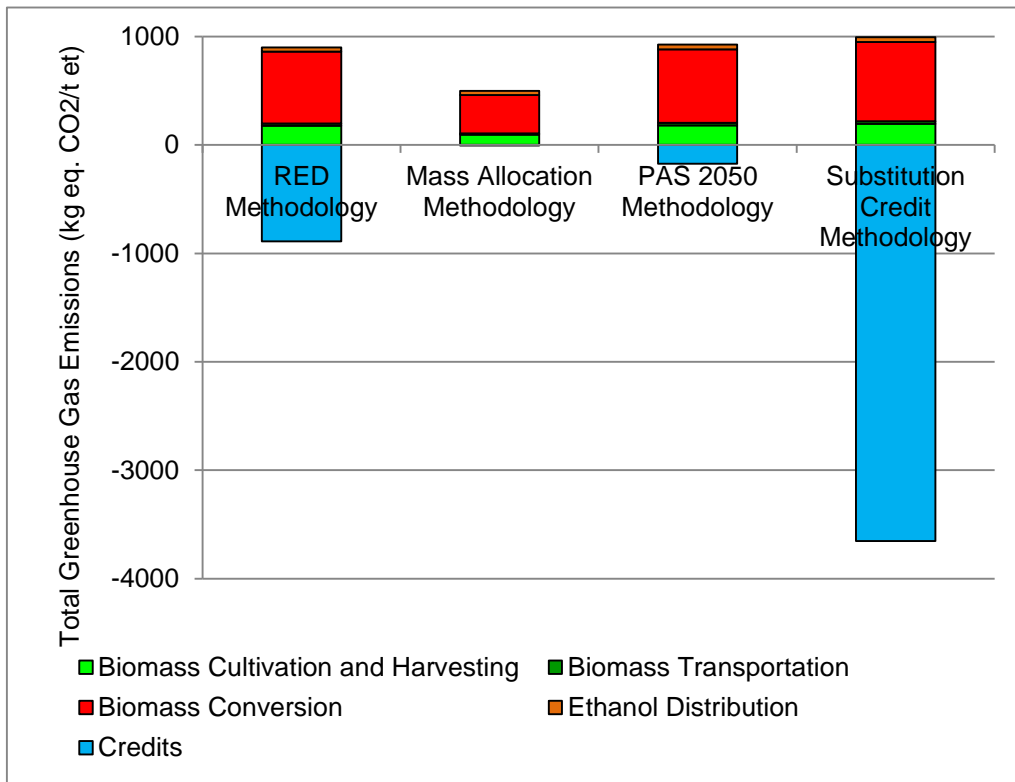


Table 9 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Fuel

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions		Net Greenhouse Gas Emissions Savings (%)
		kg eq. CO <sub>2</sub> /t	kg eq. CO <sub>2</sub> /MJ	
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	1.76	1,578	0.0591	29
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	1.76	892	0.0334	60
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	1.76	696	0.0261	69
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	1.76	10	0.0004	100

Note

\* All other parameters set at default values.

Results for the ethanol produced from miscanthus for use as a chemical are provided in Table 10. As for previous results for ethanol used as a chemical, these were generated by applying the PAS 2050 methodology and comparing them with total GHG emissions of 1,247 kg eq. CO<sub>2</sub>/t for the production of petro-ethanol. Table 10 demonstrates that only the production of ethanol from miscanthus in a biorefinery which has a CHP unit achieves reductions in net GHG emissions savings over petro-ethanol production. This outcome is accomplished regardless of whether fermentation CO<sub>2</sub> is released into the atmosphere or captured. It should be noted that the most significant consideration which favours the use of the CHP unit in the biorefinery is the credit that arises from surplus electricity displacing gross grid electricity. It is apparent that total GHG emissions associated with the production of ethanol from miscanthus in a biorefinery with a boiler and imported grid electricity are significantly higher than those for the production of petro-ethanol. This outcome is again regardless of whether fermentation CO<sub>2</sub> is released or captured. Additionally, negative outcomes occur even if the potential avoidance of 957 kg CO<sub>2</sub>/t released into the atmosphere, due to differential waste disposal options for products incorporating ethanol from miscanthus and petro-ethanol, is taken into account.

Table 10 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Chemical

Key Specifications*	Ethanol Productivity (t et/ha)	Total Greenhouse Gas Emissions kg eq. CO <sub>2</sub> /t	Net Savings Over Petro-ethanol (%)
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	1.76	2,865	-130
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	1.76	807	35
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	1.76	2,667	-114
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	1.76	753	40

Note

\* All other parameters set at default values.

## 4.2 Comparative Analysis

Very many comparisons can be performed with the workbooks developed for quantitative assessment of sustainability of ethanol produced from maize and miscanthus. However, the important aims of the SUNLIBB Project consist of improving biomass feedstocks and their processing for conversion into ethanol. Consequently, the focus of this comparative analysis is to investigate the possible effects of using genotype maize and miscanthus feedstocks and applying SCE during processing on total GHG emissions associated with ethanol production. In order to accomplish this, pilot study data from WP7 were extended for the effects of improved biomass feedstock, and SCE performance data from WP8 were incorporated in the relevant workbooks, as described previously (see Section 3).

### 4.2.1 Improved Biomass Feedstocks

Using the workbooks, it was possible to determine possible increases in ethanol productivity, in terms of t/ha, from corn stover, whole maize and miscanthus. In particular, the ethanol productivity of using low and high digestibility genotypes and generic biomass are summarised in Table 11. It can be seen that the most substantial improvements are indicated for miscanthus. The genotype miscanthus feedstock results in assumed increases in ethanol productivity relative to generic



miscanthus ranging from 28% to 34%, compared with relative increases between 3% and 11% for corn stover and whole maize.

Table 11 Effect of Improved Biomass Feedstock on Ethanol Productivity

Biomass Feedstock	Ethanol Productivity (t et/ha)		
	Generic Biomass	Low Digestibility Genotype Biomass	High Digestibility Genotype Biomass
Corn Stover	0.36	0.38	0.40
Whole Maize	1.82	1.87	1.97
Miscanthus	1.76	2.26	2.36

Comparative analysis was performed with the maize workbook on the implied effects of improved corn stover and whole maize on net GHG emissions savings for ethanol used as a fuel by applying the RED methodology. The results are presented in Table 12 for ethanol production from corn stover and whole maize in biorefineries with boilers and imported grid electricity or CHP units, and without or with fermentation CO<sub>2</sub> capture. Overall, these results indicate that improved biomass feedstocks would increase net GHG emissions savings for ethanol produced from both corn stover and whole maize. However, there is no radical change in the previous outcomes for ethanol produced from corn stover (see Section 4.1.2) which showed that net GHG emissions saving greater than 60% can be achieved provided that ethanol production from this feedstock in a biorefinery with a boiler, imported grid electricity and no fermentation CO<sub>2</sub> is avoided. In the case of improved whole maize feedstock, there is one notable change. Previously, all technological options for producing ethanol from whole maize resulted in net GHG emissions savings below or just at the minimum required level of 60% (see Section 4.1.2). However, in one particular case, with high digestibility genotype whole maize in a biorefinery with a CHP unit and fermentation CO<sub>2</sub> capture, it is suggested that net GHG emissions savings clearly higher than 60% might be achieved. However, this implies technologically prescriptive conditions would be required in regulations to ensure that this favourable outcome could be replicated commercially.

Outcomes for net GHG emissions savings for ethanol, as a chemical, produced from corn stover and whole maize relative to petro-ethanol are much less qualified but more negative, as indicated in Table 13. These results were generated by applying the PAS 2050 methodology and they show increases in net GHG emissions savings over petro-ethanol production for all technological options for biorefineries converting improved corn stover and whole maize into ethanol. However, these biomass feedstock improvements are not sufficient to reduce total GHG emissions for ethanol production from corn stover and maize below those of 1,247 kg eq. CO<sub>2</sub>/t for the production of petro-ethanol. As indicated previously (see Section 4.1.2), taking the potential avoidance of 957 kg CO<sub>2</sub>/t released into the atmosphere during end-of-life waste disposal of products containing ethanol, would result in net GHG emissions lower than petro-ethanol for ethanol produced, as a chemical, from either corn stover or whole maize in a biorefinery with a CHP unit, and with or without fermentation CO<sub>2</sub> capture. However, as explained before, application of these avoided GHG emissions would depend on the ability to specify the fate of products containing such ethanol in advance of eventual waste disposal.

Table 12 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Fuel: Effects of Improved Biomass Feedstock

Key Specifications*	Net Greenhouse Gas Emissions Savings (%)		
	Generic Maize	Low Digestibility Genotype Maize	High Digestibility Genotype Maize
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	34	35	38
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	67	68	70
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	73	75	77
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	106	107	108
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-12	-10	-5
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	21	23	26
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	27	30	35
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	60	62	66

Note

\* All other parameters set at default values.

Table 13 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Chemical: Effects of Improved Biomass Feedstock

Key Specifications*	Net Greenhouse Gas Emissions Savings over Petro-Ethanol (%)		
	Generic Maize	Low Digestibility Genotype Maize	High Digestibility Genotype Maize
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-113	-108	-99
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	-44	-40	-31
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-111	-106	-97
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	-44	-39	-31
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-113	-108	-99
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	-44	-39	-30
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-110	-105	-96
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	-43	-39	-30

Note

\* All other parameters set at default values.

The outcomes of the investigation of the effects of biomass feedstock improvement on net GHG emissions for ethanol produced from miscanthus are somewhat more positive. Table 14 compares the speculated effects of using low and high digestibility miscanthus instead of generic miscanthus for the production of ethanol, as a fuel, in biorefineries with boilers and imported grid electricity or CHP units, and without and with fermentation CO<sub>2</sub> capture. These results were generated from the miscanthus workbook with application of the RED methodology. As for maize, the use of improved miscanthus feedstocks increases net GHG emissions savings for ethanol used as a fuel. Whilst a biorefinery using a boiler and imported grid electricity and without fermentation CO<sub>2</sub> capture still have net GHG emissions savings lower than the required minimum of 60%, this level is clearly exceeded for all other technological options with improved miscanthus feedstocks. Hence, the assumed benefits for ethanol as a fuel from improved miscanthus feedstocks are apparent provided that biorefineries do not incorporate a combination of boilers with imported grid electricity and no fermentation CO<sub>2</sub> capture.

Table 14 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Fuel: Effects of Improved Biomass Feedstock

Key Specifications*	Net Greenhouse Gas Emissions Savings (%)		
	Generic Miscanthus	Low Digestibility Genotype Miscanthus	High Digestibility Genotype Miscanthus
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	29	42	44
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	60	68	69
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	69	82	84
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	100	107	109

Note

\* All other data set at default values.

Using the PAS 2050 methodology in the miscanthus workbook, the possible effects of improved biomass feedstock on net GHG emissions savings of ethanol produced from miscanthus, using different technological options, relative to petro-ethanol production are shown in Table 15. Again, it is indicated that net GHG emissions savings should be expected to increase with the use of low

and high digestibility genotype miscanthus relative to generic miscanthus as a feedstock for the production of ethanol. However, such increases are not sufficient to generate total GHG emissions associated with the production of ethanol from miscanthus in biorefineries which depend on boilers and imported grid electricity, without or with fermentation CO<sub>2</sub> capture, that are lower than 1,247 kg eq. CO<sub>2</sub>/t for the production of petro-ethanol. Instead, the use of improved miscanthus feedstock reinforces the positive net GHG emissions savings of ethanol from biorefineries with CHP units, without or with fermentation CO<sub>2</sub> capture.

Table 15 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Chemical: Effects of Improved Biomass Feedstock

Key Specifications*	Net Greenhouse Gas Emissions Savings over Petro-Ethanol (%)		
	Generic Miscanthus	Low Digestibility Genotype Miscanthus	High Digestibility Genotype Miscanthus
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-130	-106	-102
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	35	57	61
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-114	-91	-88
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	40	60	63

Note

\* All other parameters set at default values.

#### 4.2.2 Supercritical Carbon Dioxide Extraction

By extending the results of pilot study work in WP7 of the SUNLIBB Project and combining these with the results from WP6, it is possible to speculate on the effect of SCE on the production of ethanol from generic and improved maize and miscanthus. The possible increases in ethanol productivity, in terms of t/ha, are indicated in Table 16. With generic biomass feedstock, increases in ethanol productivity with SCE are modest for corn stover (3%) and whole maize (2%) but more marked for miscanthus (26%). The impact of combining SCE with improved biomass feedstocks,

assuming these effects are multiplicative, are assumed to range from 6% to 11% for corn stover, from 5% to 10% for whole maize, and from 62% to 70% for miscanthus.

Table 16 Effect of Supercritical Carbon Dioxide Extraction and Improved Biomass on Ethanol Productivity

Biomass Feedstock	Ethanol Productivity (t et/ha)			
	Generic Biomass	Generic Biomass + SCE	Low Digestibility Genotype Biomass + SCE	High Digestibility Genotype Biomass + SCE
Corn Stover	0.36	0.37	0.38	0.40
Whole Maize	1.82	1.85	1.91	2.01
Miscanthus	1.76	2.22	2.86	2.99

Unfortunately, these increases in ethanol productivity are not translated into increases in net GHG emissions savings for ethanol, either as a fuel or as a chemical, when produced from generic or improved corn stover, whole maize or miscanthus in biorefineries incorporating SCE with either boilers and imported electricity or CHP units, and either without or with fermentation CO<sub>2</sub> capture. This is demonstrated in Tables 17 to 20 for ethanol as a fuel or chemical from corn stover/whole maize, and ethanol as a fuel or chemical from miscanthus, respectively. As shown in Tables 17 and 19 for the net GHG emissions savings of ethanol used as a fuel, the required minimum of 60% is not achieved for any technological combination which incorporates SCE. In Tables 18 and 20, total GHG emissions associated with the production of ethanol as a chemical exceed those of 1,247 kg eq. CO<sub>2</sub>/t for the production of petro-ethanol. Again, these outcomes arise regardless of whether the biomass feedstock is generic or improved, and for all the technological options considered which incorporate SCE.

The main reason for this is the relatively high electricity requirement for SCE which has been adopted from WP6 and summarised previously in Table 3. Depending on the technological options for energy supply in the biorefinery, this either increases the amount of imported grid electricity substantially, thereby introducing additional GHG emissions from the generation of this electricity, or reduces the surplus electricity from the CHP unit, thereby decreasing the GHG emissions credit of either replacement electricity or gross grid electricity. In all cases, effective increases in total GHG emissions are not compensated by increases in total ethanol production from the application of SCE. Additionally, the impact of wax production associated with the application of SCE is not sufficiently influential via the co-product allocation procedures of the RED and PAS 2050 methodologies. This is partly because the expected quantities of wax recovered are relatively small compared to the amount of ethanol produced. For example, the estimated unit amount of wax recovered from maize is between 0.058 t/t ethanol and 0.063 t/t ethanol, and from miscanthus it is between 0.032 t/t ethanol and 0.043 t/t ethanol. Under the RED methodology, this translates into the energy content allocation of GHG emissions to the wax co-product of between 6% and 7% for ethanol production from maize, and between 3% and 4% for ethanol production from miscanthus. This is based on net calorific values of 40,000 MJ/t for wax and 26,700 MJ/t for ethanol. With the PAS 2050 methodology, allocation by economic value to the wax is much higher at between 51% and 53% for ethanol production from maize, and between 36% and 43% for ethanol production from miscanthus, based on assumed prices currently equivalent to approximately €10,000/t for wax and €630/t for ethanol.

Table 17 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Fuel: Effects of Supercritical Carbon Dioxide Extraction

Key Specifications*	Net Greenhouse Gas Emissions Savings (%)			
	Generic Maize	Generic Maize + SCE	Low Digestibility Genotype Maize + SCE	High Digestibility Genotype Maize + SCE
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	34	-166	-160	-148
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	67	-21	-18	-12
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	73	-130	-124	-112
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	106	15	18	24
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-12	-209	-201	-187
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	21	-63	-59	-51
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	27	-172	-165	-151
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	60	-27	-23	-15

Note

\* All other data set at default values.

Table 18 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Fuel: Effects of Supercritical Carbon Dioxide Extraction

Key Specifications*	Net Greenhouse Gas Emissions Savings (%)			
	Generic Miscanthus	Generic Miscanthus + SCE	Low Digestibility Genotype Miscanthus + SCE	High Digestibility Genotype Miscanthus + SCE
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	29	-138	-90	-82
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	60	-9	15	19
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	69	-101	-52	-45
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	100	28	53	57

Note

\* All other parameters set at default values.



Table 19 Total Greenhouse Gas Emissions Associated with Corn Stover and Whole Maize Conversion to Ethanol as a Chemical: Effects of Supercritical Carbon Dioxide

Key Specifications*	Net Greenhouse Gas Emissions Savings over Petro-Ethanol (%)			
	Generic Maize	Generic Maize + SCE	Low Digestibility Genotype Maize + SCE	High Digestibility Genotype Maize + SCE
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-113	-193	-189	-183
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	-44	-60	-58	-54
Corn stover used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-111	-192	-189	-182
Corn stover used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	-44	-60	-58	-54
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-113	-193	-189	-183
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	-44	-60	-58	-54
Whole maize used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-110	-192	-188	-182
Whole maize used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	-43	-60	-57	-53

Note

\* All other parameters set at default values.

Table 20 Total Greenhouse Gas Emissions Associated with Miscanthus Conversion to Ethanol as a Chemical: Effects of Supercritical Carbon Dioxide Extraction

Key Specifications*	Net Greenhouse Gas Emissions Savings over Petro-Ethanol (%)			
	Generic Miscanthus	Generic Miscanthus + SCE	Low Digestibility Genotype Miscanthus + SCE	High Digestibility Genotype Miscanthus + SCE
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation released	-130	-222	-194	-190
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation released	35	-47	-30	-27
Miscanthus used as feedstock, boiler and imported electricity, and carbon dioxide from fermentation captured	-114	-202	-185	-171
Miscanthus used as feedstock, combined heat and power (1:1 heat to power ratio), and carbon dioxide from fermentation captured	40	-38	-22	-19

Note

\* All other parameters set at default values.

## 5. QUALITATIVE RESULTS

### 5.1 Other Environmental Impacts

Although global climate change is a predominant environmental issue and GHG emissions reduction is a pressing concern, there are, of course, very many other impacts that have to be taken into account when assessing the sustainability of biorefineries. In the specified context of WP8 of the SUNLIBB Project, the most prominent environmental considerations have been identified and addressed in a qualitative manner. The details of this qualitative assessment for maize and miscanthus biorefineries and their related biomass feedstock supply pathways are reported elsewhere (Refs. 22 and 23). In particular, the issues for maize biorefineries were identified as land use; soil erosion, fertility and carbon; water use; emissions to air; emissions to water; biodiversity and other impacts, principally, local traffic levels. The issues examined for

miscanthus biorefineries were land use; carbon sequestration, soil erosion; water use; emission to air; emissions to water; biodiversity; and other impacts, namely, invasiveness and traffic levels.

The main outcomes of this qualitative assessment of environmental impacts of the maize and miscanthus biorefineries and their biomass feedstock supply pathways are summarised in Table 21. No land use issues are expected with the supply of corn stover since this is an agricultural residue which would have been produced regardless of its possible use in a biorefinery. Land use issues are considered to be site-specific for whole maize and miscanthus which are dedicated crops for use as a biorefinery feedstock. Problems for land use with these particular crops will depend on whether they are grown on land which could have been used for other productive purposes, such as food production, or on non-productive, degraded or contaminated land. Both corn stover and whole maize can possibly have negative consequences for soil erosion, fertility and carbon sequestration because they are annual crops and their use as feedstocks in biorefineries involves removing all the biomass from the land rather than incorporating some or all of it within the soil. As a perennial crop, miscanthus poses much fewer or non-existent problems for soil erosion, fertility and carbon sequestration. Indeed, it is possible that miscanthus cultivation can reduce soil erosion and increase carbon sequestration.

Table 21 Summary of Qualitative Assessment of Environmental Impacts of Maize and Miscanthus Biorefineries

Environmental Impact	Qualitative Assessment of Biorefinery with Biomass Feedstock Supply Pathway		
	Corn Stover	Whole Maize	Miscanthus
Land Use	<i>No</i>	<i>Site-specific</i>	<i>Site-specific</i>
Soil Erosion	<i>Yes, possibly</i>	<i>Yes, possibly</i>	<i>No</i>
Soil Fertility	<i>Yes, possibly</i>	<i>Yes, possibly</i>	<i>No</i>
Soil Carbon	<i>Yes, possibly</i>	<i>Yes, possibly</i>	<i>No</i>
Water Use	<i>Site-specific</i>	<i>Site-specific</i>	<i>Site-specific</i>
Emissions to Water	<i>Yes, possibly</i>	<i>Yes, possibly</i>	<i>No</i>
Emissions to Air	<i>No</i>	<i>No</i>	<i>No</i>
Biodiversity	<i>Yes, possibly</i>	<i>Yes, possibly</i>	<i>No</i>
Invasiveness	<i>No</i>	<i>No</i>	<i>Yes, possibly</i>
Traffic Levels	<i>Site-specific</i>	<i>Site-specific</i>	<i>Site-specific</i>

For all these biorefinery feedstocks, the impact on water use is site-specific because this depends entirely on where these crops are grown. Ideally, they would be grown in areas where rainfall is adequate for their water needs rather than in drier regions where artificial irrigation would be required. None of these biomass feedstocks are expected to increase emissions to air from their cultivation, harvesting and transportation above the levels seen for normal agricultural practices and their supporting activities. It should be noted that most biorefinery designs using these and similar lignocellulosic feedstocks assume that lignin, waste solids and, possibly, biogas from waste water treatment will be burnt to generate the heat and, possibly, the electricity they require. This is usually necessary not only as a means of disposing of these materials which currently have low economic values but also to reduce or eliminate natural gas or other fossil fuel consumption by the biorefinery, thereby suppressing GHG emissions. However, such biomass combustion can increase certain emissions to air, such as oxides of nitrogen (NOx) and particulates, relative to natural gas

combustion. Hence, such emissions might have to be controlled by suitable techniques in such biorefineries.

It is possible that the use of maize as biomass feedstocks in biorefineries could reduce biodiversity due to the fact that its supply, either as corn stover or whole maize, involves the removal of crop cover for significant parts of the year for wildlife and because they can be grown as monocultures. Again, because miscanthus is a perennial crop, it should enhance biodiversity rather than threaten it. However, whilst maize is an established crop which has no issues of invasiveness, concerns have been expressed about the potential for miscanthus, as a relatively new crop, to spread as a weed. Hence, biosecurity measures are likely to be necessary for the cultivation, harvesting and transportation of miscanthus as a feedstock for biorefineries. Finally, whether maize and miscanthus biorefineries are likely to generate unacceptable levels of traffic will depend on site-specific considerations for their proposed location.

## **5.2 Socio-Economic Impacts**

Another aspect of sustainability assessment which is often raised concerns socio-economic impacts. In the SUNLIBB Project, the engineering or microeconomics of maize and miscanthus biorefineries are addressed by cost modelling in WP7. The broad scope of socio-economic impacts of biorefineries and bioenergy, in general, can be seen from the sustainability indicators, proposed by the Global Bioenergy Partnership (GBEP), which have the following social and economic dimensions (Ref. 24):

- Price and supply of a national food basket (Indicator 10),
- Change in income (Indicator 11),
- Jobs in bioenergy sector (Indicator 12),
- Incidence of occupational, injury, illness and fatalities (Indicator 16),
- Gross value added (Indicator 19),
- Training and re-qualification of the workforce (Indicator 21),
- Energy diversity (Indicator 22),
- Infrastructure and logistics for distribution of bioenergy (Indicator 23), and
- Capacity and flexibility of use of bioenergy (Indicator 24).

Some socio-economic studies of bioenergy have focused specifically on macroeconomic and jobs (see, for example, Refs. 25 and 26). The macroeconomic impact of biorefineries concerns their direct and indirect consequences for local, national and regional economies. Job creation by biorefineries is a major social consideration, possibly qualified in terms of the location, wage level and training qualifications of new jobs. Provided that suitable statistics are available at the

required scale, then both macroeconomic and social impacts of biorefineries can be assessed, quantitatively, by means of the established technique of input-output analysis (see, for example, Refs. 26 and 27) complemented by the emerging technique of Social Impact Assessment (SIA) which addresses job attributes such as the level of required job qualifications, job duration and gender balance (see, for example, Ref. 28). Additionally, multi-criteria decision analysis (MCDA) has been applied to the socio-economics of biorefineries (see, for example, Refs. 29 and 30). Furthermore, it has been proposed that the social aspects of sustainability should be incorporated into a form of LCA referred to as social LCA or SLCA (Refs. 31 and 32).

Since such techniques are still undergoing development and as data and statistics necessary for their application to maize and miscanthus biorefineries are limited, a quantitative assessment of these elements of socio-economics was beyond the scope of WP8 of the SUNLIBB Project. Instead, it is possible to address, briefly, key aspects of the socio-economics of maize and miscanthus biorefineries in a qualitative manner. In this context, it is necessary to identify the essential features of biorefineries and their biomass feedstock pathways that influence their socio-economics, and compare these with the current production of petrol/gasoline and petro-ethanol.

It is apparent that the provision of biomass feedstocks for biorefineries is more labour intensive than the extraction and processing of crude oil. The unit costs of biomass provision for biorefineries is dependent on cultivation, harvesting and transportation costs whereas the unit cost of supplying feedstock of petroleum refinery is strongly affected by the global price of crude oil. Hence, although the unit costs of providing biomass feedstock can be higher than those for supplying crude oil, these are not subject to the considerable fluctuation which beset crude oil. However, both biorefining and petroleum refining are capital intensive activities and, as explained subsequently, these are determined chiefly by economies of scale.

Locational issues must also be taken into account. Biomass feedstocks can be sourced wherever crops such as maize and miscanthus can be grown. Such locations are more diverse and dispersed throughout rural areas than the places where crude oil is found and has conventionally been extracted on a large scale. It is also possible to cultivate crops for biomass feedstocks in different areas at different times. Depending on land availability and the not inconsiderable issue of competition with other crop cultivation, especially for food, this offers potential flexibility for biomass feedstock supply. Additionally, countries without crude oil resources can grow their own biomass feedstocks, thereby reducing import dependence and increasing national security of supply. Although the advent of shale oil production using fracking technology has expanded the potential for sourcing crude oil, such operations are still restricted to where suitable deposits are present and can be exploited. Furthermore, even shale oil deposits, which are expected to be more widespread than conventional deposits, are, ultimately, depletable which means that, in general and over time, biomass feedstock sources are comparatively more ubiquitous, due to the many locations where suitable crops can be grown, and more sustainable, because these crops are renewable.

Scale is also an important consideration. As such, it is more favourable for crude oil extraction, transportation and refining than to biomass feedstock cultivation, harvesting, transportation and biorefining. More energy can be extracted per unit time from an oil well than from fields which grow biomass feedstocks. Transportation of crude oil is on a scale many orders of magnitude greater than that for biomass feedstocks. There is also a substantial difference in scale between conceptual biorefineries and conventional petroleum refining facilities. For example, the

conceptual NREL corn stover biorefinery has an assumed annual ethanol output of less than 200,000 t/a (Ref. 11). This contrasts with the maximum annual output capacity for petroleum refineries in the USA of more than 5,000,000 t/a (Ref. 33). As a consequence, the unit capital costs and unit labour requirements of conceptual biorefineries are higher than those of conventional petroleum refineries.

Taken together, these key aspects suggest the following probable socio-economic impacts. In comparison with the production of fuel and chemicals from crude oil, maize and miscanthus biorefineries are likely to:

- Improve rural economies and rural employment, by providing additional sources of income, more from whole maize and miscanthus production as major crops rather than from corn stover recovery which depends on existing agricultural residues,
- Expand, diversify and enhance energy security for national economies in countries which can grow crops for biomass feedstocks and, especially, for those countries lacking crude oil resources, and
- Increase national employment due to the relatively smaller scale of biorefineries and their subsequently higher labour intensity compared with conventional petroleum refineries.

Obviously, such potentially positive socio-economic impacts need to be quantified when the detailed specifications of commercially-viable biorefineries and their biomass feedstock pathways have been completely established and when suitable assessment techniques and necessary statistics and data become available. However, it must be noted that commercial viability, combined with clear global climate change mitigation impacts, are essential prerequisites for the successful deployment of biorefineries. Currently, new biorefineries and their biomass feedstock pathways must also be economically competitive with existing petroleum refineries and their supply infrastructure. Unless they receive financial incentives, subsidies or other means of support as “low carbon” technologies, this means that biorefineries must be able to compete in the current market place. Their relatively smaller scale and higher labour intensity, which have potential socio-economic benefits, are, at the moment, disadvantages for their microeconomics. Hence, it is essential to improve the microeconomics of biorefineries and their biomass feedstock pathways, whilst simultaneously ensuring their credentials as real global climate change mitigation measures. This requires continuing and concerted efforts directed towards technically-feasible and commercially-viable means of improving their performance. This includes the integrated development of improved biomass feedstocks and processing technologies, such as those addressed in the SUNLIBB Project, which increase biorefinery yields within economic constraints and necessary GHG emissions reductions.

## 6. CONCLUSIONS

This report documents the development of suitable MS Excel workbooks for quantitative assessment of primary energy inputs and prominent GHG emissions associated with biorefineries that use sugar cane/bagasse, corn stover or whole maize, and miscanthus as biomass feedstocks. The basic nature of these workbooks, their application and their considerable functionality to accommodate technical and methodological options, which extends beyond the results reported here, are described, and subsequent results from sensitivity and comparative analysis are presented. The main conclusions from these analyses are summarised as follows:

- There is limited effects from choice of calculation methodology on total GHG emissions associated with the production of ethanol, in a biorefinery without capture of CO<sub>2</sub> from fermentation, using sugar cane as a biomass feedstock and bagasse as a fuel; using sugar cane and bagasse as a biomass feedstock; and using whole maize or miscanthus as biomass feedstocks,
- There are significant effects from the choice of calculation methodology on total GHG emissions associated with the production of ethanol, in a biorefinery with capture of CO<sub>2</sub> from fermentation, using sugar cane as a biomass feedstock and bagasse as a fuel; using sugar cane and bagasse as a biomass feedstock; and using whole maize or miscanthus as biomass feedstocks,
- The choice of calculation methodology causes significant differences in total GHG emissions associated with the production of ethanol from corn stover as a biomass feedstock, in a biorefinery either without or with fermentation CO<sub>2</sub> capture,
- Where ethanol has been produced for use as a fuel, the required minimum of 60% net GHG emissions savings under the RED after 2017 is only achieved clearly for ethanol produced from sugar cane as a biomass feedstock and bagasse as a fuel, or sugar cane and bagasse as a biomass feedstock in a biorefinery with either a boiler and imported grid electricity but only with fermentation CO<sub>2</sub> capture; from corn stover in a biorefinery with a boiler and imported grid electricity but only with fermentation CO<sub>2</sub> capture, and in a biorefinery with CHP and either without or with fermentation CO<sub>2</sub> capture; and from miscanthus in a biorefinery with either a boiler and imported grid electricity but only with fermentation CO<sub>2</sub> capture,
- Where ethanol has been produced for use as a fuel, no combinations of biorefinery configuration design considered here with whole maize as a biomass feedstock can achieve the required minimum of 60% net GHG emissions savings under the RED after 2017,
- Where ethanol has been produced as a chemical and initial CO<sub>2</sub> absorption by biomass or avoided CO<sub>2</sub> emissions associated with end-of-life disposal (amounting to 957 kg CO<sub>2</sub>/t ethanol) are taken into account, there are net GHG emissions savings over petro-ethanol (1,247 kg eq. CO<sub>2</sub>/t) for ethanol from sugar cane as a biomass feedstock and bagasse as a fuel, and sugar cane and bagasse as a biomass feedstock for all technical options for biorefineries; and from corn stover, whole maize and miscanthus as biomass feedstocks for

biorefineries, either without or with fermentation CO<sub>2</sub> capture, but only with CHP,

- Improved biomass feedstocks, based on speculated fermentable sugar and lignin recovery from maize and miscanthus genotypes, reduce GHG emissions associated with ethanol produced from biorefineries but do not alter, radically, previous outcomes for ethanol as a fuel evaluated against RED minimum net GHG emissions after 2017 and for ethanol as a chemical compared with petro-ethanol over a life cycle including production and end-of-life phases,
- On the basis of its current requirements and performance, the use of supercritical CO<sub>2</sub> extraction, as a means of pre-treating maize and miscanthus and recovering wax as a co-product, increases GHG emissions associated with ethanol production, due mainly to its relatively high electricity consumption, and reduces the ability of ethanol from biorefineries to meet minimum net GHG emissions savings of 60% for ethanol as a fuel under the RED, and to achieve lower net GHG emissions savings for ethanol used as a chemical relative to petro-ethanol,
- Qualitative assessment of other environmental impacts suggests that there might be possible problems with soil erosion, fertility and carbon, and emissions to water for corn stover and whole maize, and with invasiveness for miscanthus as biomass feedstocks for biorefineries,
- Qualitative assessment of other environmental impacts also suggests that there might be site-specific problems with land use for whole maize and miscanthus, with water use and traffic levels for corn stover, whole maize and miscanthus as biomass feedstocks for biorefineries, and
- Qualitative assessment of socio-economics for biorefineries and their biomass feedstock pathways, relative to petroleum refineries and their conventional supplies of crude oil, indicated potential benefits to improve rural economies and employment; expand, diversity and enhance national energy security; and increase national employment provided that they can compete economically through the development and implementation of technically-feasible and commercially-viable measures such as improved biomass feedstocks and processing technologies which do not compromise net GHG emissions savings.



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