Programme Area: Bioenergy

Project: Carbon Accounting Evidence Collation

Title: Bioenergy Life Cycle Assessment Review Report

Abstract:

This report documents the outcomes of Work Package 2 of this project which has the main objectives of analysing previous relevant LCA studies by providing a critique of the robustness of the evidence base based on both data and methodologies used; a measure of certainty behind the data reviewed; and details of the confidence the reviewer may have in interpreting the data. As a basis for this, a concise summary of the context of bioenergy LCA studies has been produced to cover the types of questions that, typically, they attempt to answer and the appropriate methodologies that they should use to do this, and to highlight some of the areas where there are conflicting views as to the appropriate approach.

Context:

The ETI appointed North Energy Associates (NEA) to lead a new Carbon Life Cycle Assessment (LCA) Evidence Analysis project in its Bioenergy Programme. LCAs are used to understand the greenhouse gas emissions associated with bioenergy from across the supply chain, from feedstock production to energy production. Several different methodologies can be used in LCAs and this ETI project assessed the strengths and weaknesses associated with applying these methodologies to bioenergy value chains. It also reviewed sources of data for LCAs and produced a compendium of the best and most reliable data across different UK-relevant bioenergy feedstocks and value chains. This compendium has formed the basis of a series of carbon balance calculations across a range of bioenergy value chains so that emissions from different feedstocks can be compared.

CARBON LIFE CYCLE ASSESSMENT EVIDENCE ANALYSIS:
Deliverable D2 – Bioenergy Life Cycle Assessment Review Report

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CARBON LIFE CYCLE ASSESSMENT EVIDENCE ANALYSIS: Deliverable D2 – Bioenergy Life Cycle Assessment Review Report

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Executive Summary

1. The aims of this project on "Carbon Life Cycle Assessment Evidence Analysis" for the Energy Technologies Institute are to identify and review the existing evidence base, in terms of relevant life cycle assessments (LCAs) which calculate greenhouse gas (GHG) emissions associated with potentially major bioenergy value chains for the United Kingdom; to compile a compendium of the best and most reliable ranges of basic data used in such calculations; to develop suitable workbooks for consistent calculation of GHG emissions associated with these bioenergy value chains; and to produce results which can be compared and used to identify and prioritise key knowledge gaps.

2. This report documents the outcomes of Work Package 2 of this project which has the main objectives of analysing previous relevant LCA studies by providing a critique of the robustness of the evidence base based on both data and methodologies used; a measure of certainty behind the data reviewed; and details of the confidence the reviewer may have in interpreting the data.

3. As a basis for this, a concise summary of the context of bioenergy LCA studies has been produced to cover the types of questions that, typically, they attempt to answer and the appropriate methodologies that they should use to do this, and to highlight some of the areas where there are conflicting views as to the appropriate approach.

4. In setting this context, the essential outcomes were that the most significant contributions to total GHG emissions for bioenergy value chains involving energy crops are direct and indirect land use changes, although there is no established consensus on modelling the latter; and, for forests, carbon stock changes simulated by suitable models, and the choice of counterfactuals for forest management and the use of timber for bioenergy or as wood products.

5. The process of reviewing relevant LCA studies, as one part of the evidence base, is explained in terms of the selection and screening criteria adopted; the Bioenergy LCA Database where basic information on the selected LCA studies is recorded; the details of the full reviews that have been conducted; and the findings that were drawn from the systematic analysis of these full reviews.

6. The main findings from the review process were that a quite large number (initially 161, subsequently confirmed as 147) of relevant LCA studies were selected, and, after screening, these were reduced to a somewhat smaller number (49) for full reviews. The chief reason why selected LCA studies did not pass screening was that they adopted attributional LCA methodology instead of CLCA methodology, as required by the defined LCA goal and scope of this project. From the 49 reviewed LCA studies, only some (55) of the potential (190) relevant whole bioenergy value chains (without carbon capture and storage) were covered by 8 LCA studies, most (7) with high transparency.

7. Taking into account the analysis of the reviewed LCA studies and the impacts of actual variability and modelling uncertainty, it is apparent that there are limits to findings on confidence and critical data that can be derived from them for the evidence base for specified bioenergy value chains in this project. Instead, it is explained that the Bioenergy LCA Data Compendium offers a more appropriate, fully transparent and crucially comprehensive means of providing this evidence base using both primary and statistical sources of relevant data for use in suitable bioenergy LCA workbooks that are being developed in Work Package 4.

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Glossary

Attributional Life Cycle Assessment	a life cycle assessment in which the environmental impacts under consideration are apportioned individually, by some specified means of allocation, between each of the multiple products and/or services from a product system.
Carbon Life Cycle Assessment	a life cycle assessment applied, specifically, to the evaluation of greenhouse gas emissions, generally, or, more specifically, on the prominent emissions of carbon dioxide, methane and nitrous oxide.
Collective Consequences	the environmental impacts of a group of products and/or services that are provided by a given product system which are treated in a combined manner rather than divided between them by means of allocation (see co-product/co-service allocation).
Consequential Life Cycle Assessment	a life cycle assessment in which the environmental impacts under consideration are determined collectively, by means of system expansion (see system expansion), to all of the multiple products and/or services from a product system so that their displacement effects are taken into account.
Co-product/co-service	a product or service that is provided in conjunction with other products or services; in such cases of multiple product or service provision, the principal product or service is usually designated as the main product or service whilst other products or services are often referred to as by-products and by-services.
Co-product or co-service allocation	means by which environmental impacts are divided between co-products and/or co-services.
Counterfactual	a product or service which has been replaced by the provision of a particular product or service.
Displacement Effects	the complete subsequent impacts caused when the provision of a product or service replaces an existing product or service.

Ex Ante Life Cycle Assessment	a life cycle assessment which quantifies the environmental impacts of a product system “before the event”, or from its future implementation.
Ex Post Life Cycle Assessment	a life cycle assessment which quantifies environmental impact of a product system “after the event”, or from its past implementation.
Functional Unit	the specified characteristic feature(s) of the product(s) and/or service(s) from a product system that are the subject of a life cycle assessment.
Goal of a Life Cycle Assessment	an elaboration of the purpose of a life cycle assessment covering its intended application and audience, the general nature of the environmental impact(s) under consideration, and the general nature, scale and system time horizon of the product system(s) under consideration.
Impact Time Horizon	the particular period of time over which product system impacts that have a cumulative effect on the environment are quantified in a life cycle assessment, specified in terms of the number of years, usually, after the point in time they originally arise.
Life Cycle Assessment	a technique for quantifying the impacts, usually but not exclusively on the natural environment, in its role as the source of resources and as a sink for emissions, associated with an activity, typically involved in the provision of a product or service, over a defined duration or life cycle which can encompass all or part of the acquisition and conversion of its raw materials, and, if relevant, its use and final disposal.
Methodology of a Life Cycle Assessment	all the specified procedures or rules of calculation applied to the quantification of environmental impacts by a life cycle assessment.

Purpose of a Life Cycle Assessment	a statement or question which a life cycle assessment seeks to address or answer and which encapsulates its goal and scope which provide necessary details (see goal and scope of a life cycle assessment).
Process Chain	an activity or series of activities that are directly involved in the provision of a chosen product or service and that are the subject of a life cycle assessment (see also value chain).
Product System	an activity or series of activities that are involved in the provision of specified product(s) and/or service(s).
Product System Scale	the physical size or magnitude of the product system(s) under consideration in a life cycle assessment study.
Scope of a Life Cycle Assessment	an elaboration of the purpose of a life cycle assessment covering the specific causes of the environmental impact(s) under consideration and the relevant impact time horizon(s), the specific composition, spatial system boundary and temporal system boundary of the product system(s) under consideration, the perspective on the environmental impact(s) of multiple products or services from the product system(s), the functional unit and the full metrics of the reported results.
Spatial System Boundary	an imaginary line drawn around and completely enclosing the part or whole of a product system that has been designated for investigation by a life cycle assessment without reference to any particular period of time (see also temporal system boundary).
Substitution Credit	the avoided environmental impact of a product or service which has been replaced by the provision of a particular co-product or co-service.
Sustainability	the ability of a product system to maintain its function(s) over its specified life cycle by avoiding natural resource depletion and without permanently impairing or significantly compromising the natural environment.

System Boundary	an imaginary line drawn around and completely enclosing a part or whole of a product system that has been designated for investigation so that all inputs and outputs which cross this line can be quantified by a life cycle assessment (see also spatial system boundary and temporal system boundary).
System Expansion	the procedure by which the system boundary is widened to include more activities that are related to the product system under investigation by a life cycle assessment.
System Time Horizon	the particular period of time over which a product system is investigated by a life cycle assessment (see temporal system boundary), specified in terms of the number of years, usually, from the past (see ex post) or into the future (see ex ante).
Temporal System Boundary	an imaginary line drawn around and completely enclosing the part or whole of a product system that has been designated for investigation by a life cycle assessment over a period of time specified by the system time horizon (see system time horizon).
Value Chain	an activity or series of activities that are directly involved in the provision of a chosen product or service and that are the subject of a life cycle assessment (see also process chain).

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Contents

1. INTRODUCTION

This project on "Carbon Life Cycle Assessment Evidence Analysis" for the Energy Technologies Institute (ETI) is being undertaken by North Energy Associates Ltd (NEA), Forest Research (FR) and the National Non-Food Crops Centre (NNFCC). The primary aims of this project are to identify and to review the existing evidence base, in terms of relevant life cycle assessment (LCA) studies which calculate greenhouse gas (GHG) emissions associated with potentially major bioenergy value chains for the United Kingdom (UK), and, from these and other suitable sources, to compile a compendium of the best and most reliable ranges of basic data used in such calculations. The secondary aims are to develop suitable workbooks for calculating, in a consistent manner, GHG emissions associated with these bioenergy value chains, and to produce results which can be compared and used to identify and prioritise key knowledge gaps.

The work programme for this project consists of the following 6 Work Packages (WPs):

- WP0; Project Management
- WP1; Goal and Scope Definition
- WP2; Bioenergy LCA Review and Data Collection
- WP3; Interim Workshop
- WP4; Carbon Balance Calculations, Analysis and Business Cases
- WP5; End of Project Review

The overall purpose of WP2 is to analyse previous relevant LCA studies by providing a critique of the robustness of the evidence base based on both data and methodologies used, a measure of certainty behind the data reviewed and details of the confidence the reviewer may have in interpreting the data. In preparing the basis for this, a concise summary of the background and context of bioenergy LCA studies has been produced to cover the types of questions that bioenergy LCA studies typically attempt to answer and the appropriate methodologies that they should use to do this, and to highlight some of the areas of bioenergy LCA studies where there are conflicting views as to the appropriate approach. The process of reviewing relevant LCA studies, as one part of the evidence base for this project, is explained in terms of the selection and screening criteria adopted, the Bioenergy LCA Database where basic information on the selected LCA studies is recorded, the details of the full reviews that have been conducted and the findings that were drawn from the analysis of these full reviews. The development of the Bioenergy LCA Data Compendium, as a means of recording critical and all other data, which forms the rest of evidence base for this project, is also described.

2. SETTING THE CONTEXT

2.1 Approach

The context for examining the LCA of bioenergy begins by explaining the meaning of the word "bioenergy" and drawing a distinction between this broad term and another widely used term which is "biofuels". The particular reasons why bioenergy are usually regarded as a potentially suitable energy option for widespread application as a means for addressing important current challenges are considered since some of them have been questioned in a number of LCA studies. Subsequently, the basic features of LCA are described to provide a sound basis for a chronological summary of prominent issues raised by the application of LCA to bioenergy. The nature of LCA methodology is then investigated by considering differences between attributional LCA (ALCA) and consequential LCA (CLCA), by examining some of the stated purposes of bioenergy LCA studies and by explaining the systematic approach required to LCA goal and scope definition. Finally, the key points for setting the context for bioenergy LCA are summarised.

2.1.1. Bioenergy

Although there is no single agreed definition of the term bioenergy, it is generally considered to consist of the provision of any form of energy from recent organic material or "biomass". Within its relatively wide coverage, bioenergy includes "biofuels" which are liquid and gaseous fuels that are typically but not exclusively used in transportation. Such separate identification of biofuels means that bioenergy is often assumed to comprise all other forms of energy, such as electricity, heating and cooling as well as some gaseous fuels, that are not used in transportation. However, many of the concerns investigated by the application of LCA to biofuels also apply to bioenergy and, hence, all forms of energy obtained from biomass are addressed here.

Bioenergy has numerous characteristics which make it an attractive source of renewable energy for possible utilisation on a global scale. Its most central asset is its potential for "carbon neutrality" in which the biogenic carbon dioxide (CO_2) released into the atmosphere during the combustion or use of biomass, directly, or biomass-derived fuels can be balanced by the CO_2 absorbed from the atmosphere during its original growth. This is a very significant potential asset in a world facing global climate change due to increasing levels of CO_2 and other greenhouse gases (GHGs) in the atmosphere. The urgent need for global climate change mitigation options also underpins the possibility of combining bioenergy with carbon capture and storage (CCS), referred to as BECCS, so that CO_2 might actually be removed from the atmosphere.

The other attractive features of bioenergy are that it is a potentially renewable source of energy; it can produce stored forms of energy; it can be obtained from a very wide variety of biomass sources; and it can provide diverse forms of energy which can be used for various purposes. The potential renewability of bioenergy is based on the regeneration of biomass through regrowth. The ability of bioenergy to produce fuels which store energy is a particular advantage over intermittent sources of renewable energy. Its utilisation of a variety of biomass sources mean that it can be exploited in many different countries throughout the world. The diversity of bioenergy is a result of the numerous different ways in which biomass can be converted through thermal, chemical and other processes into many current and possible future forms of delivered energy.

2.1.2. Life Cycle Assessment

Amongst the many different means for evaluating the potential benefits and drawbacks of bioenergy, LCA has featured prominently. LCA is a well-established technique for quantifying the impacts of the life cycle of a product or service on the natural environment as a natural sink for emissions and as a natural source of resources. The genesis of LCA owes much to increasing concerns about damage to the natural environment and the depletion of natural resources that rose to prominence in the 1960's and 1970's, coinciding with the release of a number of influential publications (see, for example, Refs. 1 to 3). In response to these concerns, a variety of techniques were developed which were, effectively, precursors to LCA. These techniques included energy analysis as a means of evaluating the amount of energy required to produce products and services (see, for example, Refs 4 to 6). Energy analysis, which was applied to the evaluation of numerous technologies throughout the 1970's and 1980's, used an approach based on systems analysis which was later adopted in LCA.

The need for detailed evaluation of impacts on the natural resources and on natural environment grew during the 1990's. This resulted in the development of LCA which was officially formalised in the International Standards ISO 14040 (Ref. 7), originally in 1997, and ISO 14044 (Ref. 8), more recently in 2007. These International Standards provided a formal set of principles and rules by which LCA studies should be conducted. In addition to establishing a methodology for undertaking calculations and reporting results, the main steps in LCA were identified as defining the goal and scope of the LCA; assembling a life cycle inventory (LCI); conducting life cycle impact assessment (LCIA) by means of categorisation, classification and characterisation; and, finally, interpreting the results of the LCA.

It was intended that these International Standards would provide a basis for applying LCA in all possible circumstances. Although they set out the approaches required to quantify and interpret all impacts on natural resources and the natural environment from the complete life cycle of a product or service, they also offered necessary flexibility to focus on only certain impacts or examine only certain parts of the life cycle. In practice, many LCA studies were restricted to assembling the LCI and evaluating specific impacts. Due to the rising concern over global climate change during the 1990's (see, for example, Ref. 9), an increasing number of LCA studies concentrated on the estimation of greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These essentially partial LCA studies are sometimes referred to as "carbon LCAs".

With increasing emphasis on the mitigation of global climate change, LCA studies were undertaken for a number of different purposes. These included ex ante studies for the analysis of policies and the development of new processes, products and services, and ex post studies for monitoring and reporting environmental performance as a voluntary activity for "carbon footprinting" or product labelling or as a regulatory requirement. Regardless of their differing applications, LCA studies are expected to state, explicitly, their purposes, articulate these through goal and scope definition, and, in doing so, fix the methodological details of their calculations. Provided that they are applied strictly and completely, these principles should ensure that an LCA study produces a relevant and reliable answer to the question contained in its stated purpose. Unfortunately, LCA studies can fall short of these essential requirements causing problems which are compounded by failure to provide the necessary transparency stipulated by the International Standard.

2.2 Chronology of Bioenergy Life Cycle Assessment

Over a period of almost half a century, LCA and its precursors have been applied to evaluation of bioenergy and related activities, especially those involving agriculture and forestry. During this time, such studies have addressed a variety of concerns which could undermine the expected benefits of some or all types of bioenergy. These concerns have emerged over time as the understanding of bioenergy systems and their implications has developed and improved. A number of studies have reached controversial conclusions which have generated considerable debate amongst LCA practitioners and, often, much confusion amongst everyone else. The most prominent controversies are summarised here in chronological order.

2.2.1 Energy Analysis

Mainly in response to the first oil shock in 1973/74, energy analysis, as an earlier form of LCA, was used to test whether alternative fuels would provide more or less energy than is consumed during their provision including, for bioenergy technologies, biomass cultivation, harvesting, transportation, conversion and distribution. The starting point for such concerns was initial investigation of the dependence of modern agriculture on fossil fuels, in general, and oil, in particular (see, for example, Ref. 10). Such analysis was extended, specifically, to the proposed production of bioethanol from maize by means of fermentation in the United States of America (USA) where the energy analysis of alternative fuels eventually became a formal requirement. This involved calculation of the "net energy ratio" of alternative fuels equating to the ratio of primary energy inputs to their delivered energy outputs.

Some studies indicated that the production of such alternative fuels would result in net energy ratios greater than one (see, for example, Ref. 11). These were damning conclusions for fuels that had put forward as partial solutions to the immediate "oil crisis" and, ultimately, to the expected "energy crisis". By this stage, bioethanol production from maize had been initiated and expanded in the USA. Consequently, reviews were conducted of all relevant energy analysis studies and these concluded that those studies which generated net energy ratios greater than one assumed unduly high energy inputs and low bioethanol productivity (Refs. 12 and 13).

2.2.2 Greenhouse Gas Emissions and Biofuels

Although the debate over net energy ratios continued for some time afterwards, concerns had already switched to the evaluation of GHG emissions associated with biofuel production. This involved the actual application of LCA, as such, to the estimation of total emissions of CO_2, CH_4 and N_2O. In the United Kingdom (UK), claims and counter-claims led to a review of LCA studies on the production of biodiesel from oilseed rape (OSR). Subsequent development of biofuel regulations, which incorporated LCA, in the UK, the rest of the European Union (EU), the USA and elsewhere, resulted in a quite sudden abundance of published studies, some of which questioned the expected benefits of biofuels as means of reducing GHG emissions relative to diesel and petrol obtained from conventional crude oil. Whilst some of these studies were undertaken by academics or for non-governmental organisations, others were produced for biofuel producers as part of regulatory reporting. Amongst the concerns raised by these studies, the most prominent were their transparency; their treatment of major contributions to total GHG emissions, especially soil N_2O emissions; the possible impact of land use change; and the details of LCA application within regulatory methodologies.

2.2.2.1 Transparency

During the 1990's and early 2000's, a number of conflicting results had been published from LCA studies in the UK and elsewhere on the production of biodiesel from OSR (see, for example, Refs. 14 to 26). A comparative assessment of all these LCA studies, apart from those which were published after the review period (Refs. 25 and 26), was commissioned by the UK Department for Environment, Food and Rural Affairs, Defra (Ref. 27). The purpose of this assessment was to determine the causes of differences in results from the LCA studies. In some instances, it was possible to identify these causes but many of the significant and controversial assumptions could not be investigated due the lack of adequate transparency in some of the LCA studies.

This deficiency was addressed by producing a standard set of fully transparent calculations for the GHG emissions associated with biodiesel production from OSR under UK conditions. The intention of providing such calculations was to focus debate on the main contributions to total GHG emissions which might be the subject of real differences and, hence, disagreement. To a certain extent, this approach began to resolve the key discrepancies which included different assumptions about OSR cultivation inputs and yields; biodiesel productivity and sources of processing energy; and allocation procedures. However, the main outcome of the review was emphasis on the need for adequate transparency in all LCA studies.

The vital issue of transparency in LCA studies relates to the ability to examine the all assumptions and basic data that are incorporated into the calculations. A number of objections were, and can be raised over placing such detailed information in the public domain for general scrutiny. These objections include infringement of commercial confidentiality from revealing all data in the calculations, and revelation of intellectual property, in effect, by providing access to such calculations which, due to their extent and possible complexity, may be enshrined in computer models or tools. However, there are practical measures which can be taken that provide necessary transparency without infringing commercial confidentiality by means such as data aggregation, and avoid revealing intellectual property, for example, by presenting key elements of computer models and tools without enabling replication of software or giving access to essential functionality.

Regardless of the actual means adopted to achieve transparency, its importance is not a simple matter of adherence to academic standards or, even, strict compliance with the principles of LCA. It is a crucial requirement which underpins fundamental confidence in the results of LCA studies. Without transparency, potential recipients of the results of LCA studies might not appreciate their relevance, know their meaning and understand how they can be used correctly. In the absence of transparency and in the face of a diversity of conflicting results, confusion can be caused amongst the audience for LCA studies. This can lead to uncertainty over the validity of any given LCA study and, worryingly, to the conclusion that its basis is arbitrary so that its subsequent results are entirely subjective. Consequently, the audience may feel free to pick whichever LCA results meet their preconceptions and abandon any pretence of objective, evidence-based analysis.

2.2.2.2 Soil Nitrous Oxide Emissions

One minimum facet of transparency within an LCA study is the ability to see the relative magnitudes of different contributions to total impacts on the natural environment and natural resources. By examining LCA studies which provided sufficient transparency, it became apparent that a relatively few contributions dominated the total GHG emissions associated with the production of certain biofuels. In particular, for biodiesel production from OSR and bioethanol production from maize and wheat, noticeably large relative contributions were connected with the application of artificial nitrogen (N) fertilisers. These contributions were partly due to the manufacture of artificial N fertilisers but often mainly caused by subsequent N_2O emissions from the soil, depending on specific circumstances.

This latter issue of soil N_2O emissions was somewhat contentious at the time as there was some disagreement over how they should be calculated. Such calculations had to be based on modelling which, in essence, relates the amount of N fertiliser applied to a crop to the eventual N_2O emissions into the atmosphere. A number of models were available but no specific one had gained universal acceptance in LCA studies. However, standard methods to estimating N_2O emissions from managed soils, involving the application of artificial or natural N fertilisers or the incorporation of agricultural residues, were being developed during the 2000's for use in national GHG emissions inventories as required by Intergovernmental Panel on Climate Change (IPCC) reporting. Hence, although these methods had been developed for other purposes, they began being adopted in LCA studies in which N was added to the soil either via artificial or natural N fertilisers or by incorporating agricultural residues.

Any modelling of soil N_2O emissions has to accommodate the various pathways by which N added to the soil emerges as N_2O released into the atmosphere. There are three major pathways which result in direct N_2O emissions, and indirect N_2O emissions caused by volatilisation and deposition, and leaching/run-off. It should be pointed out that not all the details of all the mechanisms involved in these pathways were then or, indeed, are now fully understood. Additionally, the pathways can be complex and they can depend on a variety of factors. Consequently, models which attempt to simulate these pathways and estimate eventual N_2O emissions from the soil can be complicated and afflicted by potential uncertainty.

In recognition of the practical implications of modelling, the IPCC advocated three methods for estimating soil N_2O emissions, referred to as Tier 1, Tier 2 and Tier 3 (Ref. 28). With the IPCC Tier 1 method, soil N_2O emissions are estimated using given, simple linear relationships based on the original amount of N supplied either through the application of artificial or natural N fertilisers, or the incorporation of agricultural residues. The IPCC Tier 2 method requires the use of more sophisticated relationships which take into account factors such as soil type and climate. Adopting IPCC Tier 3 involves actually measuring soil N_2O emissions and/or deriving estimates with suitable models, such as the De-Nitrification De-Composition (DNDC) (Refs. 29 and 30) and DAYCENT computer simulations (Refs. 31 and 32).

It should be noted that the original purpose of these methods was to provide standard means by which soil N_2O emissions could be estimated and incorporated into national inventories for reporting GHG emissions. Whilst the IPCC provided the simple relationships, and default, minimum and maximum values for relevant parameters in the Tier 1 method, it is necessary for those opting to use Tier 2 or 3 methods to provide their own, more sophisticated relationships, or to undertake their own measurements and/or to apply suitable models, respectively.

For simplicity, most LCA studies adopt, where necessary, default values from the IPCC Tier 1 method for estimating soil N_2O emissions. This is convenient as the relationships provided by the IPCC are not only relatively simple but they also require no site specific information such as soil type and weather conditions. This is because the relationships and their values were derived from meta-analyses of published measurements of soil N_2O emissions (see, for example, Refs. 33 and 34). Hence, they can be applied as generally representative means of estimating soil N_2O.

However, the IPCC Tier 1 method is clearly very approximate as exemplified by the very large ranges that can be generated by using the cited minimum and maximum values of the parameters for estimating soil N_2O emissions. These ranges can easily exceed an order of magnitude. For example, the soil N_2O emissions factor for artificial N fertiliser application derived by combining default values for parameters in the IPCC Tier 1 method is 0.0208 kg N_2O/kg N, compared with emissions factors obtained by combining minimum and maximum values of 0.0049 kg N_2O/kg N and 0.1021 kg N_2O/kg N, respectively. This translates into a full range of over a factor of 20 in the possible estimate for soil N_2O emissions based on the IPCC Tier 1 method. It will be appreciated that subsequent adoption of the IPCC Tier 1 method can introduce considerable uncertainty into LCA studies, especially for those involving any crops which receive relatively high applications of artificial N fertiliser.

Hence, the reliability of using the IPCC Tier 1 method for estimating soil N_2O emissions in relevant LCA studies has been questioned. In particular, it was suggested that using this method might underestimate the soil N_2O emissions from crops grown for current biofuel production. This concern was mainly based on the apparent discrepancy between measured N_2O in the atmosphere and the amount estimated using the IPCC Tier1 method based on global N fertiliser application (Ref. 35). Partly in response to this, but mainly in recognition of the need for reliable estimates of soil N_2O emissions in national GHG emissions inventories, attention has been directed towards field work for measuring such emissions and deriving more representative relationships or models, in keeping with IPCC Tier 2 and Tier 3 methods, respectively.

In the UK, this has involved a major project which conducted field experiments measuring direct N_2O emissions from the soil during and after the cultivation and harvesting of prominent arable crops at a number of different sites over a 3 year period (Ref. 36). It was observed that pulses of N_2O emissions were connected to the timings of artificial N fertiliser applications and subsequent rainfall and its magnitude. By means of statistical analysis, the direct N_2O emission factor for artificial N fertiliser application was related to the annual rainfall, the soil type, in terms of its clay content, and the application rate. On this basis, the default value of 0.0157 kg N2O/kg N from the IPCC Tier 1 method reduces to 0.0072 kg N_2O/kg N. Taking into account related projects, it was inferred that indirect N_2O emissions due to volatilisation and atmospheric deposition from artificial N fertilisers were also related to the annual rainfall, the soil type, in terms of its clay content, and the application rate. However, it was suggested that indirect N_2O emissions due to leaching/run off from artificial N fertilisers were related to crop type rather than the application rate. Conclusions were also put forward on soil N_2O emissions from crop residue incorporation.

Regardless of the specific details and the implications for the UK national GHG emissions inventory, this and other research indicates that local conditions, which, in this case, are represented by rainfall and soil type, affect soil N_2O emissions. This means that LCA studies for any crops which require the application of significant amounts of artificial or natural N fertilisers, and/or the incorporation of agricultural residues, have to take site-specific factors into account to avoid calculating errors which also introduce substantial uncertainties.

2.2.2.3 Indirect Land Use Change

As interest in biofuel production from cultivated crops gained momentum during the 2000's, concerns began to be raised over possible conflicts over land for food production, as crystallised in the "food versus fuel" debate. In terms of LCA studies, this materialised in attempts to incorporate estimated GHG emissions resulting from the displacement of food crop cultivation by biofuel crop cultivation, encapsulated by the term "indirect land use change" (iLUC).

Concern had initially been directed towards the possible contributions to GHG emissions associated with biofuel production from land that had been converted to the cultivation of crops for the provision of feedstocks. Such conversion, referred to as "direct land use change" (dLUC), is known to cause the destruction of existing carbon stocks, in above and below ground biomass. This involves the conversion of stored carbon to CO_2, or, possibly in some cases, CH_4, depending on particular circumstances. The amount of carbon released by this process is determined by the characteristics of the land and its biomass prior to conversion, with different quantities being stored in grasslands, peatlands, scrubland, forests, etc.

The term "carbon debt" of land conversion was coined to represent the total amount of CO_2 that would be released by destroying the existing carbon stock and preventing the existing biomass from absorbing CO_2 during the following 50 years (Ref. 37). Subsequent analysis calculated the time required to "repay" this carbon debt by means of any GHG emissions savings from the use of resulting biofuels as alternatives to fossil fuels. It was demonstrated that the repayment time could be extremely long, ranging from decades to centuries. Of the cases examined, pay back times of decades were calculated for the conversion of wooded Cerrado in Brazil to sugar cane for bioethanol; of Cerrado grassland in Brazil to soybeans for biodiesel; and of abandoned cropland in the USA to maize for bioethanol. Pay back times approaching a century or more were estimated for the conversion of tropical forest and peatland rainforest in Indonesia and Malaysia to oil palms for biodiesel; of grassland in the USA to maize for bioethanol; and of tropical rainforest in Brazil to soybeans for biodiesel.

In general, the main conclusion from such analyses was that dLUC involving the destruction of any large carbon stocks, for whatever reason, should be avoided. However, this approach was extended by incorporating possible impacts of iLUC (Ref. 38). In this extended approach, it was proposed that the use of existing arable land for biofuel crop cultivation in one country would lead to a chain of displacement that would eventually cause the creation of new arable land in another country. This was based on the assumption that available arable land was severely constrained, especially in the face of a growing world population with increasing preference of land-intensive diets. Overall, it was concluded that, due to iLUC, the total GHG emissions associated with the production and use of bioethanol from maize in the USA would exceed those from the production and use of petrol (gasoline).

Since the logic of this analysis could be extended to cover arable crop-derived biofuels produced anywhere, including the UK, an independent investigation into the indirect effects of biofuels, including concerns over iLUC, was undertaken in 2008. This culminated in the publication of the Gallagher Review in the UK (Ref. 39). The Gallagher Review included the recommendation that, although there was considerable uncertainty about the central tenet of iLUC and its impact on GHG emissions, a cautious approach should be adopted in which the introduction of biofuels should be significantly slowed.

Further analysis suggested that EU Member States (MSs) would not be able to achieve, simultaneously, proposed targets for biofuel supply and GHG emissions savings if iLUC impacts of biofuel crops were taken into account (Ref. 40). This and other work on concerns over iLUC and the expected GHG emissions savings from crop-based biofuels subsequently caused a series of reports to be commissioned by the European Commission (EC). These reports included initial evaluation of the possible implications of iLUC on EC Biofuels Policy (Ref. 41), and a review of existing literature on this topic (Ref. 42). Most crucial, existing models of global land use, which are at the very heart of estimating iLUC impacts on GHG emissions, were investigated (Ref. 43). The initial evaluation of the possible implications of iLUC on EC Biofuels Policy was updated (Ref. 44) and provisional findings were published (Ref. 45). In general, it was concluded that iLUC contributions to total GHG emissions from crop-based biofuels could, potentially, be very large but, again, the degree of uncertainty was also very considerable.

Clearly, the issue of iLUC revolved around the reliability and accuracy of global land use models. For a variety of reasons, including recognised limits to the availability of global data and the capability of simulations to represent global interactions, existing models were not able to provide sufficient confidence for resolving concerns over iLUC impacts on GHG emissions associated with crop-based biofuels. In the absence of markedly improved global land use models, and, hence, relying on judgment and compromise, the EC in 2012 proposed iLUC factors, which consist of extra GHG emissions for specific types of biofuel crops (Ref. 46). Provisional values for these iLUC factors, which affect cereals and other starch-rich crops, sugars and oil crops, have now been incorporated into amendments to relevant EC Directives (Ref. 47). However, it must be appreciated that, beyond the confines of regulation, the issue of iLUC in LCA calculations is still unresolved.

2.2.2.4 Regulation

During the late 2000's, the evaluation of GHG emissions began to be incorporated into official regulations for biofuels in a number of countries. For example, the Renewable Transport Fuel Obligation (RFTO) came into force in the UK in 2008 with "carbon reporting" requirements specified in 2008 (Ref. 48), with subsequent modifications in 2009 (Ref. 49) and 2010 (Ref. 50). Across the EU, Directives which address biofuels include the mandatory calculation and reporting of the GHG emissions associated with the supply of biofuels which count towards agreed renewable energy targets. The details of these regulatory calculations, which are ostensibly based on LCA principles, were first published in the Renewable Energy Directive, or RED (Ref. 51) and the Fuel Quality Directive, or FQD (Ref. 52) in 2009. The GHG emissions calculation methodology in the RED and FQD have been broadly adopted in regulations of EU MSs and articulated in tools such as BIOGRACE (Ref. 53).

Since its initial release, the RED/FQD methodology has attracted sustained criticism (see, for example, Refs. 54 and 55). These criticisms include a contradictory procedure for allocating GHG emissions between for biofuel co-products, namely cogenerated electricity and all other co-products; and the lack of definitive specification of wastes and residues whose provision and avoided GHG emissions are excluded from calculations. In general, it can be argued that the methodology is attempting to address, simultaneously, the requirements of regulation and policy analysis whilst failing to meet, fully, the distinct and different objectives of either. The fundamental reason for this is that the purpose of the methodology, as an application of LCA, is not stated explicitly, and, additionally, its goal and scope are not defined, as demanded by strict principles of LCA. Hence, instead of all details of the methodology being dictated by the LCA purpose, goal and scope, seemingly arbitrary choices have been incorporated which affect subsequent results.

2.2.3 Greenhouse Gas Emissions and Bioenergy

The evaluation of GHG emissions associated with different types of bioenergy, other than just biofuels, started in the 1990's. For example, in the UK, a series of studies were commissioned by the Energy Technology Support Unit (see, for example, Refs. 56 - 60) and consistent estimation of GHG emissions for a range of bioenergy technologies was undertaken for the Department of Trade and Industry in 2003 (Ref. 61). Although, in some instances, these studies included coverage of biofuels, the provision and use of other biomass feedstocks, such as miscanthus, switchgrass, reed canary grass, straw and forest residues, were also investigated. From these and other relevant studies, the Biomass Environmental Assessment Tool (BEAT) was developed, initially, for the Environment Agency (EA) in 2005 and then, as $BEAT_2$, jointly for Defra in 2007 (Ref. 62).

Obviously, the evaluation of bioenergy technologies involving biomass feedstock crops requiring the application of fertilisers and/or the removal of agricultural residues instead of their incorporation, or the use of arable land that might otherwise have produced food crops, had the potential to raise concerns, such as soil N_2O emissions and iLUC impacts, in similarity with LCA studies of biofuels. However, in most cases, the significance of these particular concerns was reduced, relative to crop-based biofuels, due to lower fertiliser application rates, relatively minor net contributions to total GHG emissions from agricultural residue removal as opposed to incorporation, and assumptions about the use of unproductive or abandoned land for biomass feedstock cultivation. Instead, the major issue that emerged during the 2010's was forest carbon dynamics and their effects on the evaluation of GHG emissions associated with the provision of bioenergy from forest biomass. Related issues involved the overall CO_2 fluxes of harvested and unharvested forests and GHG emissions due to the displacement effects of wood fuel and wood products. Around the same time, reviews and meta-analyses of bioenergy LCA studies began to be published and proposed sustainability criteria for using solid and gaseous biomass sources in electricity, heating and cooling were published by the EC.

2.2.3.1 Forest Carbon Dynamics

As explained in Section 1.2, one of the principal benefits of bioenergy is the potential for carbon neutrality. This concept is normally described in terms of the balance between the amount of CO_2 absorbed from the atmosphere by growing biomass and the amount of CO_2 released into the atmosphere when this biomass used as a source of energy. For annual biomass crops, this balance is readily apparent since the absorption and release of CO occurs within a relatively short timescale of 12 months or less. However, longer timescales for carbon neutrality have to be considered for biomass feedstocks such as wood from short rotation coppice (SRC), short rotation forest (SRF) and long rotation forest, in which a rotation defined is the period of time from initial planting to final felling. These longer timescales are relevant when examining options for global climate change mitigation since the timing of CO_2 absorption and release has to be taken into account.

The importance of the timing of so-called carbon or CO_2 fluxes depends on whether, overall, they reduce, balance or increase current and/or future CO_2 emissions into the atmosphere. This is best illustrated by considering wood from trees in a forest available, as an option, for fuel to-day. If burnt to-day, the effect on the atmosphere, from the current perspective, is to increase the level of CO_2 as its absorption occurred in the past. From a current perspective, past CO_2 fluxes have already occurred and have, presumably, been taken into account previously. However, this simple illustration does not recognise the potential effects of how the forest might be managed into the future.

If all the trees in a forest are clear felled and not replaced, then there is still a net increase in CO_2 levels in the atmosphere, from the current perspective. Such unsustainable management of the forest means that wood is being treated as a non-renewable or depletable energy resource, in the same way as fossil fuels and with similar consequences in terms of CO_2 emissions. Additionally, if the clear felled and non-replaced trees were capable of further growth, then, from a future perspective, CO_2 absorption has, in effect, been forgone. However, if new trees are planted after clear felling, over a period of time into the future, depending on species, conditions and management, CO_2 will be gradually absorbed from the atmosphere. Eventually, at the end of this period, cumulative future CO_2 absorption can balance the initial CO_2 release due to wood fuel combustion, resulting in overall carbon neutrality.

It might be pointed out that such re-balancing of CO_2 only occurs over a period of time exceeding about 50 years for long rotation forests and this is too long for viable options which are needed to mitigate global climate change now. Hence, from to-day's perspective, such forest management would still be regarded as non-carbon neutral. However, this does not take into account practical possibilities of the management of the forest as a whole. For instance, realistic sustainable management of forests can involve having groups, or stands of trees, of successive ages covering the entire planned rotation of the forest. Such an arrangement means that the CO_2 emissions from burning wood fuel from the stand which has been felled at the end of its rotation can be balanced by the CO_2 absorbed, collectively, by all the other stands. By taking into account of the whole forest managed in this manner, carbon neutrality can be realised at any given instant and maintained over the duration of the rotation.

In general whether wood fuel from a forest, or any other biomass source with a potentially regenerative cycle greater than one year, is carbon neutral depends on the specific details of its management as a whole and over time. This aspect of management determines the balance, or otherwise, of CO_2 fluxes. These fluxes can be assessed by modelling carbon dynamics. Such modelling is needed for various reasons, especially for evaluating contributions to the "land use, land use change and forestry" (LULUCF) components of national GHG emissions inventories. In the UK, forest carbon dynamic models have been developed and used for this purpose by Forest Research (FR).

Simulated results from forest carbon dynamic models can also be incorporated into LCA studies of forest bioenergy. These results were included in some earlier LCA studies for forest bioenergy in the UK during the 2000's. Additionally, $BEAT_2$ was enhanced in 2010 for the EA by including the effects of carbon dynamics on the supply of wood fuel from forests in Canada, Fennoscandia and the Baltic States, Russia and the UK for use in UK electricity generation (Ref. 63). This utilised the outputs of FR's CSORT model which was subsequently applied to estimating total GHG emissions associated with the use of wood, for fuel and other purposes, from forests in Scotland. These results were reported to the Scottish Government in 2012 (Refs. 64).

As part of the assessment, for the then-Department of Energy and Climate Change (DECC), of the carbon impacts from the use of biomass in the UK, which also covered bioenergy from energy crops (Ref. 65), the CSORT model was used to simulate carbon dynamics of UK forests, with results reported initially in 2012 and in revised form in 2014 (Ref. 66). These results consisted of estimated total GHG emissions per unit area of forest, annualised over future periods of time or "time horizons" of 20, 40 and 100 years. They reflected the continuing management of coniferous and broadleaf forests, and the restoration of neglected broadleaf forests. The effects of various factors were taken into account, such as the forest rotation cycle (first, second or third); the use of wood fuel in different applications and their displacement of different fossil fuels; the application of CCS with wood-fired technologies; and the material usage of wood products, their possible replacement by wood products from outside the UK or by UK non-wood products, and their end-of-life fates.

In addition to these factors, the most significant consideration, in terms of the questions that had to be addressed by this LCA study, was which tree parts, composed of branchwood, bark, roundwood and sawlogs, would be used for wood fuel and wood products. The many combinations of production profiles generated a very large number of scenarios, between 69 and 282 depending on specified details, for investigation. In addition to "absolute" results, the study produced "relative" results which compared the total GHG emissions of providing wood fuel and wood products from forests with those of "leaving carbon in the forest" by abandoning harvesting.

Due to the very large number of different scenarios examined, highly diverse results were obtained. In general, reductions in GHG emissions were indicated by the absolute results of the majority of scenarios considered and also by the relative results of a number of scenarios. In particular, absolute and relative reductions in GHG emissions were obtained for scenarios which were similar to the "conventional mix" of wood products from UK forests, consisting of sawlogs for sawn timber; roundwood for particleboard, medium-density fibreboard (MDF), fencing and pallets; bark for horticultural mulch or fuel; branchwood for fuel; and sawmill offcuts for particleboard, MDF and fuel. However, it was also concluded that certain scenarios should be avoided as their relative results suggested that, in terms of global climate change mitigation, instead of providing a source of wood fuel, it would be better to leave the forests unexploited yet still managed.

All these results contributed to the analytical background of the UK bioenergy strategy, which was published in 2012 (Ref. 67) and which generated a degree of controversy. In particular, attention was focused on one specific scenario which involved using the "whole tree" for fuel (Ref. 68) and which led to the publication of "Dirtier than Coal?" (Ref. 69) by a group of concerned environmental organisations in the UK. In fact, the scenario involving the use of all parts of the tree for fuel was amongst those that had already been identified as options to be avoided. Additionally, confusion was apparent over the meaning of the term "whole tree" as it applied to all the products available from the felling of a mature forest stand and the "thinnings" that inevitably arise during the course of the necessary management of that stand.

Of possible wider significance was evocation of the concept of carbon debt which was used to point out that the CO_2 emissions released into the atmosphere during the combustion of wood would only be re-absorbed over a relatively long period of time in the future by any trees that were subsequently planted. However, it was later noted that this particular interpretation, based on the effective time delay of re-balancing carbon fluxes, is only one of three phenomena covered by carbon debt; the other two phenomena being permanent reductions in forest carbon stocks due to increased harvesting and so-called “foregone sequestration” based on the potential for managed forests to absorb and store more carbon if left alone rather than harvested (Ref. 70). All these phenomena were already incorporated into the CSORT model and, hence, accounted for in subsequent results.

These and other issues were addressed by the SUPERGEN Bioenergy Hub in the UK in 2013 (Ref. 71). This report and the subsequent workshop concentrated on the factors that affect the carbon balances of heat and electricity generated from biomass feedstocks derived in the UK from energy crops and wastes as well as forests. In particular, it was noted that different bioenergy LCA studies produced different results which were due not only to real differences in bioenergy value chains but also to differing LCA purposes, goals and scopes. Earlier that year, DECC held a stakeholder engagement workshop on a preliminary version of the Biomass Emissions and Counterfactual (BEAC) model which it had been developing for the carbon assessment of biomass feedstocks relevant to the UK (Ref. 72). The BEAC model, which incorporated certain results from the CSORT model, was subsequently used to investigate the GHG emissions associated with importing wood fuel from North America for electricity generation in the UK (Ref. 73).

As a part of further work on the modelling of forest carbon dynamics, FR developed the CARBINE model which was applied in a number of subsequent bioenergy LCA studies. In particular, it was used, in combination with other models, to quantify the total GHG emissions associated with future biomass consumption in the EU (Ref. 74). In this study, energy demand in the EU-27, energy supply represented a number of possible scenarios, and estimated direct GHG emissions from fossil fuel consumption were simulated by the VTT-TIAM model (Ref. 75). The CARBINE model was used to calculate carbon stock changes and GHG associated with the provision of bioenergy feedstocks from forests within and outside the EU (Ref. 76). GHG emissions from dLUC and the provision of bioenergy feedstocks from energy crops in the EU were evaluated with the MITERRA-Europe model (Ref. 77). All other indirect GHG emissions for relevant bioenergy value chains were estimated by means of bespoke workbooks.

The chosen scenarios, which extended to 2030 and, speculatively, to 2050, incorporated different assumptions about the use of EU-produced and imported biomass. In addition to a reference scenario based on existing 2020 bioenergy use targets with no further expansion, there were decarbonisation scenarios which relied either on the expanded or reduced use of bioenergy after 2020. The decarbonisation scenarios with expanded bioenergy use emphasised either imported wood fuel, EU wood fuel or EU energy crops. All scenarios included the use of wood fuel produced from forests in the EU and, principally, in Canada and the USA. Different approaches to forest management were taken into account. The headline conclusions of this study were that, considered as a whole, a significant increase in bioenergy use by the EU is likely to lead to a decrease in total GHG emissions, although support for sustainable forest bioenergy supply is necessary to ensure that a significant increase in forest bioenergy use in the EU results in a net decrease, rather than a net increase, in its GHG emissions contribution.

2.2.3.2 Counterfactuals

Many bioenergy LCA studies incorporate the influence on estimated GHG emissions of so-called “counterfactuals” which consist of the effects of any action that is an alternative to the one under investigation. In effect, a counterfactual is a form of displacement based on what would have happened if a particular action had not taken place. Counterfactuals are sometimes referred to by LCA practitioners as "reference systems" and they are addressed by a procedure known as "system expansion". There are many different types of counterfactual. One of the simplest counterfactual to consider consists of the GHG emissions from fossil fuel combustion that are avoided by the alternative use of a low carbon source of energy such as bioenergy. A more complicated counterfactual would be the GHG emissions caused by iLUC when energy crops are grown on land which could have been used to provide food or fibre, thereby initiating a potentially long and complex chain of land use displacement.

There are also a number of different types of counterfactual that need to be accounted when considering forest bioenergy. For this source of biomass, the most prominent counterfactual is based on the possibility of not harvesting wood fuel and wood products from a forest and, instead, leaving it unexploited. In this instance, if the forest continues to grow and, therefore, absorb and store carbon, the counterfactual to wood fuel and wood product harvesting is foregone carbon sequestration, as discussed previously in relation to carbon debt. It should be appreciated that the evaluation of this particular counterfactual is somewhat dependent on whether the forest does continue as a "carbon sink" into the future. This assumption is critical as a forest can also become a "carbon source" when disrupted by wildfire, wind damage, disease, pests, etc.

As also explained earlier, different parts of a tree can be used for different purposes. Hence, the use of roundwood for wood fuel, for example, means that it is not available for providing wood products. Consequently, these products have to be obtained from another tree, possibly in another forest, or replaced by a suitable non-wood product. This chain of replacement is another form of counterfactual which can become quite difficult to envisage, especially if other considerations, such as end-of-life disposal is taken into account. Such conceptual difficulties can arise because it may be necessary to consider, in effect, "counterfactuals of counterfactuals", and so on. For example, if roundwood is used for wood fuel instead of particleboard then this wood product must be sourced elsewhere. At the end of its life, this particleboard might be disposed of in an incinerator which recovers heat that displaces fossil fuel. Hence, wood fuel production from roundwood has caused GHG emissions from alternative particleboard production as well as its disposal which will, in the future, prevent GHG emissions from fossil fuel combustion.

Though potentially complex, the GHG emissions associated with any counterfactuals can, with care, be determined technically. In the case of specific products being replaced by quite different products, as when, for example, the non-wood alternative to particleboard is blockwork, it is necessary to base calculations on the specified "equivalence" of counterfactuals. Such equivalence is normally determined by a technical function which is shared by a product and its counterfactual. In the case of particleboard and blockwork, this function might be identified as a unit area of wall which could be constructed from either of these materials. The amounts of both of these materials used in such a function will determine the relevant equivalence between the product and its counterfactual. However, the main challenge is not establishing this equivalence technically but deciding which counterfactual chain of replacement or displacement would, in fact, have occurred. This challenge arises because the counterfactual circumstances are, or might seem highly hypothetical.

Ideally, the appropriate selection of counterfactuals might be resolved by suitable economic modelling although, in practice, reliance is often placed on subjective judgment. In this respect, the way in which counterfactuals are accommodated in GHG emissions calculations encounters problems similar to those associated with incorporating the effects of iLUC. Similarly, counterfactual modelling is either limited or non-existent. Hence, in order to restrict the subjectivity of selecting counterfactuals using informed judgement, an approach is usually adopted involving sensitivity analysis. This consists of either evaluating the range of results that can be generated by considering all expected counterfactuals or two of the most likely but distinctly different counterfactuals.

However, results can be very sensitive to the choice of counterfactuals, in some instances, leading to inconclusive outcomes, as can occur with similar approaches to investigating the possible effects of iLUC. Such sensitivity was apparent from the relatively large range of results possible from the 29 scenarios, which cover many different counterfactuals, derived in 2014 using the BEAC model to investigate the potential supply of wood fuel from North America for electricity generation in the UK (Ref. 73). In particular, depending on the choice of factors including counterfactuals, GHG emissions associated with electricity generation from such imported wood fuel could vary from less than to more than those from fossil fuel-fired electricity generation.

2.2.3.3 Reviews and Meta-Analyses

The ever-growing collection of bioenergy LCA studies has prompted a number of reviews and meta-analyses to be undertaken at various times. There are many reasons for doing this, including attempts to discern the general patterns in results so that overall conclusions can be drawn, in terms of estimated total GHG emissions, and/or to explain differences in results from individual LCA studies. Whilst such objectives can be justifiable, it is important to recognise the limitations of such work and, thereby, to avoid misleading conclusions. For example, it might be imagined that the range of results that can be found in the published literature reflect real variations or, possibly, uncertainties in estimated GHG emissions. However, differences in results can be readily generated by basic differences in calculation methodologies. In particular, LCA studies can be conducted for different purposes and this alone can produce differences in results. This can foster confusion over the outcomes of bioenergy LCA studies, especially if they do not state their purpose, goal, scope and subsequent methodology explicitly and completely. These are important aspects of transparency which was mentioned previously in relation to the comparative assessment of LCA studies and their results.

Such problems afflicted some of the early work involving the reviews and meta-analyses of bioenergy LCA studies. More recently, greater care has been taken as a means of creating a consistent basis for comparing, contrasting and applying the results of different bioenergy LCA studies. This has been achieved by either adopting screening procedures to eliminate incompatible results or by focusing on the evaluation of certain important contributions to total GHG emissions, such as the simulation of carbon fluxes using forest dynamic modelling.

A screening procedure was used to present an overall picture of estimated GHG emissions associated with the generation of electricity from biomass in the IPCC Special Report on Renewable Energy in 2012 (Ref. 78). This reduced an initial collection of 369 bioenergy LCA studies to 84 after necessary screening for quality and relevance, of which only 52 could provide unambiguous results for subsequent comparative use. Such screening still produced a very large range between the minimum and maximum values of results although the majority of results were very tightly clustered around the median value. The overall conclusion was that the total GHG emissions of generating electricity from biomass were lower than those associated with fossil fuel-fired electricity generation. However, doubts over the global climate change mitigation benefits of this form of bioenergy can persist from this meta-analysis due to the degree of overlap between these results. This is especially the case as the screening procedure excluded the effects of “land use-related net changes in carbon stocks and land management impacts” (Ref. 78). Additionally, it was noted that differences in calculation methodologies were one cause of the observed variations in results.

The debate over the potential benefits or otherwise of obtaining biomass from forests for bioenergy in 2012 prompted a number reviews of bioenergy LCA studies which incorporated forest carbon dynamic modelling. In terms of the EU, the first most significant review was conducted for the EC in 2014 by the Joint Research Centre (JRC) at Ispra in Italy (Ref. 79). This review accessed a large body of then-currently available literature and performed meta-analysis using 8 LCA studies which concerned the provision of bioenergy from dedicated stemwood and harvest residues. In particular, estimates of the payback time, which is the period over which the total GHG emissions associated with bioenergy derived from forests equals those from the fossil fuel that it displaces, were compared. Wide variations in payback times were observed reflecting differences in the details of the forests investigated and the assumptions adopted. Overall, it was concluded that "the carbon neutrality assumption for forest bioenergy may be misleading and it is fundamental to integrate all the carbon pools in the analysis (above ground biomass, below ground biomass, dead wood, litter, soil and harvested wood products) and their evolution in the time horizon of the analysis for both the bioenergy scenario and the counterfactual".

Given the significance of forest carbon dynamic modelling to bioenergy LCA studies involving wood fuel supply from forest, the JRC also organised a workshop on "Modelling EU Bioenergy Use: supply/demand trends and climate change effects" at Ispra on 21 and 22 April 2016. This brought together participants from three relevant projects funded by the EC, consisting of the completed projects on "Carbon Impacts of Biomass Consumed in the EU" (Ref. 74) and the "Study on Impacts on Resource Efficiency of Future EU Demand for Bioenergy (ReceBio)" (Ref. 80), and ongoing work on renewable energy scenario modelling led by the Technical University of Vienna. Additionally, Imperial College London represented the completed "Support for EU Bioenergy Policies (BIOMASS FUTURES)" project (Ref. 81), and the then-ongoing "Strategic Initiative for Resource Efficient Biomass Policies (BIOMASS POLICIES)" project and the "Sustainable Biomass for the Bioeconomy (S2Biom)" project. The workshop was also attended by staff from various EC Directorate-Generals and the JRC. As well as forest carbon dynamic modelling, the workshop discussed relevant models for energy systems, land use and agricultural commodities, and a report on the outcomes of this workshop is expected to be published later in 2016.

The JRC review and meta-analysis of forest bioenergy was also included in a review of literature on biogenic carbon and forest bioenergy LCA which was published in 2014 (Ref. 82). After introducing and explaining forest management and wood utilisation, forest carbon dynamic modelling, and the essential LCA concepts and issues, 36 relevant studies or reviews of forest bioenergy LCA studies were reviewed and their metrics were summarised. It was concluded that there was, at least, consensus on some of the basic phenomena covered in these forest bioenergy LCA studies. There was agreement that biogenic carbon has to be included in the strategic assessment of GHG emissions associated with forest bioenergy although variations in results could occur due to the influence of forest management practices, which can either reduce or increase forest carbon stocks; assumptions about the many different factors that have to be taken into account; and, of course, the choice of LCA calculation methodologies. Various circumstances were also identified which could lead to positive or negative outcomes for forest bioenergy in terms of net GHG emissions savings which can vary over time.

2.2.3.4 Sustainability Criteria

In keeping with the intentions of the RED and FQD for liquid and gaseous biofuels, the EC proposed sustainability criteria for the regulation of biomass used for electricity generation, heating and cooling in 2010 (Ref. 83). These criteria incorporated minimum levels of net GHG emissions savings based on a specified calculation methodology. In Great Britain, these criteria and the related calculation methodology were effectively incorporated into guidance from the Office of Gas and Electricity Markets (Ofgem) for the reporting of GHG emissions reductions, under the Renewables Obligation, by the operators of certain sizes of biomass-fired power plants (Ref. 84). The calculation methodology also formed the basis for the UK Solid and Gaseous Biomass Carbon Calculator (B2C2) for operators generating electricity and electricity co-produced with useful heat (Ref. 85) and for operators of biomass-fired heating plants reporting under the Non-Domestic Renewable Heat Incentive (Ref. 86).

The GHG emissions calculation methodology incorporated in the EC's proposed sustainability criteria has attracted similar criticism to that directed towards the RED and FQD. Most tellingly, as an application of LCA, the sustainability criteria lack an explicitly-defined goal. Hence, the subsequent details of the calculation methodology are not justified and appear to be arbitrary. In general, the methodology is a hybrid approach which, like the RED and FQD, mixes regulation with policy analysis whilst failing to satisfy either purpose. For example, the methodology uses exergy, as a measure of available energy, as the basis for allocating GHG emissions between electricity, heating and cooling in biomass-fired combined heat and power plants. As with the RED and FQD, GHG emissions have been allocated between any co-products from biomass feedstock provision, other than electricity co-generation, on the basis of their energy contents. Whilst carbon stock changes from dLUC have to be accounted in the GHG emissions calculations, those from forests which supply wood fuel are not incorporated. Additionally, it is stated that "wastes, secondary biomass and primary forest and agricultural crop residues, including tree tops and branches, straw, bagasse, husks, cobs and nut shells, and residues from processing, including crude glycerine (glycerine that is not refined), shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials" (Ref. 83). However, any avoided GHG emissions from the disposal of these wastes are not taken into account.

2.2.4 Life Cycle Assessment Methodologies

2.2.4.1 Attributional and Consequential Life Cycle Assessment

Partly due to the possibility of generating different results based on regulatory rules and in other LCA studies, a debate about methodologies began in the late 2000's. This led to differentiation between two methodologies referred to as "attributional LCA" (ALCA) and "consequential LCA" (CLCA). In particular, a paper from Ecometrica in the UK, stated that ALCA "provides information about the impacts of the processes used to produce (and consume and dispose of) a product, but does not consider indirect effects arising from the changes in the output of a product", whereas CLCA "provides information about the consequences of changes in the level of output (and consumption and disposal) of a product, including effects both inside and outside the life cycle of the product" (Ref. 87).

The main differences in the GHG emissions calculation methodologies of ALCA and CLCA can be summarised (Refs. 87 and 88). In particular, the ALCA methodology excludes GHG emissions from the construction of plant and the manufacture of machinery; possibly does not take into account counterfactuals or reference systems as alternatives to biomass feedstock land use or waste disposal; and applies co-product allocation, possibly based in economic value. The CLCA methodology includes GHG emissions from the construction of plant and the manufacture of machinery; does take into account land use or waste disposal reference systems; and adopts system expansion, "substitution credits" or counterfactuals for the treatment of co-products.

However, these and other specific details of calculation methodologies should really reflect differences in the stated purposes and defined goals and scopes of these different types of LCA study. The Ecometrica paper states that ALCA "provides information about the impacts of the processes used to produce (and consume and dispose of) a product but does not consider indirect effects from changes in the output of a product" in contrast to CLCA which "provides information about the consequences in the change in the level of output (and consumption and disposal) of a product, including effects both inside and outside the life cycle of the product" (Ref. 87). This leads to the suggestion that ALCA produces results for the average unit of product which are "useful for consumption-based carbon accounting" and, by possible extension, monitoring and regulation, whilst CLCA "models causal relationships originating from the decision to change the output of a product" which is relevant for policy-makers.

It can, however, be argued that both these calculation methodologies are capable of generating results for a process "as it is" or "as it might be" (Ref. 89). Instead, the key difference between ALCA and CLCA would seem to be the fundamentally different ways in which co-products are treated in calculations. In particular, ALCA attempts to partition or "attribute" GHG emissions between co-products whereas CLCA is intended to determine the GHG emissions "consequences" of all co-products by means of system expansion. It is in these ways that ALCA is particularly suited to the purposes and goals of monitoring and regulation because it assigns environmental impacts, such as GHG emissions, to a particular product or service, whilst CLCA is appropriate for the purpose and goals of policy analysis since it determines the overall outcomes for environmental impacts of providing a given product or service.

Over time, ALCA and CLCA have become shorthand terms for describing the application of LCA in regulation and policy analysis, respectively, especially with regard to biofuels and bioenergy. However, this characterisation is not entirely accurate, particularly when ALCA is used to describe the methodology of regulatory measures such as the EC's RED and FQD for biofuels and proposed sustainability criteria for bioenergy. This is because, as explained elsewhere, the application of LCA in these regulations involves the effectively hybridisation of methodology which combines elements of ALCA and CLCA (see, for example, Refs. 54, 55 and 90). Although the methodological details of these regulatory measures are set out in some detail, the actual meaning of subsequent results is unclear. This has led many to doubt the usefulness of results generated by the methodologies specified in the EC's RED, FQD and sustainability criteria.

In particular, it has been pointed out that the application of such methodologies does not enable the "real" GHG emissions associated with the production and use of biofuels and bioenergy to be quantified (see, for example, Refs. 54, 71, 91 and 92). Whilst correct, it could be argued that this was never the actual intention of these regulatory LCA methodologies. The problem is that the actual intention of the regulations is not specified in strict and explicit LCA terms by stating the LCA purpose and elaborating this by defining the LCA goal and scope, as required by ISO 14040 (Ref. 7). If these fundamental principles of LCA had been followed then this would have resulted in specification of the correct methodology which is appropriate for the stated LCA purpose. Hence, it might be concluded that this represents a failure in the application of LCA principles rather than deficiencies with the LCA methodology.

At this point, it is probably useful to recap on the officially required features of the LCA goal and scope. ISO 14040 specifies that "the goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated" (Ref. 7). ISO 14040 also requires that the LCA scope should specify the functions of the product system(s) to provide and/or use and/or dispose of the given product or service under investigation; the functional unit which is used to express the essential nature, characteristics or purpose of a given product or service; the product system(s) to be studied; the product system(s) boundaries; and the co-product allocation procedures (Ref. 7).

With regard to these features, a product system is an activity or series of activities that are involved in the provision of specified product(s) and/or service(s). A system boundary is an imaginary line drawn around and completely enclosing a part or whole of a product system that has been designated for investigation so that all inputs and outputs which cross this line are quantified by the LCA study. Such system boundaries have both spatial and temporal dimensions, and, for completeness, both should be specified in the defined LCA scope. Co-product allocation determines how impacts, in general, or GHG emissions in particular are treated when multiple products and/or services are generated by the product system under consideration. Broadly speaking, co-product allocation consists of either partitioning impacts between co-products on some particular basis, or applying system expansion or the use of counterfactuals.

2.2.4.2 Stated Purposes of Bioenergy Life Cycle Assessment

It is an unfortunate observation that many bioenergy LCA studies and, indeed, other types of LCA studies, usually do not state their intended purposes and define their goals and scopes explicitly. Sometimes it is possible to discover the purpose, goal and scope of an LCA study by examining its specific details but this is a rather inefficient process which can lead to incorrect conclusions. Apart from avoiding such misinterpretation, the explicit definition of the LCA goal and scope is a formal requirement of ISO 14040 (Ref. 7). In many LCA studies, the exact composition of the goal and scope becomes apparent from the actual details of calculations, provided, of course, that these are accessible and transparent. Instead, the LCA purpose, which can, potentially, encompass the goal and scope, is only stated occasionally. In essence, this is the very least that should be established in any LCA study.

When this occurs, the LCA purpose is usually framed as a question or a related series of questions that must be answered by the LCA study. For example, in the project on "Carbon Impacts of Using Biomass in Bio-energy and Other Sectors" (Ref. 66), DECC, as the client, specified the following questions regarding the provision of bioenergy from UK forests:

- Is it better to leave wood in the forest or harvest it for timber, other wood products (e.g. panel boards) and/or fuel?
- Is it better to use harvested wood to provide materials or fuel?
- Are there particular options involving the use of UK wood that clearly offer the biggest benefits?
- Are there other options that should be avoided?
- What would be the impacts of using imported wood rather than UK-grown wood for timber, other wood products and/or fuel?

These questions clearly related to policy concerning wood fuel supply and use in the UK. In fact, the results of this project informed discussions over development of the UK bioenergy strategy at that time (Ref. 93). Hence, given their policy context, these questions dictated that CLCA should be adopted in this particular project with specific methodological details consisting of quantification of prominent GHG emissions, and application of a spatial system boundary with potentially global extent and temporal system boundaries covering specified periods of time from "now" into the future. The prominent GHG emissions were identified as CO_2, CH_4 and N_2O. The application of a global spatial system boundary and future temporal system boundary meant that, in addition to other considerations, carbon stock changes in forest were taken into account and GHG emissions associated with the construction of plant and the manufacture of machinery were included in calculations. The chosen time horizons for the temporal system boundaries were 20, 40 and 100 years. The overall consequential nature of these policy questions also required the adoption of counterfactuals throughout this LCA study.

The stated purpose of the LCA required in the project on “Carbon Impacts of Biomass Consumed in the EU” could be discerned from original tender call published by the EC’s Directorate-General for Energy (DG-ENER) in 2012 (Ref. 94). This specified a requirement “to deliver a qualitative and quantitative assessment of the direct and indirect GHG emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios, in order to provide objective information on which to base further development of policy on the role of bioenergy as a source of energy with low associated GHG emissions”. In particular, the quantitative assessment needed to address:

- Impacts on carbon sequestration and biogenic carbon emissions arising from using forest biomass,
- Impacts of using land for energy crops,
- Indirect land use change (iLUC),
- Other indirect impacts of diverting woody biomass to energy from other uses,
- The full biomass/bioenergy life cycle and key GHGs, and
- Carbon and GHG impacts by 2030, with indicative projections to 2050 and over time horizons of 20, 50 and 100 years.

This requirement was subsequently elaborated in the form of a defined LCA goal as “to quantify the global emissions of prominent GHGs (CO_2, CH_4 and N_2O) from all relevant sources resulting from implementation of possible EU policies represented by defined scenarios adopted for supplying and consuming energy, especially bioenergy, in the EU between 2010 and 2050” (Ref. 74). Again, it is apparent that this requirement concerns policy; in this case, the preparation of a sustainable bioenergy policy for the EU for the period after 2020. Hence, as previously, the requirement of this project determined that CLCA should be adopted with specific methodological details consisting of quantification of prominent GHG emissions, and application of spatial system boundary with potentially global extent and temporal system boundaries extending from “now” up to given future years. The application of a global spatial system boundary and future temporal system boundaries meant that, in addition to other considerations, carbon stock changes in forest and dLUC for energy crops were taken into account and GHG emissions associated with the construction of plant and the manufacture of machinery were included in calculations. For this particular project, the impacts of iLUC were avoided by constraining the cultivation of energy crops to previously-unproductive land. The temporal system boundaries reflected projections from a base year of 2010 out to 2050 with time horizons of 20, 50 and 100 years. Again, the overall consequential nature of these policy requirements required the adoption of counterfactuals throughout this LCA study.

2.2.4.3 Systematic Goal and Scope Definition

It is apparent that a systematic procedure is required to LCA goal and scope definition which ensures proper compliance with the official requirements of ISO 14040. Such a procedure should not only assist the definition of the LCA goal and scope, as well as establishing both the stated LCA purpose and the subsequently-appropriate LCA methodology, it should also document relevant outcomes in a fully explicit and transparent manner. This would provide clear evidence of the correct application of

LCA in all its aspects in any given situation. Additionally, it would give confidence in the subsequent use and comparison of results.

Such a systematic procedure has recently been proposed for defining the LCA goal and scope (Ref. 89). This involves checklists for LCA goal and scope definition which contain questions that must be answered for full elaboration of the LCA purpose and complete specification of the LCA methodology. These LCA goal and scope definition checklists are reproduced in Appendix A. The details of these checklists are based on the requirements of ISO 14040 for LCA goal and scope definition. In addition to the questions that are fundamental to LCA goal and scope definition, Appendix A contains examples of answers relevant to bioenergy policy analysis.

3. LCA REVIEW PROCESS

3.1 Review Process Stages

The main purpose of reviewing existing bioenergy LCA studies in WP2 was to determine their robustness and the confidence with which they can be regarded, in the broadest sense, as an evidence base for this project. This was interpreted as assembling and assessing the potential of existing bioenergy LCA studies to provide relevant results and/or basic data which could be used in subsequent LCA calculations that would satisfy the agreed goal and scope of this project. Hence, relevant considerations for the review included the calculation methodologies adopted by such LCA studies and the certainty of the data that they contain. It should be noted that the relevant evidence base consists not only of LCA studies but also LCA calculation tools, LCA databases and other reviews of LCA studies. For convenience, this evidence base is referred collectively as “LCA studies”.

There were three distinct stages to the process of reviewing LCA studies. The first stage consisted of searching for and selecting LCA studies which are relevant to the overall scoping list of agreed bioenergy value chains, thereby determining their inclusion in the Bioenergy LCA Database which has been used for recording their pertinent details. The second stage involved screening the LCA studies to establish which ones were subjected to full reviews which formed the third stage in the review process. This whole process, including all its relevant details, was designed, discussed and finally agreed by the review team and the ETI to ensure that it was systematic, rigorous and, above all, objective.

Provisional scoping lists for the bioenergy value chains addressed in this project were initially set out in Deliverable D1 on “Goal and Scope Definition” (Ref. 95). These scoping lists were replicated in the Interim Bioenergy LCA Workshop Pre-read Report (Ref. 96), considered further and confirmed at the Interim Bioenergy LCA Workshop which was held at the ETI offices in Loughborough on 11 October 2016.

The final scoping lists are reproduced in Appendix B. It will be noted that the bioenergy value chains are broken down into specific parts; namely the supply of biomass feedstocks, in the form of pellets, from forests and energy crops, consisting of short rotation coppice (SRC), short rotation forest (SRF), miscanthus and wheat straw, and the conversion of biomass feedstocks into electricity, heat, hydrogen or ethanol. In the context of review activities, such breakdowns are necessary since some of the LCA studies, which are relevant to this project, may only address one part of the specified bioenergy value chains.

The Bioenergy LCA Database consists of an MS Excel workbook (ETI Bioenergy LCA Database v07.xlxs) for recording the following information on LCA studies selected for this project:

- Reviewer; Records the initials of the person(s) who has(have) entered the details of the LCA study,

- LCA Reference Number; Provides a unique and concise means of referring to the LCA study,

- Title of the LCA Study; Records the full title (not in quotation marks) of the LCA study,

- Author(s) or Editor(s); Records the full list of authors or editors, if relevant, each consisting of initial(s) then family name, for the LCA study,

- Publishing Details; Records all relevant publishing information for the LCA study, equivalent to that required for others to search for the study: for journal papers, the full journal title, volume and/or issue number, date or year, and page numbers; for a conference paper, the full conference title, place and country, and inclusive dates; for a book, the publisher's name, place and country, and year of publication; for a separately published report, the name of the organisation, place and country and date or year of publication,

- Digital Object Identifier; Records the DOI of the LCA study,

- Accessibility; Records the accessibility of the LCA study with all documents that are freely available being specified as open access (OP) and all documents that must be purchased being specified as subscription only (SO),

- Licensing/Intellectual Property Issues; Records the initial indication of any licensing or intellectual property issues as Y (yes) or N (no),

- Hyperlink; Records the hyperlink to the LCA study, if available,

- Countries Covered; Records the list of all the countries covered by the LCA study, providing details of specific country regions where applicable,

- Biomass Sources Covered; Records the list of the original sources of biomass covered in the LCA study, principally using the terminology of the provisional scoping list of biomass sources (see Deliverable D1; Ref. 1),

- Biomass Feedstock Covered; Records the list of the types of biomass feedstock covered in the LCA study for subsequent supply to a biomass conversion technology, principally using the terminology of the provisional scoping list of biomass sources (see Deliverable D1; Ref. 1),

- Biomass Conversion Technologies Covered; Records the list of the biomass conversion technologies covered in the LCA study, principally using the terminology of the provisional scoping list of biomass sources (see Deliverable D1; Ref. 1),

- Other Technologies Covered; Records the list of any other relevant technologies covered in the LCA study,

- Stated LCA Purpose; Records the stated LCA purpose of the LCA study, if available, otherwise recorded as "not stated",

- Defined LCA Goal; Records the defined LCA goal of the LCA study, if available, otherwise recorded as "not defined",

- Defined LCA Scope; Records the defined LCA scope of the LCA study, if available, otherwise recorded as "not defined",

- Screening for Review; Records the recommendation for reviewing the LCA study, using the screening criteria, as Y (yes) or N (no), and

- Reason for Not Reviewing; Records the brief reason for not reviewing the LCA study, in terms of the screening criteria.

- Other Comments; Records any further information relevant for this project.

- Review Completed; Records the completion of a full review summary sheet for the LCA study.

- LCA Study (S), Calculation Tool (T), Database (D) or Review (R); Records the general classification of the type LCA study.

3.2 Selection

The search terms, search engines and sources used to identify possible LCA studies by the review team in this project are summarised in Appendix C. In general, search terms were adopted which were relevant to the agreed scope of this project. This included separate and combinations of terms which not only reflected the relevant bioenergy value chains and their significant parts but also the relevant aspects of assessment techniques and their coverage. The overall search process was intentionally inclusive rather than exclusive to ensure that it was as thorough as possible and avoided missing any important LCA studies. This involved using not only specific search terms, such as “Miscanthus”, but also generic terms, such as “energy crops”. Given the geographical coverage of the scope, it was necessary to search for LCA studies which applied to a number of different countries and regions.

The members of the review team applied their established experience and extensive knowledge of this field of research throughout this process. In some instances, outcomes of other recent review work on relevant bioenergy value chains by team members were adopted as starting points for searches. Additionally, relevant references in identified LCA studies were included in the search process. Well-known sources of publication for both bioenergy and LCA were investigated as a matter of course. Generalised, academic and commercial-oriented search engines were used to find and access copies of LCA studies. This was assisted by recent developments in open access publishing which seems to be being applied retrospectively to some journal publications. Lists of identified LCA studies were also cross-checked amongst members of the review team to avoid prominent omissions as well as actual duplications during finalisation of the Bioenergy LCA database.

The selection criteria for including an LCA study in the Bioenergy LCA Database involved answering positively to the following questions:

- Does the LCA study cover one or more of bioenergy value chains in the provisional scoping lists?

- Does the LCA study cover one or more significant parts of bioenergy value chains in the provisional scoping lists?

It should be noted that these criteria mean that LCA studies that are not specifically concerned with bioenergy technologies might still be identified and recorded in the Bioenergy LCA Database. For example, since CCS is included in the bioenergy value chain scoping list, any LCA studies on this technology, especially those parts which address CO_2 transportation and injection underground are relevant to this project. Hence, there are some LCA studies in the Bioenergy LCA database which relate to the application of CCS to fossil fuels rather than bioenergy. The LCA studies selected in this project for subsequent screening and reviewing are listed, with their LCA Reference Numbers (Ref. Nos.), in the alphabetical order of their titles in Appendix D.

3.3 Screening

The screening criteria determined which LCA studies were subjected to full reviews. Hence, these criteria are based on their relevance to the aims of this project which, ultimately, are specified by the stated LCA purpose and the defined LCA goal and scope. However, it was recognised that screening by the specifically-stated LCA purpose of this project would be unrealistically restrictive since this purpose is unlikely to be shared precisely by many other LCA studies. Additionally, since the defined LCA goal and scope are detailed elaborations of the stated LCA purpose, each and every one of their features were unlikely to be reflected in many other LCA studies. Hence, it was appropriate to focus on certain key aspects of the defined goal and scope which can be regarded as indicating broadly shared relevance, resulting in screening criteria that required positive answers to the following questions:

- Is one of the environmental impacts under consideration in the LCA study contributions to global climate change?

- In relation to contributions to global climate change, are all prominent GHG emissions, particularly consisting of CO_2, CH_4 and N_2O, quantified, either separately or in aggregated form, in the LCA study?

- Are the impacts of co-products/co-services treated collectively, using spatial system boundary expansion (or substitution credits or counterfactuals) within the general context of CLCA, rather than separately, by means of allocation within the general context of ALCA, in the LCA study?

In general, it was likely that all LCA studies which had been selected would already have satisfied the first screening criterion that they address contributions to global climate change. Most LCA studies also passed the second screening criterion of quantifying CO_2, CH_4 and N_2O, either as separate GHG emissions or as aggregated total GHG emissions, derived using global warming potentials (GWPs). However, any LCA study that evaluated only one prominent GHG emissions was excluded from full review since potentially significant contributions are likely to have been overlooked. The third screening criterion, which concerns how co-products/co-services are treated by means of LCA methodology, was the most important since it has a very fundamental effect on the details and outcomes of any LCA study. Whether stated explicitly or incorporated implicitly in LCA studies, this particular aspect of LCA methodology plays a very basic role in determining broad relevance to the defined LCA goal of this particular project. This means that, in general, LCA studies that are intended, explicitly or implicitly, to address policy analysis and development, and do so by applying CLCA, were specifically relevant to this project and, hence, were subjected, accordingly, to full review.

This meant that an alternative version of this screening criterion involved answering the following question:

- Does the LCA study apply CLCA methodology rather than any other form of LCA methodology such as ALCA methodology?

It should be appreciated that terms such as “CLCA” and “ALCA” are not adopted in all LCA studies. Hence, it was often necessary to decipher their actual LCA methodologies or LCA purpose by means of clues, the most significant of which can be how co-products/co-services are treated. It was possible for the experienced reviewers to spot such clues, along with the answers to the other two screening criteria, by relatively quick examination of a selected LCA study.

It should also be noted that, for this project, the stated LCA purpose results in a particular aspect of the defined LCA scope which is that the temporal system boundary extends from deployment “to-day” to the end of bioenergy value chain life cycle. This means that, strictly speaking, it should include all plant construction, machinery manufacture and their maintenance. However, it was recognised that, for a variety of reasons, many LCA studies exclude GHG emissions associated with plant construction, machinery manufacture and their maintenance. Hence, such LCA studies which pass the three screening criteria were still subjected to full reviews even though they did not meet all the requirements for the policy analysis of bioenergy value chains that are intended for implementation from now or sometime in the future.

3.4 Reviewing

The final stage in the review process consisted of the full review of those selected and screened LCA studies using the LCA Review Summary Sheet, the template for which is presented in Appendix E. This records the basic details of an LCA study; documents its stated LCA purpose, and defines the LCA goal and LCA scope, or indicates if these aspects are missing; summarises the coverage and key assumptions of the technologies addressed in the LCA study; reports the key LCA methodological assumptions; and provides an overview of the transparency of the LCA study. This last aspect, which can be categorised as “low/moderate/high transparency”, is very important as it concerned access to the calculations performed in the LCA study, their related details and their sources of data.

Given the work involved in selecting and reviewing a possibly large number of LCA studies, this activity was undertaken by a team of experienced reviewers. Collectively within NEA, FR and the NNFCC, 10 people were engaged in this work. It was obviously necessary to ensure consistency and quality control across the output of this team so that reliable and meaningful conclusions could formed about the LCA study reviews. This was achieved by, first, the review team adopting and implementing the instructions set out for full reviews in the LCA Review Summary Sheet, reproduced in Appendix E; and second, by one member of the review team checking and, if necessary, editing the full reviews that are presented in Appendix F. Throughout this process, queries about the requirements of full review instructions, exchanges of views, subsequent explanations and eventual decisions were shared amongst the team either via e-mail, telephone or meetings. In addition to examining full reviews for completeness of coverage and consistency in the use of terms, the final editing procedure also involved seeking any necessary further clarifications over important point with individual reviewers.

As part of this final stage of the review process, both “headline results”, usually in the form of estimated total GHG emissions, were identified and added to the full reviews, and “critical data”, which are known or assumed to have a major influence on the outcomes of an LCA study, were noted for subsequent use. The comparison of headline results is included in the following review analysis (see Section 4). Where relevant, critical data have been incorporated, along with data from other sources, into the Bioenergy LCA Data Compendium (see Section 5). The identification of such critical data depended on the transparency of the LCA study and relied, to a degree, on the experienced judgment of the reviewer.

It was originally proposed that a "traffic light" system would be used to qualify headline results and critical data so that green, amber and red would represent high, moderate and low confidence, respectively. However, it was not possible to apply this system for two important reasons. The first reason concerns the basic practicalities of qualifying confidence in headline results and critical data from LCA studies with varying degrees of transparency. This will become clear when the issue of transparency and limitations of the relevant headline results are discussed in the LCA review analysis (see Section 4). The second reason concerns usefulness of LCA studies as a means of providing critical data. This will become apparent when the necessary purpose of the Bioenergy LCA Data Compendium is explained (see Section 5).

4. LCA REVIEW ANALYSIS

4.1 Basic Statistics

The basic selection and review statistics are summarised in Table 1. In total, 161 LCA studies, from the period between 1992 and 2016, were initially selected for screening and possible reviewing. The clear majority (90%) of these LCA studies were reports and papers, with the remainder consisting of a small number (7%) of reviews of LCA studies and very few calculation tools and databases. The initially selected LCA studies were intended to have passed the selection criteria. In particular, these LCA studies were expected to be within the scope of this project, especially regarding the chosen bioenergy value chains. However, it was not until further, more detailed examination that a few LCA studies were found to be "out of scope" because their biomass feedstocks and/or biomass conversion technologies were not relevant to this project. Hence, by excluding these LCA studies, the initial selection of 161 LCA studies was reduced to a confirmed selection of 147 LCA studies. Following application of the screening criteria, 49 LCA studies were subjected to full reviews.

Table 1 Basic Selection and Review Statistics

Specification	Total Number	Number of LCA Studies	Number of Calculation Tools	Number of Databases	Number of Reviews
Selected: initial	161	145	4	2	11
Selected: confirmed	147	130	4	2	11
Reviewed:	49	44	4	1	0

It will be noted from Table 1 that none of the reviews of LCA studies were passed for full reviews here. This is because these reviews of LCA studies could have been undertaken for entirely different purposes to this project and/or different review criteria might have been applied by the original investigators. Instead these reviews of LCA studies played another important role in this project, variously, by identifying relevant LCA studies and/or by providing helpful summaries of relevant LCA studies. Additionally, it is instructive to reveal how many reviews of LCA studies have been conducted.

As mentioned previously, the selected and screened LCA studies in this project include those that address CCS applied to bioenergy value chains or to other energy value chains, principally those based on fossil fuels. In total, there were 14 of the reviewed LCA studies concerned with CCS, of which only 3 reviewed LCA studies dealt with the application of CCS to biomass conversion technologies. Hence, 38 reviewed LCA studies were specifically related to whole bioenergy value chains or their significant parts which are relevant to this project.

Before examining certain broad but significant features of the reviewed LCA studies, it is necessary to consider some of the general reasons why 98 LCA studies did not pass the screening criteria and, hence, were not reviewed. These reasons are summarised briefly in Appendix D. This shows that the main reason for not reviewing LCA studies was that they adopted ALCA methodology, either wholly or partly, so that they are inconsistent with the LCA goal and scope of this project. This affected 36 selected LCA studies or 37% of those not reviewed. The next most common reason was that LCA studies either did not address climate impacts in terms of estimating GHG emissions or did not evaluate all the prominent GHG emissions (CO_2, CH_4 and N_2O). This reason for not passing the screening criteria applied to 20 selected LCA studies or 20% of those not reviewed. Incidentally, in the majority of instances (9 LCA studies or 9%), these particular rejected LCA studies only investigated carbon stock changes in forests and did not account for GHG emissions from other sources and activities.

The next most numerous reason for not passing the screening criteria was that the selected sources were not, in fact or strictly speaking, LCA studies, instead focusing mainly on modelling or methodologies (14 LCA studies or 14%). Other reasons for not reviewing selected LCA studies consisted, specifically, of the fact that they were LCA studies of CCS which did not incorporate types of storage which were relevant to the UK (12 LCA studies or 12%), or that they were reviews of other LCA studies (11 LCA studies or 11%), which were not directly suitable for current purposes, as discussed previously. The various remaining reasons for not being reviewed included selected LCA studies which were prominent in the field but were actually out of scope for this project (for example, LCA Ref. No. 122).

One of the most important features of the reviewed LCA studies was their transparency. As specified in the template for the full review summary sheet, transparency relates to the calculations performed in the LCA studies and was categorised as:

- "low transparency" indicates very little or no access to all the calculations, or no access to those calculations that make major contributions to total GHG emissions,
- "moderate transparency" indicates some access to those calculations that make major contributions to total GHG emissions, and
- "high transparency" indicates access to all calculations or access to all those calculations that make major contributions to total GHG emissions.

The emphasis on calculations is highly significant for LCA studies as their general purpose is to quantify environmental and/or resource impacts. Hence, access to all or the most influential calculations, along with the assumptions on which they are based and the sources of data which they use, has a major role in determining the level of confidence that can be placed in their outcomes, in terms of their results, findings and recommendations. All the reviewed LCA studies were qualified with respect to their adjudged transparency and subsequent statistics are summarised in Table 2.

Table 2 Transparency Statistics for Reviewed LCA Studies

	Number of Reviewed LCA Studies		
	Low Transparency	Moderate Transparency	High Transparency
Totals as Published	23	16	10
Totals as Published and with Access to Supporting Information	17	17	15

It will be seen that this qualification of transparency depends on whether only the published LCA study was examined or whether actual or potential access to supporting information, usually in the form of MS Excel workbooks, could be taken into account. This distinction is significant as a number of reviewed LCA studies either were based on the application of open-access or, in effect, proprietary calculation tools (at least 17 reviewed LCA studies or 35%) or were, in fact, calculation tools (4 reviewed LCA studies or 8% of the 49 reviewed LCA studies). As would be expected, accounting for access to details in calculation tools increased the number of reviewed LCA studies regarded as having high transparency.

Overall, when access to such supporting information is taken into consideration, there is an almost even split between the levels of transparency observed in the reviewed LCA studies with 35% being adjudged low transparency, 35% moderate transparency and 30% high transparency. Given that confidence is partly correlated to transparency, it should be noted that only 15 reviewed LCA studies were qualified as having high transparency.

As a consequence of high transparency and subsequent access to calculation details, it was possible to determine other important features of the reviewed LCA studies. In particular, it was found that 5 of the reviewed LCA studies (10%) actually adopt ALCA methodology, at least partially (LCA Ref. Nos. 9, 11, 17, 62 and 72). The reviews of these LCA studies were still relevant to this project because ALCA methodology had been applied, in general, been applied to only certain bioenergy value chains whilst CLCA methodology had been used for other relevant bioenergy value chains. For example, for various reasons, no counterfactuals had been considered for agricultural and forest residues (LCA Ref. No. 9); or allocation by price had been applied to forest residues (LCA Ref. Nos. 11 and 17); or allocation by energy or exergy had been adopted for the outputs of CHP plants (LCA Ref. Nos. 9, 11, 17, 62 and 72).

Similarly, by examining necessary details, it was possible to determine that 24 of the reviewed LCA studies (49%) definitely take into account GHG emissions associated with plant construction and machinery manufacture and may possibly incorporate GHG emissions associated with plant and machinery maintenance (LCA Ref. Nos. 11, 12, 17, 21, 22, 23, 30, 32, 34, 58, 62, 67, 71, 75, 90, 91, 94, 97, 99, 104, 110, 112, 126 and 137). This is important because such LCA studies should exactly fit the defined LCA goal and scope of this project.

4.2 Coverage of Bioenergy Value Chains

Apart from the possible coincidence of LCA goal and scope, the specific coverage of bioenergy value chains, or their significant parts (mainly biomass feedstock supply; biomass feedstock conversion; and CO_2 transportation and storage for CCS), affects the relevance of reviewed LCA studies to this particular project. This coverage is summarised for wood pellets supply from forests in Table 3; pellets supply from energy crops in Table 4; and biomass feedstock conversion technologies in Table 5.

The summary in Table 3 shows that there is apparently complete coverage by the reviewed LCA studies of the supply of wood pellets from forests chosen for this project. However, the summary in Table 4 indicates that there are some gaps in the coverage by the reviewed LCA studies of the supply of pellets from energy crops for this project; specifically, wood pellet production from poplar and willow SRC in France and the Netherland; and wheat straw pellet production in the UK (although wheat straw bale production was covered reviewed LCA studies). It should also be noted that a number of reviewed LCA studies covered wood chip rather than wood pellet production from SRC. The summary in Table 5 also illustrates almost complete coverage by reviewed LCA studies of the specified biomass feedstock conversion technologies for this project, with the exception being hydrogen and district heat production from the gasification of biomass feedstocks.

Table 3 Coverage of Wood Pellet Supply from Forests by Reviewed LCA Studies

Country/ Countries	Region(s)	Forest Type	Reviewed LCA Study Ref. No.
Canada	Western	Conventional Forest (conifer)	10, 21, 113, and 126
Scandinavia and Baltic States	-	Conventional Forest (conifer)	21, 72, 82, 128, and 147
United Kingdom	-	Conventional Forest (broadleaf)	10, 21, and 23
		Conventional Forest (conifer)	10, 21, 23, and 137
United States of America	Southern/ South Eastern	Conventional Forest (broadleaf)	10, 21, and 113
		Conventional Forest (pine)	10, 21, and 113
		Plantation Forest (pine)	10
	North Western	Conventional Forest (conifer)	10, and 21

Table 4 Coverage of Pellet Supply from Energy Crops by Reviewed LCA Studies

Country	Sources of Biomass Feedstock	Reviewed LCA Study Ref. No.
Belgium	Short Rotation Coppice (poplar and willow)	50
France	Short Rotation Coppice (poplar and willow)	
Netherlands	Short Rotation Coppice (poplar and willow)	
Poland	Short Rotation Coppice (poplar and willow)	102
United Kingdom	Miscanthus	10, 11, 22, 71, and 152
	Short Rotation Coppice (poplar and willow)	10, 11, 22, 71, 151, and 152
	Short Rotation Forest (broadleaf)	10
	Short Rotation Forest (conifer)	10
	Wheat Straw (agricultural residue)	
United States of America, Southern and South Eastern Regions	Short Rotation Forest (broadleaf)	10, and 113
	Short Rotation Forest (conifer)	10, and 113

Table 5 Coverage of Biomass Feedstock Conversion Technologies by Reviewed LCA Studies

Biomass Feedstock Conversion Technologies	Reviewed LCA Study Ref. No.
Small-scale Heat Only Production (boilers)	10,11, 17, 21, 22, 23, 41, 50, 67, 94, 137, and 159
Medium-scale Heat Only Production (boilers)	10,11, 21, 22, 50, 67, 126, 147, and 159
Medium-scale Combined Heat and Power Generation	10,21, 22, 23, 72, 137, 148, and 159
Large-scale Combined Heat and Power Generation	10,17, 21, 22, 23, 72, and 159
Electricity Only Generation (steam cycle)	10, 11, 17, 21, 22, 23, 26, 50, 64, 82, 113, 128, 137, 147, 148, and 159
Electricity Generation (steam cycle) and District Heat Production	105, and 147
Hydrogen Production from Gasification	75
Hydrogen and District Heat Production from Gasification	
Electricity Generation (combined cycle gas turbine) from Gasification	12*, 17, 89, 148, and 159
Ethanol from Lignocellulosic Processing	10*, 17, 21, 64, 67, 86, 111, 151, 159

Note * also including CCS

One particular aspect for the coverage of biomass conversion technologies summarised in Table 5 is that some of the reviewed LCA studies do not address the biomass feedstocks specifically relevant to this project. Hence, in order to consider this further, the coverage of reviewed LCA studies represented complete bioenergy value chains chosen for this project is summarised in Table 6. This shows that such coverage is considerably more restricted than implied by Tables 3 to 5. Whilst the majority of chosen bioenergy value chains are covered, there are notable gaps. These consist of steam cycle electricity generation with district heating; combined cycle electricity generation using gasification; and hydrogen production using gasification without and with district heating.

Theoretically, it can be possible to assemble evaluations for whole bioenergy value chains by combining the information in reviewed LCA studies which, separately, address pellet supply and biomass conversion technologies. However, this approach depends entirely on the compatibility and, crucially, the full transparency of the individual reviewed LCA studies. Hence, the potential for combining LCA studies could only be explored when their compatibility and transparency had been established, and this very exacting process was not pursued here. Instead, the transparency of those 8 reviewed LCA studies which do cover the chosen bioenergy value chains was investigated and the findings are presented in Table 7. This demonstrates that all LCA studies apart from one had high transparency, and the one exception was adjudged to have moderate transparency.

Consequently, these particular reviewed LCA studies might seem to provide a suitable evidence base for the LCA of the bioenergy value chains within the scope of this study. Unfortunately, this potentially positive conclusion needs to be set in proper context. Considering the necessary coverage of 8 types of wood pellet supply from forests and 11 types of pellet supply from energy crops, combined with 10 types of biomass conversion technologies (excluding variants with CCS) results in a total of 190 different bioenergy value chains. Hence, it will be appreciated that the coverage of 55 bioenergy value chains, as indicated by Table 6, represents only part of the necessary technological scope of this project.

Table 6 Coverage of Whole Bioenergy Value Chains Relevant to the Scope of this Project by Reviewed LCA Studies

Biomass Feedstock Conversion	Reviewed LCA Study Ref. No.	Source of Biomass Feedstock
Small-scale Heat Only Production (boilers)	10	Western Canada conventional forest (conifer)
	10, 23	UK conventional forest (broadleaf)
	10, 23, 137	UK conventional forest (conifer)
	10	Southern USA conventional forest (broadleaf)
	10	Southern USA conventional forest (conifer)
	10	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	10,11, 22	UK SRC (poplar and willow)
	10	UK Miscanthus
Medium-scale Heat Only Production (boilers)	10	Western Canada conventional forest (conifer)
	10	UK conventional forest (broadleaf)
	10	UK conventional forest (conifer)
	10	Southern USA conventional forest (broadleaf)
	10	Southern USA conventional forest (conifer)
	10	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	10, 11	UK SRC (poplar and willow)
	10, 22	UK Miscanthus
Medium-scale Combined Heat and Power Generation	10	Western Canada conventional forest (conifer)
	10	UK conventional forest (broadleaf)
	10	UK conventional forest (conifer)
	10	Southern USA conventional forest (broadleaf)
	10	Southern USA conventional forest (conifer)
	10	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	10, 11	UK SRC (poplar and willow)
	10, 22	UK Miscanthus
Large-scale Combined Heat and Power Generation	10	Western Canada conventional forest (conifer)
	10	UK conventional forest (broadleaf)
	10	UK conventional forest (conifer)
	10	Southern USA conventional forest (broadleaf)
	10	Southern USA conventional forest (conifer)
	10	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	10	UK SRC (poplar and willow)
	10, 22	UK Miscanthus

Table 6 Coverage of Whole Bioenergy Value Chains Relevant to the Scope of this Project by Reviewed LCA Studies (continued)

Biomass Feedstock Conversion	Reviewed LCA Study Ref. No.	Source of Biomass Feedstock
Electricity Only Generation (steam cycle)	10, 113	Western Canada conventional forest (conifer)
	10, 23	UK conventional forest (broadleaf)
	10, 23, 137	UK conventional forest (conifer)
	10, 113	Southern USA conventional forest (broadleaf)
	10, 113	Southern USA conventional forest (conifer)
	10, 113	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	10, 11, 22	UK Miscanthus
	10, 22	UK SRC (poplar and willow)
Electricity Generation (steam cycle) and District Heat Production		Any within the scope of this project
Hydrogen Production from Gasification		Any within the scope of this project
Hydrogen and District Heat Production from Gasification		Any within the scope of this project
Electricity Generation (combined cycle gas turbine) from Gasification		Any within the scope of this project
Ethanol from Lignocellulosic Processing	10	Western Canada conventional forest (conifer)
	10	UK conventional forest (broadleaf)
	10	UK conventional forest (conifer)
	10	Southern USA conventional forest (broadleaf)
	10	Southern USA conventional forest (conifer)
	10	Southern USA plantation forest (pine)
	10	Northwestern USA conventional forest (conifer)
	151	Poland SRC (willow)
	10, 151	UK SRC (willow)
	17	UK Wheat Straw

It is also necessary to comment on the coverage of reviewed LCA studies on CCS for the CO_2 transportation and storage components required for the CCS variants of the bioenergy value chains within the scope of this project. In total, 14 reviewed LCA studies addressed CCS (LCA Ref. Nos. 10, 12, 30, 32, 55, 62, 89, 90, 91, 97, 99, 104 and 112). Of these, 3 reviewed LCA studies included CCS in the evaluation of bioenergy value chains (LCA Ref. Nos. 10, 104 and 112). The most of these particular reviewed LCA studies demonstrated low transparency (7 LCA studies or 50%), some showed moderate transparency (5 LCA studies or 36%) and only a few were adjudged to exhibit high transparency (2 LCA studies or 14%). One particular reviewed LCA study contained very detailed basic data on the construction and operation of a CO_2 transportation system, involving supercritical CO_2 transport by overland and subsea insulated pipelines, and a storage systems, using injection of CO_2 into depleted natural gas and oil reservoirs (LCA Ref. No. 104).

Table 7 Transparency of Reviewed LCA Studies Representing Whole Bioenergy Value Chain Relevant to the Scope of this Project

Reviewed LCA Study Ref. No.	Transparency
10	High (with open access to calculation tool; BEAC)
11	High (with open access to workbooks via the calculation tool; $BEAT_2$)
17	High (all data documented in study)
22	High (provided access to supporting workbooks)
23	High (provided access to supporting model and workbooks)
113	High (when combined with the calculation tool; BEAC)
137	High (provided access to supporting model and workbooks)
151	Moderate (extensive but incomplete data in published study)

4.3 Comparison of Results

As part of this exploration of the evidence base for the LCA of bioenergy value chains, it was instructive to examine the availability of headline results in the reviewed LCA studies. There have been many attempts to perform meta-analyses of LCA studies to compare results, in the form of total GHG emissions, discern possible patterns or trends in results and even to produce ranges of results that are supposed to be representative of these chains, perhaps suggesting their variability or, indeed, uncertainty. In order to form any meaningful conclusions, such work needs to ensure that the LCA studies that are used share basic commonality of methodology, expressly in terms of the same LCA goal and scope. Since key aspects of the defined LCA goal and LCA scope have been applied in the selection and screening criteria of this review, it should provide a sound basis for any such presentation and possible comparison of headline results.

However, before these findings from the analysis of reviewed LCA studies are provided, it is necessary to explain the practical constraints in accessing and considering headline results on a common basis. It will be appreciated that any LCA study will be conducted for its own stated or unstated purpose and that this is likely to influence what results are communicated and how they are presented, especially in terms of the functional unit. Sometime relevant results are available in suitable units or in units that can be easily converted to those under consideration. However, it is often possible that a functional unit will have been chosen for entirely justifiable reasons which would require significant extra information, which might not be available in the original LCA study, or considerable analytical effort based on potentially questionable assumptions. For example, a number of reviewed LCA studies were based on a functional unit which was 1 ha of land or forest to able comparisons between different uses for its biomass. In such instances, it was extremely difficult, if not virtually impossible, to convert headline results into, say, total GHG emissions per unit output of a given bioenergy value chain.

For these and other practical reasons, the number of potentially comparable headline results that could be extracted from the reviewed LCA studies was somewhat limited. This is demonstrated with the ranges of headline results, given in terms of total GHG emissions per MWh of output (biomass energy, heat, electricity, hydrogen or ethanol), as specified in the agreed LCA scope for this project, for wood pellets from forests in Table 8; pellets from energy crops in Table 9; and whole bioenergy value chains of relevance to this project in Table 10. As can be seen from Table 8, there are extremely few relevant headline results for wood pellets from forests and this is largely because most reviewed LCA studies focus on timber products or wood chips rather than wood pellets. The outcome is even worse for pellets from energy crops, as demonstrated by the complete lack of relevant headline results in Table 9, mainly due to reviewed LCA studies addressing other forms of biomass feedstocks, such as wood and Miscanthus chips, and Miscanthus and wheat straw bales, rather than pellets.

Table 8 Range of Headline Results from Reviewed LCA Studies for Wood Pellets from Forests Relevant to the Scope this Project

Country/ Countries	Region(s)	Forest Type	Range of Headline Results (kg CO_2eq/MWh)
Canada	Western	Conventional Forest (conifer)	N/A
Scandinavia and Baltic States	-	Conventional Forest (conifer)	+7 to +90
United Kingdom	-	Conventional Forest (broadleaf)	N/A
		Conventional Forest (conifer)	N/A
United States of America	Southern/ South Eastern	Conventional Forest (broadleaf)	N/A
		Conventional Forest (pine)	N/A
		Plantation Forest (pine)	N/A
	North Western	Conventional Forest (conifer)	N/A

Table 9 Range of Headline Results from Reviewed LCA Studies for Pellets from Energy Crops Relevant to the Scope of this Project

Country	Sources of Biomass Feedstock	Range of Headline Results (kg CO_2eq/MWh)
Belgium	Short Rotation Coppice (poplar and willow)	N/A
France	Short Rotation Coppice (poplar and willow)	N/A
Netherlands	Short Rotation Coppice (poplar and willow)	N/A
Poland	Short Rotation Coppice (poplar and willow)	N/A
United Kingdom	Miscanthus	N/A
	Short Rotation Coppice (poplar and willow)	N/A
	Short Rotation Forest (broadleaf)	N/A
	Short Rotation Forest (conifer)	N/A
	Wheat Straw (agricultural residue)	N/A
United States of America, Southern and South Eastern Regions	Short Rotation Forest (broadleaf)	N/A
	Short Rotation Forest (conifer)	N/A

The summary provided by Table 10 appears to be more positive in relation to the coverage of whole bioenergy value chains relevant to the scope of this project, as a number of headline results are shown. However, the ranges of some of these headline results are extremely large, extending from large negative to large positive total GHG emissions, as in the case of steam cycle electricity generation using wood pellets from forests. This is due to the range of results being dominated by one particular reviewed LCA study (LCA Ref. No. 113) which considered 29 different scenarios for wood pellet supplies (consisting of different sources of wood pellets, different forest types and management practice and different land use, residue, sawmill co-product and timber product counterfactuals) and 2 different time horizons (40 and 100 years), thereby generating a very diverse set of headline results. It should also be noted that, due to the extremely large numbers and ranges of results that can be generated using LCA Ref. No. 10, these were not incorporated into Table 10.

Table 10 Range of Headline Results from Reviewed LCA Studies for Whole Bioenergy Value Chains Relevant to the Scope of this Project

Biomass Feedstock Conversion	Source of Biomass Feedstock	Range of Headline Results (kg CO_2eq/MWh)
Small-scale Heat Only Production (boilers)	UK conventional forest (broadleaf)	N/A
	UK conventional forest (conifer)	N/A
	UK SRC (poplar and willow)	+40 to +151
Medium-scale Heat Only Production (boilers)	UK SRC (poplar and willow)	+32 to +144
	UK Miscanthus	+83 to +169
Medium-scale Combined Heat and Power Generation	UK conventional forest (conifer)	N/A
Large-scale Combined Heat and Power Generation	UK conventional forest (broadleaf)	N/A
	UK conventional forest (conifer)	N/A
	UK Miscanthus	+97 to +202
Electricity Only Generation (steam cycle)	Western Canada conventional forest (conifer)	-17 to +3988
	UK conventional forest (broadleaf)	N/A
	UK conventional forest (conifer)	N/A
	Southern USA conventional forest (broadleaf and conifer)	-2504 to +5174
	Southern USA plantation forest (pine)	-2093 to +929
	Northwestern USA conventional forest (conifer)	N/A
	UK Miscanthus	+209 to +389
	UK SRC (poplar and willow)	+72 to +461
	UK SRF (broadleaf)	N/A
	UK SRF (conifer)	N/A
Electricity Generation (steam cycle) and District Heat Production	Any within the scope of this project	N/A
Hydrogen Production from Gasification	Any within the scope of this project	N/A
Hydrogen and District Heat Production from Gasification	Any within the scope of this project	N/A
Electricity Generation (combined cycle gas turbine) from Gasification	Any within the scope of this project	N/A
Ethanol from Lignocellulosic Processing	Poland SRC (willow)	+46
	UK SRC (willow)	+37
	UK Wheat Straw	+40 to +54

4.4 Confidence and Critical Data

It will be apparent from even a cursory inspection of any collection of LCA studies that they can display considerable differences their results. Without careful examination and detailed understanding of such LCA studies, such disparities can present an impression of confusion and undermine confidence in results and conclusions. There are many possible causes of differences between LCA studies. The most fundamental causes are differences in the purpose, goal and scope, and the subsequent calculation methodology adopted by LCA studies. In other words, LCA studies can be established, explicitly or implicitly, to address different "questions" and, hence, it is hardly surprising that they produce different "answers".

This is the reason why so much attention has been directed towards determining the purpose, goal, scope and methodology of the LCA studies in this review. This has been achieved by applying a rigorous, systematic and, above all, objective approach to selecting and screening LCA studies in an attempt to ensure that, as far as possible, they coincide with the goal of this project and mirror, wholly or partly, its agreed scope. In particular, this has led to a focus on LCA studies which adopt CLCA methodology in evaluation of the chosen bioenergy value chains. As demonstrated, this has reduced those LCA studies that are relevant to this project from an initial selection of 161 to a screened total of 49, of which only 8 cover some of the whole rather than partial bioenergy value chains that are covered by its technical scope.

The intentional elimination of fundamental differences in purpose, goal, scope and, crucially, methodology does not mean that there are no remaining disparities between LCA studies. This is because there are other potential causes of differences in results which can be classified, broadly, as the effects of actual variability and modelling uncertainty. Such variability arises from differences in the values of parameters that are encountered as a matter of course in the implementation of bioenergy value chains, whereas such uncertainty is based on limits to actual knowledge or modelling capability. These effects are most pronounced in relation to critical data which can be regarded as the data that makes the greater contributions to final results in LCA studies.

Hence, it is contended that overall confidence in any LCA study is a combination of, first, whether it is relevant to the declared purpose, goal, scope and subsequent methodology; second, whether it displays high transparency; and, third, whether the impacts on critical data of variability and uncertainty are appropriately acknowledged. This means that variability needs to be quantified so that its influence on final results can be accommodated. It also means that uncertainty needs to be suitably qualified, especially in terms of knowing whether all potential sources of GHG emissions have been taken into account and whether their subsequent modelling is reliable. These aspects of confidence and critical data can be illustrated by referring to the screened LCA studies which cover whole bioenergy value chains of relevance to the scope of this project and are adjudged to have the high transparency required for such investigation.

The LCA studies which meet these very particular requirements for the concerns over confidence and critical data are LCA Ref. Nos. 10, 11, 17, 22, 23, 113 and 137. At this point, attention needs to be drawn to the fact that NEA and/or FR have been involved, directly or indirectly, in all of these LCA studies. Staff of NEA, formerly with the Resources Research Unit of Sheffield Hallam University, collaborated with FR on LCA Ref. No. 17 which concerns "Carbon and Energy Balances for a Range of Biofuels Options". This contributed to the development of LCA Ref. 11 which is $BEAT_2$ by the then-AEA Energy and Environment and NEA. $BEAT_2$ was used by NEA in LCA Ref. No. 137 in the "Scottish Government Biomass Incentives Review: best use of wood fibre" and, in collaboration with ADAS UK Ltd, in LCA Ref. No. 22 for evaluating "Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: energy crops". FR and NEA worked together in preparing LCA Ref. No. 23 which addressed "Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: forests". Finally, outputs from the CSORT forest carbon dynamics model of FR and data from $BEAT_2$ were incorporated into LCA Ref. No. 10 which is BEAC model that was subsequently used to generate results for LCA Ref. No. 113 which determines "Life Cycle Impacts of Biomass Electricity in 2020: scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK".

It must be emphasised that, in this instance, focus on these particular LCA studies results entirely from the combination of their relevant coverage of whole bioenergy value chains *and* their transparency which enables them to be discussed when addressing specific issues of confidence and critical data. Aspects of critical data, variability and uncertainty in these LCA studies is best explored by considering them in chronological order.

LCA Ref. No.17, on "Carbon and Energy Balances for a Range of Biofuels Options", published in 2003, only covers one whole bioenergy value chain appropriately with CLCA methodology, as consistent with the scope of this project, and that is the production of ethanol from wheat straw. This bioenergy value chain does not match the scope of this project exactly as it was based on the provision of straw bales rather than pellets for lignocellulosic processing. However, the LCA study does quantify variability throughout all calculations for this and all other bioenergy value chains. This demonstrated that the impact on final results is relatively limited as, for example, the "error bar" for total GHG emissions associated with ethanol production from wheat straw is only ± 15%. The largest contribution to total GHG emissions for this bioenergy value chain was due to the manufacture of extra N fertiliser that it was assumed would have to be applied to compensate for the removal of wheat straw which, counterfactually, would have been incorporated into the soil. It is acknowledged that, at the time, there was only very little information on which to base, in effect, modelling assumptions about straw removal as opposed to incorporation.

Based on the application of CLCA methodology within the technological scope of this project, LCA Ref. No. 11, which is $BEAT_2$ released in 2008, addresses 3 relevant bioenergy value chains; small- and medium-scale heat only production, using boilers, with wood pellets provided from UK poplar and willow SRC; and steam cycle electricity only generation with UK Miscanthus pellets. The effects of variability are incorporated into calculations for all bioenergy value chains by taking account of variations in input parameters, such as fuel consumption, fertiliser application rates, etc., and relevant GHG emissions factors. However, this was only accommodated where appropriate data are available and, as such data were limited, not all potential variability was quantified. With the available data, the derived error bars are quite limited to between ±8% and ±12% for the relevant bioenergy value chains. The largest contributions to the total GHG emissions associated with these particular bioenergy value chains are from biomass feedstock drying. However, the effects of dLUC were not included although the impacts of iLUC were avoided by assuming that these biomass feedstocks would be produced on mown set-aside land in the UK. This "reference system" or counterfactual was taken into account in the calculations.

$BEAT_2$ workbooks were modified for specific application to LCA Ref. No. 22, for assessing "Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: energy crops" in 2011. This covers 5 relevant bioenergy value chains; small-scale heat only production, using boilers, with wood pellets provided from UK poplar and willow SRC; medium-scale heat production, using boilers, with UK Miscanthus pellets; large-scale CHP generation with UK Miscanthus pellets; and steam cycle electricity only generation with UK SRC wood pellets and UK Miscanthus pellets. The main impacts of variability are due to assumed differences in biomass feedstock yield; distance of road transport; drying method; and conversion plant thermal efficiency, load factor and scale. Taking all these impacts into account resulted in larger error bars for estimated total GHG emissions of between ±24% and ±73%. The larger contributions to total GHG emissions are, in descending order of magnitude, biomass feedstock drying; harvesting and chipping; road transport; and, depending on specific circumstances, plant construction. Whilst the impacts of dLUC and iLUC are not taken into account, the GHG emissions of alternative land use were modelled by ADAS UK Ltd. This generated large variations in results which depended on the details of assumed land use displacement.

LCA Ref. No. 137, in the 2012 "Scottish Government Biomass Incentives Review: best use of wood fibre", also used suitably modified $BEAT_2$ workbooks to investigate the use of wood from forests in Scotland for bioenergy. Within the technological scope of this project with its focus on wood pellets, 2 relevant bioenergy value chains were covered, consisting of small-scale heat only production, with boilers, and steam cycle electricity only generation both with wood pellets from UK conventional conifer forests. It should be noted that medium-scale CHP generation was also addressed but this was based on the use of wood chips rather than pellets. This LCA study did not take into account of variability and results were published in the form of annualised GHG emissions per unit area of forest rather than per unit energy output. However, net carbon stock changes in forest were simulated by FR with the CSORT forest carbon dynamics model and the counterfactual effects of the alternative production and disposal of wood products, were incorporated. It is apparent that the wood product carbon stock balance, simulated by the CSORT model, can dominate results, with GHG emissions associated with bioenergy and wood product processing making similar or lower contributions to total GHG emissions depending on circumstances governed by assumed production profiles of bioenergy and wood products.

A similar approach was adopted in LCA Ref. No. 23 on "Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: forests" which was released in revised form in 2014. This LCA study addressed 4 relevant bioenergy value chains, consisting of small-scale heat only production, with boilers, and steam cycle electricity only generation all using wood pellets from UK broadleaf and conifer forests. As with the previous LCA study, it should be noted that medium-scale CHP generation was also addressed but this was based on the use of wood chips. The same aspects of the previous LCA study also apply in terms of excluding variability, publishing final results per unit forest area rather than per unit energy output, using the CSORT model for simulating carbon stock balances, and incorporating counterfactual effects of wood products. As before, the importance of simulated wood product carbon stock balances for final results is apparent.

LCA Ref. No. 10, which is BEAC model, was released in 2015. BEAC addresses 53 bioenergy value chains that are relevant to the technological scope of this project, as catalogued previously in Table 6. Variability is incorporated into BEAC and the values chosen are summarised. However, no information is provided on the reasons for, or sources of, these assumed values of variability. The CSORT model of FR is used for simulating forest carbon dynamics. Relative contributions to total GHG emissions depend on the bioenergy value chain and its basic assumptions, including counterfactuals, available from amongst an extremely large number of options. However, prominent contributions include soil and biomass carbon stock changes, other GHG emissions from land use, and the chosen counterfactuals.

The very considerable capability of the BEAC model is due to its amalgamation of data from numerous sources and outputs from modelling. This enables an extremely large number of possible scenarios for bioenergy value chains to be considered which can generate large ranges in subsequent results. This was demonstrated by the headline results that can be obtained from LCA Ref. No. 113 for investigating "Life Cycle Impacts of Biomass Electricity in 2020: scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity

generation in the UK". Although such results are, to an extent, qualified by reference to biomass feedstock availability, it is apparent that no guidance is provided on which scenarios should be chosen in terms of their likely relevance and relative importance. Unfortunately, without such guidance or supporting commentary, the profusion of possible results is potentially confusing and may not always foster confidence.
Based on this particular exploration of variability and uncertainty, it is apparent that there are limits to any findings on confidence and critical data that can be derived from reviewed LCA studies for the evidence base on specified bioenergy value chains for this project. In summary, this is due to the combination of:

- the part coverage of the whole bioenergy value chains (55 out of a potential of 190 chains without CCS) within the scope of this project,
- the relatively few headline results (covering 10 out a potential of 190 chains without CCS) available for those whole bioenergy value chains that are covered and published in the relevant LCA studies, and
- the extremely large ranges of the headline results for some of the whole bioenergy value chains.

Despite these limitations, especially in relation to quantitative contributions to the LCA evidence base, the reviewed LCA studies can offer some qualitative insights, particularly in terms of the role of critical data. These insights reinforce the key points raised earlier in setting the context for the LCA of bioenergy value chains. In particular, critical data, interpreted as information which make the largest contributions to final results, clearly relate to the following issues:

- carbon stock changes in forests which supply wood pellets for bioenergy,
- management practices within forests which supply wood pellets for bioenergy,
- chosen counterfactuals for wood products, residues and co-products used alternatively to supply wood pellets for bioenergy, and
- dLUC and iLUC associated with the production of energy crops which supply pellets for bioenergy.

Other critical data, which, in some circumstances, might have relatively less influence, include biomass feedstock characteristics; biomass feedstock yields; energy crop management practices; biomass feedstock transport modes and distances; biomass feedstock storage, drying and processing; and thermal efficiencies of biomass feedstock conversion technologies. There is obviously a need to address all data, critical or otherwise, and this is achieved, more effectively, comprehensively and transparently, by the Bioenergy LCA Data Compendium as a means of assembling and recording relevant and reliable data for bioenergy LCA workbooks that can produce ranges of results for all the bioenergy value chains specifically required by the agreed LCA purpose, goal and scope of this project.

5. BIOENERGY LCA DATA COMPENDIUM

5.1 General Data Types

The Bioenergy LCA Data Compendium complements the Bioenergy LCA Database in establishing the evidence base required by this project. There are distinct differences between the purposes of these components of the evidence base. The Bioenergy LCA Database provides evidence, in the form of full reviews of LCA studies, of what work has already been reported; whether, overall, this work is relevant to the agreed goal and scope of this project; what are the available headline results that might be pertinent to the relevant bioenergy value chains; and how are issues of confidence and critical data addressed. In contrast, the Bioenergy LCA Data Compendium records the basic data required to perform LCA calculations on all the chosen bioenergy value chains so that fundamental factors, such as variability and uncertainty, which influence associated total GHG emissions, can be explored, quantified and qualified.

In this regard, it must be appreciated that LCA studies which failed to pass the screening criteria and, hence, were not subjected to full reviews are not necessarily excluded as sources of values for data in the Bioenergy LCA Data Compendium. If any LCA study or, indeed, other source of information in the public domain, could provide relevant data then it was properly considered for inclusion in the Bioenergy LCA Data Compendium. However, the most important aspect of such data was its relevance to the purpose of this project.

An essential feature of the Bioenergy LCA Data Compendium is that, rather than attempting to record “typical” or “representative” values of data, it is intended to document “likely ranges” of values which reflect variability or uncertainty, thereby providing a sound and necessary basis for investigating the impact of these factors on estimated total GHG emissions. The ability of existing LCA studies to provide ranges of values rather than selectively individual values, which may or may not be typical or representative, depends on their specific details. Indeed, due to practical considerations related to accessing necessary data, many LCA studies adopt values of data that are simply available without evidence, justification or commentary on whether they are, in some way, representative. In contrast, the Bioenergy LCA Data Compendium openly attempts to assemble values of data, from whichever public domain sources are relevant, as a means of capturing likely ranges that are caused by variability or uncertainty.

The Bioenergy LCA Data Compendium is an MS Excel workbook (ETI Bioenergy LCA Data Compendium v16.xlxs) which substantially contributes to the evidence base and records information used in the development and application of LCA workbooks for the agreed bioenergy value chains as part of WP4 of this project. Screen shots from the Bioenergy LCA Data Compendium are presented in Appendix G. In particular, Figure G1 reproduces the instructions for populating the Bioenergy LCA Data Compendium. The 150 individual worksheets for data entry into the Bioenergy LCA Data Compendium are listed, along with their unique codes, in Figure G2. The colour coding of cells to distinguish between where data can be entered, where it cannot be entered due to values being derived by embedded formulae and where data are linked to the Emissions Factor Database (EFD) is explained in Figure G3. Examples of worksheets for recording different types of data are provided in Figures G4 and G5.

The broad types of data and how they are documented in the Bioenergy LCA Data Compendium are based on extensive previous experience with the development and application of LCA workbooks for bioenergy and other technologies. In general terms, the information in the Bioenergy LCA Data Compendium is divided into two types: country/region-specific parameters and operational input datasets.

Country/region-specific parameters mainly refer to the particular sources and essential characteristics of biomass feedstocks, or the necessary details of logistics related to the transport of biomass feedstocks in their different forms. For example, in relation to sources of biomass feedstocks, country/region-specific parameters include cultivation input and feedstock yield datasets and information for deriving the net calorific value of the feedstock at any given moisture content. In terms of the logistics of biomass feedstock transport, the country/region specific parameters include the single or round trip distances involved.

Operational input datasets are combinations of specific data that are related to particular activities which form parts of the specified bioenergy value chains. These are referred to as datasets because much of the data are consistently inter-related. For example, the gross vehicle weight, maximum cargo weight and volume, diesel fuel consumption rate and vehicle purchase price are all related to each other for any given type of lorry. However, within an operational input dataset, some data may be only generally related. This includes the working life of the vehicle, its annual utilisation and its annual maintenance factor. In such instances, generic data are more likely to be adopted.

5.2 Sources of Data

Some existing LCA studies, which have either passed or failed the screening criteria and, therefore, have or have not been subjected to full reviews, have provided information, some of which is critical data, for the Bioenergy LCA Data Compendium. In particular, some LCA studies may be the most appropriate or, indeed, only sources of certain country/region-specific parameters, especially those related to biomass feedstock provision. However, based on past experience, it was known that many other sources of data would be needed to populate the Bioenergy LCA Data Compendium completely. Broadly speaking, these sources fall into two categories; statistical sources and primary sources.

Statistical sources include national-collected datasets on the production of biomass feedstocks such as energy crops. To ensure that data were as up-to-date as possible, the latest available statistical sources were used. Primary sources provide the logistical data and the majority of the operational input datasets. For example, specific shipping route software/databases offer extensive, reliable and obvious sources of information on trip distance between specific ports. Additionally, manufacturer's technical specifications are the usual source of primary data on the characteristics and performance of particular items of equipment and vehicles. It is noted that such specifications reflect existing characteristics and performance rather than possible future developments and improvements which are a matter for separate speculation and investigation beyond the remit of this project.

The use of statistical and primary sources is crucial for deriving the ranges between likely low and likely high values of associated GHG emissions which is a significant aspect of this evidence base and an essential requirement for developing and applying suitable bioenergy LCA workbooks in this project. Based on both past experience as well as examination of the details of existing LCA studies, it is abundantly apparent that most LCA studies adopt single values for many input data with rarely any indication of whether these are "average" or, indeed, "typical" or "representative" values, and, almost universally, no indication of their variability as represented by their "ranges", "error bars" or, indeed, "standard deviations". Hence, other LCA studies were rarely the main sources of such necessary information in this project.

Ideally, the appropriate approach to a thorough investigation of the effects of variability and uncertainty on total GHG emissions associated with bioenergy value chains would require an evidence base composed of the results of the statistical analysis of suitably large samples of values for all the data incorporated into the necessary LCA calculations. However, this assumes that such samples exist and could be accessed or otherwise generated, and that the resources and time were available to apply the required statistical analysis. Unfortunately, such ideal circumstances only occur occasionally in practice.

The magnitude of the challenge for creating an evidence base incorporating statistically-derived results can be demonstrated by considering the extent of the data involved in the Bioenergy LCA Data Compendium and the demands of sample sizes used in related work. Given the agreed scope of this project, literally thousands of data specifications were needed in the Bioenergy LCA Data Compendium. Furthermore, large sample sizes, in the order of many tens or hundreds, would be required for each data specification to generate statistically-meaningful values, as is apparent in work with farm-level datasets for biofuel feedstocks (see, for example, Refs. 97 and 98).

The difficulties in accessing relevant values of data for statistical analysis are also very considerable. Whilst large samples of certain statistics, such as yields, may, occasionally, be available from national databases, necessarily complete datasets of consistently inter-dependent information are much rarer. Instead, in most instances, it would be necessary to undertake suitable surveys, on a national, region or even global scale, to obtain the required raw data. Assuming that this was possible and affordable, expectations for the likely success of such surveys must tempered by what would probably be regarded by survey respondents as the unusual nature of the data requested and/or difficulties in its provision. In some cases, some of the data requested could be seen as commercially sensitive and, therefore, confidential.

Because of these and other considerations, the generation of a complete evidence base incorporating the statistical analysis of primary data is not currently practical. In reality, the best that could be achieved with the data, resources and time available was the evaluation of likely ranges of values which encompass the variability or uncertainty of the data under consideration. Despite inevitable limitations, treatment of such data in the Bioenergy LCA Data Compendium and its subsequent application in LCA calculations enables the effect of these factors to be addressed adequately in terms of the aims and objectives of this particular project.

5.3 Data Treatment

As will be seen from the guidance for completing the Bioenergy LCA Data Compendium in Appendix G, the overall intention was that recorded data would reflect their ranges between likely low and likely high values. By taking this approach which, by necessity has relied on the experience and judgment of those compiling the Bioenergy LCA Data Compendium, reasonable representations of the variability of data, rather than their extremes, should be captured. This is the reason why the terms “likely low” and “likely high” instead of “minimum” and “maximum” were adopted in the Bioenergy LCA Data Compendium.

Certain general and specific aspects of data recording in the Bioenergy LCA Data Compendium require further explanation. General aspects consist of the significance of coherent datasets, as opposed to individual data values within such datasets; the basis for specifying likely low and likely high values of data; and the generation and application of “averages” from these values. Specific aspects relate to the use of particular sources of data such as the Phyllis database.

In some instances, data are inter-dependent and, of necessity, must be recorded as coherent datasets rather than as individual values. For example, it is usually assumed that biomass feedstock yield is related to cultivation practices which include application rates for fertilisers, agrochemicals, etc. Similarly, fuel consumption rates of vehicles transporting biomass feedstocks are dependent on their sizes. In these and other cases, relevant combinations of values of data had to be recorded in the form of internally-consistent datasets.

In general, it was essential to avoid mixing values of data from different datasets in order to generate likely low and likely high values of important individual data. In this regard, the importance of data was determined by its known effect on subsequent estimates of total GHG emissions. This also influenced how likely low and likely high values were specified. In particular, these terms did not necessarily apply to the relative values of individual data but to their probable impact on estimated total GHG emissions. For example, a coherent dataset for a large road transport vehicle would include high values for its cargo weight and fuel consumption rate which would be expected to produce a lower estimate for its total GHG emissions *per unit cargo weight* compared with a smaller vehicle. Consequently, the dataset for the larger vehicle would be recorded under the "likely low" rather than the "likely high" value. Similarly, the dataset for the smaller vehicle would provide the "likely high" value. This general approach was adopted throughout the Bioenergy LCA Data Compendium.

The selection of likely low and likely high values of country/region-specific parameters and logistical data for biomass feedstock production, transportation and conversion are relatively self-explanatory (such as high yields, short transport distances and high conversion efficiencies, respectively, most probably translating into lower estimates of unit GHG emissions, and vice versa). With the operational input datasets, the rule-of-thumb, based on expected economies of scale, has been that larger machinery and vehicles result in lower estimates of unit GHG emissions, and vice versa. To assist with the compilation of the Bioenergy LCA Data Compendium, suitable formulae have been embedded in the relevant operational input dataset worksheets that derive likely low and likely high estimates of unit GHG emissions. The locations of these formulae are indicated using cell colour coding which is summarised in Appendix G.

Additionally, formulae have been incorporated to derive estimates of average data based on simple arithmetic means of the likely low and likely high values. In some appropriate instances, different formulae have been used or replaced by specified values. In the first instance, the ranges for certain data can be extremely wide, covering many orders of magnitude. Consequently, it was assumed that a more meaningful approach would be to use formulae based on logarithmic means of the likely low and likely high values. Examples where this approach has been adopted are the data for the rates of CH_4 and N_2O emissions from stored biomass feedstocks which reflect considerable uncertainty based on limited measurements. In other instances, the original sources of data quote "average" values of data and these are used instead of values derived by particular formulae. Examples of this include certain biomass feedstock production data obtained from national statistics; modelled estimates of CO_2 emissions from land use change; and quoted factors for soil N_2O emissions.

The meaning of all averages derived or quoted in the Bioenergy LCA Data Compendium must be considered in relation to their subsequent use in bioenergy LCA workbooks for estimating total GHG emissions associated with bioenergy value chains. These averages are not intended to be interpreted as "statistically representative" since they were not derived from the appropriate analysis of necessary samples of data. Instead, they are adopted simply for functional purposes in subsequent GHG emissions calculations. Given that they are based on assumed likely ranges of data with no further statistical qualification, these averages can only be regarded, at best, as "most likely" values within the limitations of existing knowledge.

One specific source of information used in the Bioenergy LCA Data Compendium that requires special consideration is the Phyllis database (Ref. 99). This was the main source of information on the relevant characteristics of biomass feedstocks. These characteristics relate mainly to the combustion and lignocellulosic processing of biomass feedstocks covered by the scope of biomass conversion technologies in this project. Data on these and other relevant characteristics were assembled in an MS Excel workbook, ETI Biomass Feedstock Characteristics v05.xlxs, so that suitable ranges of values could be provided for the Bioenergy LCA Data Compendium.

The Phyllis database is, in effect, a catalogue of published results from the testing of samples of specified biomass feedstocks. It contains a variety of data, the most important of which for this project are factors for the Milne equation (Ref. 100) used to evaluate the net calorific value of biomass feedstocks. The Milne equation factors consist of the higher heating value of dry, ash free biomass, and its hydrogen and ash contents (both on a dry basis). The Milne equation is required in the bioenergy LCA workbooks to provide the appropriate functionality for determining the net calorific value of biomass feedstocks with different moisture contents. This is necessary for bioenergy value chains involving biomass feedstock combustion, especially as the moisture content can change along the chain. Additionally, the Phyllis database is an appropriate source of values for the cellulose content (dry basis) of biomass, which is relevant for lignocellulosic processing, and the carbon content (dry basis), which is required for biogenic carbon calculations in the bioenergy LCA workbooks.

The Phyllis database is a well-known and frequently-cited source of such data, partly because of its coverage of a wide range of biomass feedstocks and partly because of its systematic documentation of relevant data. However, it is generally recognised that the Phyllis database does not attempt to qualify the data it presents by indicating "average", "representative", "typical" or other such values, which some may see as a deficiency of this particular source of data. Instead, the Phyllis database simply offers values of data from a collection of published sources without comment on their reliability, comparability or otherwise. In this respect, it would only be possible to check the effective robustness and suitability of such values by accessing and examining the original sources which are cited in the Phyllis database.

Rather than contemplating the rather daunting challenge and probably futile task of reviewing these original sources, it is more realistic and productive to accept that the Phyllis database just reports values of data from the testing of samples of relevant biomass feedstocks. Without the necessary screening of data, probably requiring access to laboratory reports and scrutiny of basic results, it seems reasonable to treat all values of data in the Phyllis database as equally valid and comparable. On this basis, it seems logical to interpret observed differences between values of data from individual sources for any given biomass feedstock in the Phyllis database as expressions of real variability between samples.

This was the approach adopted for assembling and using information from the Phyllis database in ETI Biomass Feedstock Characteristics v05.xlsx. In particular, all suitable datasets of the Milne equation factors for relevant biomass feedstocks were recorded. Those with the lowest and highest values of the higher heating value (dry, ash free), as the main factor in determining the net calorific value, were then used to represent the range, in the form of likely low and likely high values, in the Bioenergy LCA Data Compendium. Likely low and likely high values of carbon content were also based on these specific datasets. There are fewer biomass composition datasets which contain values for cellulose content in the Phyllis database but these were still able to provide the ranges necessary for the Bioenergy LCA Data Compendium.

Certain other practical considerations had to be taken into account. For example, as the relative proportions of different tree species in forests supplying biomass feedstocks for the chosen bioenergy value chains in this project could not be specified, the ranges of appropriate values were based on all the datasets for all the relevant tree species. Very occasionally, it was necessary to interpret the biomass feedstock descriptions in the Phyllis database quite liberally to ensure adequate coverage. However, it should be noted that, overall, subsequent ranges of the datasets for relevant biomass feedstocks derived in this way from the Phyllis database only appear to generate relatively limited variations in net calorific values.

6. CONCLUSIONS

The essential outcomes from setting the context of bioenergy LCA can be summarised as follows:

- Carbon neutrality is a significant potential asset of all forms of energy derived from biomass, generally referred to as bioenergy.

- Although, strictly speaking, bioenergy includes liquid and gaseous fuels, known as biofuels, that are principally used in transport, these are usually distinguished from all other forms of energy derived from biomass.

- Quantification of prominent GHG emissions, consisting of CO_2, CH_2 and N_2O, associated with biofuel and bioenergy production has a long history which stretches back over almost one quarter of a century.

- The technique that is usually applied to such quantification is LCA which is based on the principles described officially in ISO 14040 as a framework which addresses the need to define the LCA goal and scope and establishes the basic features of LCA methodology as a set of rules for conducting calculations.

- As a precursor to LCA, energy analysis, which is based on a shared reliance on systems analysis, was used to question the overall energy balance of producing bioethanol from maize in the USA almost half a century ago, although disputes over assumptions used in these calculations continued for some time afterwards.

- Biofuel LCA studies focusing on prominent GHG emissions began to be performed in the 1990's, and a review of such studies on the production of biodiesel from OSR in the UK highlighted the need for adequate transparency, as required by ISO 14040, so that results could be understood properly and compared in a meaningful manner.

- One major contribution to the total GHG emissions associated with the UK production of certain crop-based biofuels, such as biodiesel from OSR and bioethanol from wheat, was soil N_2O emissions which were estimated using the IPCC Tier 1 method with default values which are now proposed for downward revision in the UK due to the results of field trials that have been conducted there.

- Another potentially major contribution to the total GHG emissions associated with biofuels and bioenergy derived from crops which displace existing agricultural production is iLUC which can, in certain circumstances, cause a form of carbon debt and has to be simulated by means of modelling.

- Currently, there is no established consensus on the estimated impact of iLUC since conclusive modelling is not possible due mainly to the constraints of incomplete global data and limits to representing all necessary global interactions.

- Quantification of GHG emissions associated with biofuel production in the EU is a requirement of the EC's RED and FQD which specify the details of an LCA methodology that suffers from important flaws, the most significant of which is that the LCA goal is not stated, as required by ISO 14040, resulting in a hybrid approach that satisfies the objectives neither regulation nor policy analysis.

- Bioenergy LCA studies, especially those concerned with wood fuel supply from forests, began in the UK in the 1990's and it became apparent that whether carbon stock changes in forests make significant contributions to total GHG emissions, thereby bringing into question assumed carbon neutrality, depends on specific circumstances related to the forest, its management, the uses of different parts of the tree for wood fuel and timber products, and the related counterfactuals.

- By incorporating results from forest carbon dynamic modelling into bioenergy LCA studies, it is possible to identify combinations of circumstances which might be encouraged as they would achieve overall reductions in GHG emissions, and those which should be avoided as they would cause increases in GHG emissions.

- Misunderstandings over results from forest bioenergy LCA studies can arise from confusing whole trees felled at the end of stand rotation with thinnings removed during the ongoing management of such stands, and from the concept of carbon debt which encompasses three different phenomena that have to be appropriately accommodated within forest carbon dynamic models such as the CARBINE model.

- In the context of policy analysis, the results of forest bioenergy LCA studies can be very sensitive to the choice of counterfactuals which, ideally, should be subjected to economic modelling, although, for practical purposes, is usually addressed through sensitivity analysis.

- Meta-analyses, involving comparison of the results of bioenergy LCA studies, and, indeed, of any LCA studies, are only meaningful if they share the same LCA methodologies which, in turn, address the same stated LCA purpose and defined LCA goal and scope.

- Reviews of forest bioenergy LCA studies have concluded that carbon neutrality cannot be automatically assumed for the production of energy from such sources of wood, and re-emphasised the use of reliable and suitable forest carbon dynamic models to account for forest biogenic carbon.

- Quantification of GHG emissions associated with biomass for electricity, heating and cooling in the EU is incorporated into proposed sustainability criteria which include the details of a required LCA methodology that suffers from important flaws, the most significant of which is that the LCA goal is not stated, as required by ISO 14040, resulting in a hybrid approach that satisfies the objectives of neither possible regulation nor policy analysis.

- Distinctions have been made between the methodologies adopted in ALCA and CLCA which have resulted in these being frequently used as shorthand terms for LCA methodologies that are appropriate for regulation, and policy analysis, respectively, although precise and comprehensive specification of a suitable LCA methodology depends on the actual stated LCA purpose and the defined LCA goal and scope.

- The purposes and goals of LCA studies, in general, and bioenergy LCA studies, in particular, are rarely expressed explicitly, clearly and completely although some examples do exist in relation to forest bioenergy LCA studies applied to policy analysis in the UK and the EU as a whole.

- A systematic approach, involving checklists with essential questions that must be answered, has been proposed for the definition of LCA goal and scope, and for their subsequent encapsulation in the stated LCA purpose, which, together, completely establish all the details of the necessary methodology.

The main findings from the LCA study review procedure can be summarised as follows:

- A systematic approach is also needed for reviewing existing LCA studies, as a means of establishing part of the evidence base, and this has required selection and screening criteria that reflect the defined LCA goal and scope of this project.

- A quite large number (initially 161, subsequently confirmed as 147) of LCA studies, addressing relevant bioenergy value chains or their significant parts, including CCS, were identified by use of the selection criteria and, after application of the screening criteria, were reduced to a somewhat smaller number (49) for full reviews.

- The main reasons why selected LCA studies did not pass the screening criteria were that they adopted ALCA methodology instead of CLCA methodology, as required by the defined LCA goal and scope of this project; they did not address climate impacts or did not evaluate all prominent GHG emissions (CO_2, CH_4 and N_2O); or they were not strictly LCA studies.

- Of the 49 reviewed LCA studies, most (38) were focussed on relevant bioenergy value chains or significant parts of these chains, including the application of CCS to biomass feedstock conversion technologies, and the remainder (11) concerned the application of CCS to fossil fuel technologies (of which the CO_2 transport and storage systems could be relevant to CCS-enabled biomass feedstock conversion technologies).

- Of the 49 reviewed LCA studies, there was an approximately even split between those adjudged to have low, moderate or high transparency regarding access to the details of the calculations, their assumptions and their sources of data.

- Although the reviewed LCA studies covered all of the wood pellet supply from forests, and the majority of pellet supply from energy crops and biomass feedstock conversion technologies within the scope of this project, only some (55) of the potential (190) relevant whole bioenergy value chains (without CCS) were covered by these LCA studies.

- Coverage of the relevant whole bioenergy value chains (without CCS) was provided by a quite small number (8) of reviewed LCA studies, most of which (7) were adjudged to have high transparency.

- Very few published headline results that were relevant to the whole bioenergy value chains within the scope of this project could be obtained from the reviewed LCA studies, and some of the ranges of these headline results were extremely wide (in particular, for steam cycle electricity generation using wood pellets from forests due to the very large number of sources of wood pellets, forest types and management practices, and counterfactuals considered).

- Overall, the review process generated limited quantitative data, although it provided useful qualitative insights, for the evidence base required in this project.

The pertinent points from the description of the Bioenergy LCA Data Compendium can be summarised as follows:

- In contrast to the review of LCA studies, the Bioenergy LCA Data Compendium offers a more appropriate, fully transparent and crucially comprehensive means of providing the evidence base for this project.

- In particular, the structure of the Bioenergy LCA Data Compendium, its specific details and its reliance on relevant sources of information, such as statistical and primary sources, enables it to support the development of bioenergy LCA workbooks that satisfy the complete technological scope of this project and establish a basis for confidence in subsequent results.

APPENDIX A: CHECKLISTS FOR LCA GOAL AND SCOPE DEFINITION

Table A.1 Checklist for Life Cycle Assessment Goal Definition

LCA Goal Definition Questions	Examples of Relevant Answers
What is the intended application and audience?	Analysis for policy-makers
Which environmental impact is under consideration?	Global climate change.
What is the general nature of the product system(s) under consideration?	Bioenergy process chains.
What is the general nature of the scale of these product system(s)?	Specific size of individual bioenergy process chain or a collection of bioenergy process chains.
What is the general nature of the system time horizon for these product system(s)?	Ex post (backward-looking) or ex ante (forward-looking).

Table A.2 Checklist for Life Cycle Assessment Scope Definition

LCA Scope Definition Questions	Examples of Relevant Answers
Which specific causes of the environmental impact are being evaluated?	Prominent GHG emissions; e.g. CO_2, CH_4 and N_2O.
What is the impact time horizon relevant to the environmental impact?	20 years, 100 years, etc.
What is the specific composition of the product system(s)?	Representation of relevant bioenergy process chains and all their main elements.
What is the perspective on the environmental impact of multiple products and/or services from the product system(s)?	Collective consequences or individual attribution.
What is the specific spatial system boundary of the product system(s)?	Specification of geographical extent of bioenergy process chains (locally, nationally, regionally, globally, etc.) and any related counterfactuals.
What is the specific temporal system boundary of the product system(s)?	Specified number of years covered by the system time horizon.
What is the functional unit?	MJ of bioenergy, in the form of delivered energy, supplied to end users.
What are the full metrics of the reported results?	kg CO_2eq./MJ

APPENDIX B: FINAL SCOPING LISTS FOR BIOENERGY VALUE CHAINS

Table B.1 Final Scoping List of Wood Pellet Supply from Forests

Country/ Countries	Region(s)	Forest Type	Sources of Biomass Feedstock
Canada	Western	Conventional Forest (conifer)	Harvest Residues Sawmill Co-products
Scandinavia and Baltic States	-	Conventional Forest (conifer)	Harvest Residues Sawmill Co-products Small Roundwood Complete Stemwood (early thinnings) Complete Stemwood (poor quality trees)
United Kingdom	-	Conventional Forest (broadleaf)	Sawmill Co-products Small Roundwood Complete Stemwood (thinnings)
		Conventional Forest (conifer)	Sawmill Co-products Small Roundwood Complete Stemwood (thinnings)
United States of America	Southern/ South Eastern	Conventional Forest (broadleaf)	Harvest Residues Sawmill Co-products Small Roundwood
		Conventional Forest (pine)	Sawmill Co-products Small Roundwood Complete Stemwood (early thinnings)
		Plantation Forest (pine)	Sawmill Co-products Small Roundwood Complete Stemwood (early thinnings)
	North Western	Conventional Forest (conifer)	Harvest Residues Sawmill Co-products

Table B.2 Final Scoping List of Pellet Supply from Energy Crops

Country	Sources of Biomass Feedstock
Belgium	Short Rotation Coppice (poplar and willow)
France	Short Rotation Coppice (poplar and willow)
Netherlands	Short Rotation Coppice (poplar and willow)
Poland	Short Rotation Coppice (poplar and willow)
United Kingdom	Miscanthus Short Rotation Coppice (poplar and willow) Short Rotation Forest (broadleaf) Short Rotation Forest (conifer) Wheat Straw (agricultural residue)
United States of America, Southern and South Eastern Regions	Short Rotation Forest (broadleaf) Short Rotation Forest (conifer)

Table B.3 Final Scoping List of Biomass Feedstock Conversion Technologies

Biomass Feedstock Conversion	**Addition of Carbon Capture and Storage**
Small-scale Heat Only Production (boilers)	No
Medium-scale Heat Only Production (boilers)	No
Medium-scale Combined Heat and Power Generation	No
Large-scale Combined Heat and Power Generation	No
Electricity Only Generation (steam cycle)	No
	Yes
Electricity Generation (steam cycle) and District Heat Production	No
	Yes
Hydrogen Production from Gasification	No
	Yes
Hydrogen and District Heat Production from Gasification	No
	Yes
Electricity Generation (combined cycle gas turbine) from Gasification	No
	Yes
Ethanol from Lignocellulosic Processing	No

APPENDIX C: SEARCH TERMS, SEARCH ENGINES AND SOURCES

In general, the search terms used in this project consisted of appropriate combinations of the relevant assessment technique or its outcome, and generic or specific descriptions of important aspects of the chosen bioenergy value chains. The terms for the relevant assessment technique or its outcome included:

- life cycle assessment
- consequential life cycle assessment
- life cycle analysis
- LCA
- life-cycle
- greenhouse gas emissions
- GHG
- climate change
- environmental evaluation
- energy balance

The generic descriptions of important aspects of the chosen bioenergy value chains included:

- biomass
- biomass energy
- biofuels
- bioenergy
- wood fuels
- wood pellets
- energy crops
- short rotation coppice
- short rotation forests
- forests
- agricultural residues
- bioheat
- bioelectricity
- bioethanol
- biomass combustion
- biomass gasification
- lignocellulosic processing
- lignocellulosic conversion systems
- biomass heat
- biomass district heat
- biomass electricity generation
- biomass combined heat and power
- biomass CHP
- biomass hydrogen
- biomass ethanol

The specific descriptions of important aspects of the chosen bioenergy value chains included:

- miscanthus
- straw
- poplar
- willow
- hydrogen

- carbon capture and storage
- CCS
- BECCS

Other individual search terms that were used included:

- BEAC
- Supergen Bioenergy Hub
- Parliamentary Advisory CCS Report

Where relevant, specific country names, such as Belgium, Canada, France, the Netherlands, Poland, the United Kingdom and the United States of America, were added to search terms to ensure appropriate geographical coverage for the agreed scope of this project.

As appropriate, these individual or combinations of search terms were used with the following search engines:

- Science Direct
- Web of Science
- Google Scholar
- Yahoo
- ResearchGate

The following publisher's and journal websites were searched:

- Elsevier
- Springer Link
- International Journal of Life Cycle Assessment
- Chemical Engineering Journal
- IEA Bioenergy
- Biomass and Bioenergy
- Bioresource Technology
- Forest Products Journal
- Biofuels, Bioproducts and Biorefining Journal
- Biofuels Journal
- Sustainability
- Renewable and Sustainable Energy Reviews
- Journal of Industrial Ecology
- Chemical Engineering and Processing
- Journal of Forest Research
- Resources
- Environmental Science and Technology
- Journal of Cleaner Production
- GCB Bioenergy
- Applied Energy

Searches of specialist websites were also conducted, including:

- BIOBIB
- NERI
- CETRI
- United Nations Environmental Programme
- International Energy Agency
- European Commission's Joint Research Centre

- United Kingdom Department of Energy and Climate Change
- United Kingdom Department of Business and Industrial Strategy
- United Kingdom Department for Environment, Food and Rural Affairs
- United States Environmental Protection Agency
- lcacenter.org
- energinet.dk
- ccsassociation.org
- Global CCS Institute

Various university online libraries were searched, including:

- Aalborg University
- Amsterdam University
- Joanneum Research
- Norwegian Science and Technology University
- University of Bath
- University of British Columbia

Additionally, sources cited in recent bioenergy LCA review work were taken into account, particularly those for forest biomass supply specified in "Review of Literature on Biogenic Carbon and Life Cycle Assessment of Forest Bioenergy" by R. W. Matthews, L. Sokka, S. Soimakallio, N. D. Mortimer, J. H. R. Rix, M.-J. Schelhaas, T. Jenkins, G. Hogan, E. Mackie, A. Morris and T. Randle, Final Task 1 Report for Project DG ENER/C1/427, Forest Research, Farnham, United Kingdom, May 2014. This work was led by VTT Technical Research Centre of Finland and their search procedures were exhaustive. Finally, sources cited in other review studies and referenced in known bioenergy LCA studies were traced and checked accordingly.

APPENDIX D: SELECTED LCA STUDIES

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
1	A Large and Persistent Carbon Sink in the World's Forests	N	Carbon stock change modelling only
2	A Model of Carbon Capture and Sequestration with Demonstration of Global Warming Potential and Fossil Fuel Resource Efficiency	N	CO_2 storage options not relevant to UK
3	A Streamlined Life Cycle Analysis of Canadian Wood Pellets	N	Attributional LCA methodology
4	An Assessment of Carbon Pools, Storage and Wood Products Market Substitution using Life-Cycle Analysis Results	N	Only considers carbon dynamics and CO_2 emissions
5	An Environmental Impact Assessment of Exported Wood Pellets from Canada to Europe	N	Attributional LCA methodology; allocation by weight
6	Assessing the Life-Cycle Performance of Hydrogen Production via Biofuel Reforming in Europe	N	Attributional LCA methodology; allocation by energy content
7	Baseline Effects on Carbon Footprints of Biofuels: the case of wood	N	Only considers CO_2 emissions
8	Bioenergy Driven Land Use Change Impacts on Soil Greenhouse Gas Regulation Under Short Rotation Forestry	N	Not an LCA study
9	BIOGRACE II: harmonised greenhouse gas calculations for electricity, heating and cooling from biomass - version 3, Final Publishable Report, User Manual, Methodological Background Document, Calculation Rules and Additional Standard Values	Y	
10	Biomass Emissions And Counterfactual (BEAC) Model	Y	
11	Biomass Environmental Assessment Tool - version 2 ($BEAT_2$); and User Guide	Y	
12	Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration Comparing the Energy Balance, Greenhouse Gas Emissions and Economics	Y	
13	Biomass Supply and Carbon Accounting for Southeastern Forests	N	Carbon modelling only considers CO_2
14	Biomass Yield and Energy Balance of a Short-Rotation Poplar Coppice with Multiple Clones on Degraded Land during 16 years	N	Climate impact not evaluated
15	Boreal Forest Management and its Effect on Atmospheric CO_2	N	Appears to consider only CO_2 emissions
16	Carbon Accounting of Forest Bioenergy: conclusions and recommendations from a critical literature review	N	Review of LCA studies

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
17	Carbon and Energy Balances for a Range of Biofuels Options	Y	
18	Carbon Capture and Utilization: preliminary life cycle CO_2, energy and cost results of potential mineral carbonation	N	CO_2 storage option not relevant to UK
19	Carbon Capture, Storage and Utilisation Technologies: a critical analysis and comparison of their life cycle environmental impacts	N	Review of LCA studies
20	Carbon Debt and Carbon Sequestration Parity in Forest Bioenergy Production	N	Not an LCA study, and CH_4 and N_2O may not be included
21	Carbon Impacts of Biomass Consumed in the EU: quantitative assessment	Y	
22	Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: energy crops	Y	
23	Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: forests	Y	
24	Carbon in Wood Products and Product Substitution	N	Not an LCA study
25	Carbon Payback Period and Carbon Offset Parity Point of Wood Pellet Production in the Southeastern USA	N	Only considers carbon dynamics and CO_2 emissions
26	Carbon Savings with Transatlantic Trade in Pellets: accounting for market-driven effects	Y	
27	Climate Change Mitigation Challenge for Wood Utilization - the case of Finland	N	Attributional LCA and only considers carbon dynamics and CO_2 emissions
28	Climate Effects of Wood Used for Bioenergy	N	Not an LCA study; mainly addresses carbon stock timing
29	CO_2 Emissions from Biomass Combustion for Bioenergy: atmospheric decay and contribution to global warming	N	Not an LCA study of a specific situation; mainly modelling
30	Comparative Impact Assessment of CCS Portfolio: life cycle perspective	Y	
31	Comparative Life Cycle Analysis of Pellet, Natural Gas and Heavy Fuel Oil as Heat Energy Sources	N	Attributional LCA methodology; allocation by economic value
32	Comparative Life Cycle Environmental Assessment of CCS Technologies	Y	
33	Comparing Soil Carbon of Short Rotation Poplar Plantations with Agricultural Crops and Woodlots in North Central United States	N	Country/region not in scope

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
34	Comparison of Carbon Capture and Storage with Renewable Energy Technologies Regarding Structural, Economic, and Ecological Aspects in Germany	Y	
35	Counting the Cost of Carbon in Bioenergy Systems: sources of variation and hidden pitfalls when comparing life cycle assessments	N	Review of LCA studies
36	Cradle-to-Gate Life Cycle Assessment of Forest Operations in Europe: environmental and energy profiles	N	Attributional LCA methodology; allocation by economic value
37	Development and Evaluation of Forest Growth - SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow	N	Climate impact not evaluated
38	Development of British Columbia Wood Pellet Life Cycle Inventory and its Utilization in the Evaluation of Domestic Pellet Applications	N	Attributional LCA methodology; allocation by weight
39	Development of Specific Rules for the Application of Life Cycle Assessment to Carbon Capture and Storage	N	Development of rules rather than an LCA study
40	Dry Matter Losses and Methane Emissions During Wood Chip Storage: the impact on full life cycle greenhouse gas savings of short rotation coppice willow for heat	N	Attributional LCA methodology; allocation by economic value
41	ecoinvent 3	Y	
42	Effects of Boreal Forest Management Practices on the Climate Impact of CO_2 emissions from Bioenergy	N	Only considers carbon dynamics and CO_2 emissions
43	Efficacy of carbon and bioenergy markets in mitigating carbon emissions on reforested lands: A case study from Southern United States	N	Not consequential LCA methodology as counterfactuals not used
44	ELUM: A spatial modelling tool to predict soil greenhouse gas changes from land conversion to bioenergy in the UK	N	Not an LCA study; rather a modelling study
45	Energy and Climate Benefits of Bioelectricity from Low-Input Short Rotation Woody Crops on Agricultural Land over a Two-Year Rotation	N	Attributional LCA methodology
46	Energy and CO_2 Balances in Different Power Generation Routes Using Wood Fuel from Short Rotation Coppice	N	Attributional LCA methodology
47	Energy and Greenhouse Gas Balance of the Use of Forest Residues for Bioenergy Production in the UK	N	Attributional LCA methodology
48	Energy- and Greenhouse Gas-Based LCA of Biofuel and Bioenergy systems: key issues, ranges and recommendations	N	Not an LCA study; mainly concerning LCA methodology

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
49	Energy- and Greenhouse Gas-based LCA of Biofuels and Bioenergy Systems - key issues, ranges and recommendations	N	Review of LCA studies
50	Energy Budget and Greenhouse Gas Balance Evaluation of Sustainable Coppice Systems for Electricity Production	Y	
51	Environmental Assessment of Carbon Capture and Storage Deployment Scenarios in France	N	CO_2 storage option not relevant to UK
52	Environmental Assessment of German Electricity Generation from Coal-fired Power Plants with Amine-based Carbon Capture	N	CO_2 capture but not storage considered
53	Environmental Evaluation of CCS using Life Cycle Assessment - a synthesis report	N	Not an LCA study; mainly concerning LCA methodology
54	Environmental Evaluation of CCS Using Life Cycle Assessment (LCA)	N	Review of LCA studies
55	Environmental Impacts of a German CCS Strategy	Y	
56	Environmental Impacts of Future Bioenergy Pathways: the case of electricity from wheat straw bales and pellets	N	Attributional LCA methodology
57	Environmental Life Cycle Assessment of Bioethanol Production from Wheat Straw	N	Attributional LCA methodology; allocation by weight
58	Environmental Sustainability Analysis of UK Whole-Wheat Bioethanol and CHP Systems	Y	
59	Environmental Sustainability of Bioethanol Production from Wheat Straw in the UK	N	Attributional LCA methodology
60	Establishment Phase Greenhouse Gas Emissions in Short Rotation Woody Biomass Plantations in the Northern Lake States, USA	N	Country/region not in scope
61	European reference Life Cycle Database (ELCD) 3.2; and International Reference Life Cycle Data System (ILCD) Handbook: general guide for Life Cycle Assessment - provision and action steps	N	Mainly attributional LCA methodology
62	Final Report on Technical Data, Costs, and Life Cycle Inventories of Advanced Fossil Power Generation Systems	Y	
63	Forest Bioenergy Climate Impact Can Be Improved by Allocating Forest Residue Removal	Y	
64	Forest Bioenergy or Forest Carbon? - assessing trade-offs in greenhouse gas mitigation with wood-based fuels	Y	

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
65	Full Chain Analysis and Comparison of Gas-fired Power Plants with CO_2 Capture and Storage with Clean Coal Alternatives	N	CO_2 storage option not relevant to UK
66	GHG Emissions Performance of Various Liquid Transportation Biofuels in Finland in Accordance with the EU Sustainability Criteria	N	Mix of attributional and consequential LCA methodologies
67	Global Emissions Model for Integrated Systems (GEMIS) - version 4.94	Y	
68	Global Warming Potential Factors and Warming Payback Time as Climate Indicators of Forest Biomass Use	N	Only consider carbon dynamics and CO_2 emissions
69	Greenhouse Gas and Energy Based Life Cycle Analysis of Products from the Irish Wood Processing Industry	N	Attributional LCA methodology; allocation by weight
70	Greenhouse Gas Balance of Native Forests in New South Wales, Australia	N	Country not in scope
71	Greenhouse Gas Emissions from Four Bioenergy Crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses	Y	
72	Greenhouse Gas Performance of Heat and Electricity from Wood Pellet Value Chains - based on pellets for the Swedish market	Y	
73	Growth, Yield and Mineral Content of Miscanthus × Giganteus Grown as a Biofuel for 14 Successive Harvests	N	Not an LCA study
74	How Certain are Greenhouse Gas Reductions from Bioenergy? - life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues	N	Attributional LCA methodology; allocation by economic value
75	Hydrogen Production via Biomass Gasification - a lifecycle assessment approach	Y	
76	Identifying Potential Environmental Impacts of Large-Scale Deployment of Dedicated Bioenergy Crops in the UK	N	Review of LCA studies
77	Impact Due to the Use of Combustible Fuels: life cycle viewpoint and relative radiative forcing commitment	N	Uses emission factors from papers to calculate a relative radiative forcing commitment
78	Impacts of Intensive Management and Landscape Structure on Timber and Energy Wood Production and Net CO_2 Emissions from Energy Wood Use of Norway spruce	N	Only considers carbon dynamics and CO_2 emissions
79	Implications of Land-Use Change to Short Rotation Forestry in Great Britain for Soil and Biomass Carbon	N	Not an LCA study

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
80	Including UK and International Forestry in Biomass Environmental Assessment Tool ($BEAT_2$)	N	Attributional LCA methodology; allocation by economic value
81	Incorporating Uncertainty into a Life Cycle Assessment (LCA) Model of Short-Rotation Willow Biomass (Salix spp.) Crops	N	Country/region not in scope
82	Indirect Carbon Dioxide Emissions from Producing Bioenergy from Forest Harvest Residues	Y	
83	Integrated Assessment of Carbon Capture and Storage (CCS) in the German Power Sector and Comparison with the Deployment of Renewable Energy	N	Review of LCA studies
84	Is Woody Bioenergy Carbon Neutral? - a comparative assessment of emissions from consumption of woody bioenergy and fossil fuel	N	Country not in scope
85	Land-Use Change to Bioenergy Production in Europe: implications for the greenhouse gas balance and soil carbon	N	Not an LCA study
86	LCA of a Biorefinery Concept Producing Bioethanol, Bioenergy, and Chemicals from Switchgrass	Y	
87	Life Cycle Analysis of Pellet Burning Technologies	N	Only CO_2 and CH_4 are assessed
88	Life Cycle Analysis of Short Rotation Coppice through the Example of Eucalyptus and Poplar for Bioenergy in France	N	Biomass feedstock not in scope; consequential LCA for Eucalyptus only
89	Life Cycle Assessment (LCA) of an Integrated Biomass Gasification Combined Cycle (IBGCC) with CO_2 Removal	Y	
90	Life Cycle Assessment of a Hypothetical Canadian Pre-combustion Carbon Dioxide Capture Process System	Y	
91	Life Cycle Assessment of a Pulverized Coal Power Plant with Post-combustion Capture, Transport and Storage of CO_2	Y	
92	Life Cycle Assessment of a Willow Bioenergy Cropping System	N	Country/region not in scope
93	Life Cycle Assessment of Bioenergy Systems - state of the art and future challenges	N	Review of LCA studies
94	Life Cycle Assessment of Biomass Chains: wood pellet from short rotation coppice using data measured on a real plant	Y	

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
95	Life Cycle Assessment of Biomass-Based Combined Heat and Power Plants	N	Attributional LCA methodology; allocation by economic value
96	Life Cycle Assessment of Carbon Capture and Storage in Power Generation and Industry in Europe	N	CO_2 storage option not relevant to UK
97	Life Cycle Assessment of Carbon Dioxide Capture and Storage from Lignite Power Plants	Y	
98	Life Cycle Assessment of Electricity Production from Poplar Energy Crops Compared with Conventional Fossil Fuels	N	Country not in scope
99	Life Cycle Assessment of Gas Power with CCS - a study showing the environmental benefits of system integration	Y	
100	Life Cycle Assessment of Membrane-Based Carbon Capture and Storage	N	CO_2 storage option not relevant to UK
101	Life Cycle Assessment of Natural Gas Combined Cycle Power Plant with Post-combustion Carbon Capture, Transport and Storage	N	CO_2 storage option not relevant to UK
102	Life Cycle Assessment of New Willow Cultivars Grown as Feedstock for Integrated Biorefineries	Y	
103	Life Cycle Assessment of Norwegian Bioenergy Heat and Power Systems	N	Attributional LCA methodology; allocation by weight (biomass feedstocks) and energy content (energy outputs)
104	Life Cycle Assessment of Selected Technologies for CO_2 Transport and Sequestration	Y	
105	Life Cycle Assessment of Wheat Straw as a Fuel Input for District Heat Production	Y	
106	Life Cycle Assessment of Wood Pellet - environmental measurements and assessment	N	Attributional LCA methodology; allocation by economic value
107	Life Cycle Assessment Tool for Estimating Net CO_2 Exchange of Forest Production	N	Only considers carbon dynamics and CO_2 emissions
108	Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas, and Wood Pellets in Ontario, Canada	N	Attributional LCA methodology

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
109	Life Cycle Energy and Environmental Benefits of Generating Electricity from Willow Biomass	N	Country/region not in scope
110	Life Cycle Environmental Impact Assessment of Biochar-Based Bioenergy Production and Utilization in Northwestern Ontario, Canada	Y	
111	Life Cycle Evaluation of Emerging Lignocellulosic Ethanol Conversion Technologies	Y	
112	Life Cycle GHG Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage	Y	
113	Life Cycle Impacts of Biomass Electricity in 2020: scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK	Y	
114	Life Cycle Impacts of Forest Management and Wood Utilization on Carbon Mitigation: knows and unknowns	Y	
115	Life Cycle Investigation of CO_2 Recovery and Sequestration	N	CO_2 storage options not relevant to UK
116	Life Cycle Modelling and Comparative Assessment of the Environmental Impacts of Oxy-fuel and Post-combustion CO_2 Capture, Transport and Injection Processes	N	CO_2 storage options not relevant to UK
117	Life Cycle Modelling of Fossil Fuel Power Generation with Post Combustion CO_2 Capture	N	CO_2 storage options not relevant to UK
118	Life-Cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery	N	Focus on enhanced oil recovery rather than CO_2 storage
119	Life-Cycle Assessment of Straw Use in Bio-Ethanol Production: a case study based on biophysical modelling	N	Uses modelled data
120	Life-Cycle Impacts of Forest Resource Activities in the Pacific Northwest and Southeast United States	N	Attributional LCA methodology
121	Life-Cycle Inventory of Wood Pellet Manufacturing and Utilization in Wisconsin	N	Attributional LCA methodology; allocation by weight
122	Massachusetts Biomass Sustainability and Carbon Policy Study	N	Country/region not in scope
123	Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution	N	Meta-analysis of other LCA studies

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
124	Meta-Analysis of Life Cycle Assessment Studies on Electricity Generation with Carbon Capture and Storage	N	Review of LCA studies
125	Modelling of Energy and Carbon Budgets of Wood Fuel Coppice Systems	N	Only considers CO_2 emissions
126	Multi Criteria Evaluation of Wood Pellet Utilization in District Heating Systems	Y	
127	National and Global Greenhouse Gas Dynamics of Different Forest Management and Wood Use Scenarios: a model-based assessment	N	Country out of scope
128	Potential Effects of Intensive Forestry on Biomass Production and Total Carbon Balance in North-Central Sweden	Y	
129	Production and Energetic Utilization of Wood from Short Rotation Coppice - a life cycle assessment	N	Country out of scope
130	Projection of US Forest Sector Carbon Sequestration under US and Global Timber Market and Wood Energy Consumption Scenarios, 2010–2060	N	Only considers forest carbon stock changes
131	Prospective Life Cycle Carbon Abatement for Pyrolysis Biochar Systems in the UK	N	Attributional LCA methodology
132	Quantifying GWI of Wood Pellet Production in the Southern United States and its Subsequent Utilization for Electricity Production in The Netherlands/Florida	N	Attributional LCA methodology; allocation by economic value
133	Quantifying the Global Warming Potential of CO_2 Emissions from Wood Fuels	N	Only considers carbon dynamics and CO_2 emissions
134	Regional Carbon Dioxide Implications of Forest Bioenergy Production	N	Only considers CO_2 emissions
135	Renewable Energy from Willow Biomass Crops: life cycle energy, environmental and economic performance	N	Country/region not in scope
136	Research to Support the Review of the Renewable Obligation Scotland and Impact of the Renewable Heat Incentive: part 2 - biomass thresholds for electricity, CHP and heat generation	N	Mix of attributional and consequential LCA methodologies
137	Scottish Government Biomass Incentives Review: best use of wood fibre	Y	
138	Sequester or Substitute - consequences of increased production of wood based energy on the carbon balance in Finland	N	Only considers CO_2 emissions
139	Short-Rotation Forestry of Birch, Maple, Poplar and Willow in Flanders (Belgium): I -biomass production after 4 years of tree growth	N	Not an LCA study

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
140	Short-Rotation Woody Crop Systems, Atmospheric Carbon Dioxide and Carbon Management: a US case study	N	Only considers CO_2 emissions.
141	Should Life Cycle Assessment be part of the Environmental Impact Assessment? Case Study: EIA of CO_2 capture and storage in Canada	N	Focuses on LCA methodology rather than being an LCA study
142	Simulation of Environmental Impact Scores within the Life Cycle of Mixed Wood Chips from Alternative Short Rotation Coppice Systems in Flanders (Belgium)	N	Attributional LCA methodology
143	Soil Organic Carbon Changes in the Cultivation of Energy Crops: implications for GHG balances and soil quality for use in LCA	N	Attributional LCA methodology
144	Sound Principles and Inconsistencies in the 2012 UK Bioenergy Strategy	N	Not an original LCA study
145	Techno-Economic and Life Cycle Assessment on Lignocellulosic Biomass Thermochemical Conversion Technologies: a review	N	Review of LCA studies
146	The Carbon Neutrality Assumption for Forest Bioenergy: a case study for Northwestern Ontario	N	Country/region out of scope and does not calculate GHG emissions but carbon neutrality and breakeven periods
147	The Climate Effect of Increased Forest Bioenergy Use in Sweden: evaluation at different spatial and temporal scales	Y	
148	The Comparative Life Cycle Assessment of Power Generation from Lignocellulosic Biomass	Y	
149	The Economical and Environmental Performance of Miscanthus and Switchgrass Production and Supply Chains in a European Setting	N	Attributional LCA methodology
150	The Effect of Assessment Scale and Metric Selection on the Greenhouse Gas Benefits of Woody Biomass	N	Only considers CO_2 emissions
151	The Environmental and Economic Sustainability of Potential Bioethanol from Willow in the UK	Y	
152	The Influence of Organic and Inorganic Fertiliser Application Rates on UK Biomass Crop Sustainability	Y	

Ref. No.	Title of Selected LCA Study	Reviewed (Y = Yes, N = No)	Reason for Not Reviewing
153	The Potential Contribution of a Short Rotation Willow Plantation to Mitigate Climate Change	N	Attributional LCA methodology; allocation by economic value
154	The Potential for Short-Rotation Woody Crops to Reduce US CO_2 Emissions	N	Attributional LCA methodology
155	The Potential Role of Forest Management in Swedish Scenarios Towards Climate Neutrality by Mid Century	Y	
156	The UK Solid and Gaseous Biomass Carbon Calculator	N	Attributional LCA methodology
157	Understanding the Carbon and Greenhouse Gas Balance of UK Forests	Y	
158	Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy	N	Attributional LCA methodology; allocation by energy content
159	Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: Well-to-Tank Appendix 4 – version 4.0 description, results and pathway input data per pathway	Y	
160	Willow Short-Rotation Coppice in Multiple Land-Use Systems: evaluation of four combination options in the Dutch context	N	Climate impact not evaluated
161	Yield and Spatial Supply of Bioenergy Poplar and Willow Short-Rotation Coppice in the UK	N	Climate impact not evaluated

APPENDIX E: TEMPLATE FOR FULL LCA REVIEW SUMMARY SHEET

Instructions for the completion of a Review Summary Sheet are provided in *italics*.

Details of LCA Study/Calculation Tool/Database/Review: *Record the title, author(s), publishing details and DOI.*
Stated LCA Purpose, and Defined LCA Goal and Scope: *If explicitly documented, record any of these aspects. If not documented, record that they were missing and, if possible, indicate the likely implicit LCA purpose.*
Technological Coverage: *Provide a very brief summary of the types of technology covered, such as the source and nature of a biomass feedstock, its processing and final conversion depending on the bioenergy value chain(s) or other technologies relevant to the bioenergy value chain scoping list.*
Technological Assumptions: *Provide a very brief summary of any key assumptions made about the technology and its scale of application, such as a single biomass conversion plant with a quoted output or the national supply of biomass feedstock or subsequent bioenergy.*
Methodological Assumptions: *Provide a very brief summary of any stated assumptions about how LCA calculations were performed, especially the extent of spatial and temporal system boundaries; the inclusion or exclusion of GHG emissions associated with plant construction and machinery manufacture, and maintenance; and the values of any Global Warming Potentials applied in deriving total GHG emissions. For LCA studies involving forest biomass feedstocks, record whether (and, if possible, how, in very concise terms) net changes in biogenic carbon stocks are evaluated. For LCA studies involving energy crops, including short rotation forests, short rotation coppice and miscanthus, record whether (and, if possible, how, in very concise terms) indirect land use change was taken into account. For LCA studies involving wheat straw, record whether (and, if possible, how, in very concise terms) the counterfactual to its removal for fuel use was evaluated.*
Overview of Transparency: *Specify the transparency of all the calculations performed, in which:* • *"low transparency" indicates very little or no access to all the calculations, or no access to those calculations that make major contributions to total GHG emissions,* • *"moderate transparency" indicates some access to those calculations that make major contributions to total GHG emissions, and* • *"high transparency" indicates access to all calculations or access to all those calculations that make major contributions to total GHG emissions.*
Reviewer: *Name of person recording this information*

APPENDIX F: FULL LCA REVIEW SUMMARY SHEETS

Ref. No. 9: Details of LCA Study/Calculation Tool/Database/Review: BIOGRACE II: harmonised greenhouse gas calculations for electricity, heating and cooling from biomass - version 3, Final Publishable Report, User Manual, Methodological Background Document, Calculation Rules and Additional Standard Values, 2015.
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated aims and objectives of this tool was to "harmonise calculations of GHG emissions for electricity, heat and cooling from biomass across the European Union in order to: (a) develop and disseminate a GHG Excel tool for electricity and heat from biomass, (b) convince policy-makers from 6 European Union Member States to decide to harmonise greenhouse gas emissions calculations, and (c) cause that companies (including verifiers and owners of voluntary sustainability schemes) give feedback on the Excel tool and use it". The LCA goal and scope are effectively established by compliance with the methodology set out in "Report from the Commission to the Council and the European Parliament on Sustainability Requirements for the Use of Solid and Gaseous Biomass Sources in Electricity, Heating and Cooling" SEC (2010) 65 and 66, European Commission (EC), Brussels, Belgium, June 2010 and subsequent clarifying documentation.
Technological Coverage: A wide range of EU and imported biomass feedstock sources and types are specified, of which only wood pellets from poplar short rotation coppice (SRC) is completely within the current scope of this project. The tool focuses on the provision of biomass feedstocks to conversion plants for which users must enter their own data.
Technological Assumptions: Default data are embedded within the tool for all chains for providing biomass feedstocks to plants. For SRC, the default yield is 20 t/ha/a at 50% moisture content.
Methodological Assumptions: The main functional unit is 1 MJ of energy in biomass feedstocks delivered to the plant (although results are derived for 1 MJ of heat and/or electricity produced at the plant). Based on the methodology specified by the EC sustainability criteria, a hybrid LCA methodology is adopted. This includes elements of attributional LCA methodology for certain biomass feedstocks (such as allocation of all GHG emissions from cultivation and harvesting to forest stemwood and none to forest residues; no reference system for straw removal; and allocation by exergy for combined heat and power generation). Carbon stock changes in forests are not taken into account. Direct land use change is accommodated but not indirect land use change. GHG emissions associated with manufacture and maintenance of plant, machinery and vehicles are not included. GHG emissions are disaggregated into CO_2, CH_4 and N_2O. The default Global Warming Potentials are 25 kg CO_2eq/kg CH_4 and 298 kg CO_2q/kg N_2O. All values, including defaults, in the tool.
Overview of Transparency: High transparency (all calculations, assumptions and sources of data in the workbooks which form the tool are accessible)
Reviewer: Nigel Mortimer
Headline Results: Results that are specifically within scope consist of GHG emissions for the supply of SRC wood pellets at 158 kg CO_2eq/MWh of heat available.

Ref. No. 10: Details of LCA Study/Calculation Tool/Database/Review: Biomass Emissions And Counterfactual (BEAC) Model, by A. L. Stephenson, Department of Energy and Climate Change, London, United Kingdom, 9 January 2015.
Stated LCA Purpose, and Defined LCA Goal and Scope: The purpose of the BEAC model is to answer a number of questions including: "what are the greenhouse gas impacts of different bioenergy pathways, considering the emissions associated with growing, processing and transporting the biomass, as well as the consequences of 'counterfactual' land-uses?" There is no further definition of the LCA goal or the LCA scope other than specification of the bioenergy pathways considered.
Technological Coverage: It is possible to evaluate an extremely large number of bioenergy pathways with this tool. In terms of the current scope of this project, relevant biomass sources include wood pellets from long and short rotation forests in the United Kingdom; Pacific, Interior and boreal North Canada; and South and North West United States of America; wood pellets from short rotation coppice in the United Kingdom; and Miscanthus pellets from the United Kingdom. Relevant biomass conversion technologies include heat from boilers; combined heat and power plants; dedicated power only plants without and with carbon capture and storage; and ethanol from lignocellulosic processing.
Technological Assumptions: Information on all technological assumptions are provided in this tool which consists of an MS Excel workbook. Default values of data are embedded in the tool are too extensive to list here. However, the primary means of operating the tool is to specify scenarios, based on biomass sources, their management and counterfactuals.
Methodological Assumptions: Although one of the main outputs from this tool is GHG emissions per ha/a, in terms of the current scope of this project, results can be generated for 1 MWh energy output at the biomass plant. The tool adopts consequential LCA methodology which takes into account carbon stock changes, direct land use changes, land use displacement (in effect, indirect land use change), management practices and counterfactuals (especially in the case of products previously used for other [usually material] purpose being diverted to bioenergy use). Available time horizons consist of 20, 40 and 100 years. GHG emissions associated with the manufacture of plant, machinery and vehicles are not included. Results are aggregated into total GHG emissions using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O.
Overview of Transparency: High transparency
Reviewer: Nigel Mortimer
Headline Results: The user of this tool can generate an extremely large number of results and these cannot be summarised concisely here. However, one example is the 5 kg CO_2eq/MWh of delivered electricity (at the power plant) generated from wood pellets derived from sawmill residues in South United States of America (with no drying and with a counterfactual of burning for sawmill residues). Headline results from "Life Cycle Impacts of Biomass Electricity in 2020: scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK" are provided here in the relevant review.

Ref. No. 11: Details of LCA Study/Calculation Tool/Database/Review: Biomass Environmental Assessment Tool - version 2 ($BEAT_2$); and User Guide, AEA Energy and Environment, Issue 2, May 2008.
Stated LCA Purpose, and Defined LCA Goal and Scope: One of the aims of this tool is "to provide both Defra and the Environment Agency staff with the means of assessing biomass schemes by providing a comparison of the greenhouse gas emissions from proposed (biomass) plant." The tool was provided to assist policy-makers, planners and developers to determine the GHG emissions associated with proposed schemes. The LCA goal is not defined as such and the defined LCA scope only specifies the bioenergy value chains covered.
Technological Coverage: In total, 110 bioenergy value chains, then considered appropriate (current and near-term future) for the UK using UK and imported biomass feedstocks, were covered in this tool. However, in relation to the LCA goal and scope of this project, only the following bioenergy value chains are relevant: poplar and willow short rotation coppice (SRC) providing wood pellets for domestic and industrial heating by combustion, and miscanthus providing pellets for electricity generation by combustion.
Technological Assumptions: Default data are embedded within the tool for all bioenergy value chains. For SRC, the default yield is 14 t/ha/a at 50% moisture content. Both cut-and-chip harvesting (option a) and stick harvesting with separate chipping (option b) are considered. The Miscanthus default yield is 18 t/ha/a at 30% moisture content. The default input heat ratings and thermal efficiencies for domestic and industrial wood pellet-fired boilers 30 kW and 800 kW, respectively, and 89% and 80%, respectively. For the Miscanthus pellet-fired power only plant, the default output power rating is 10 MW and the default thermal efficiency is 25%.
Methodological Assumptions: The functional units include 1 MWh of heat or electricity at the plant. Overall, the tool adopts a mixture of consequential LCA (CLCA) and attributional LCA (ALCA) methodologies (for example, forest residue and wheat straw provision incorporates allocation by price, and evaluation of combined heat and power used weighting between heat and power). However, the chains with SRC pellet-fired heating and Miscanthus pellet-fired electricity only generation are consistent with CLCA methodology. In particular, reference systems of mown fallow set-aside (probably no longer appropriate) are assumed for SRC and Miscanthus plantations with no account for direct or indirect land use change. GHG emissions associated with manufacture and maintenance of plant, machinery and vehicles are included. GHG emissions are disaggregated into CO_2, CH_4 and N_2O. The default Global Warming Potentials are 23 kg CO_2eq/kg CH_4 and 296 kg CO_2eq/kg N_2O. All values, including defaults, can be changed at different levels of user access to the tool and its individual MS Excel workbooks.
Overview of Transparency: High transparency (all calculations, assumptions and sources of data in the workbooks which form the tool are accessible)
Reviewer: Nigel Mortimer
Headline Results: Results that are specifically within scope consist of GHG emissions for domestic heating with combustion of SRC wood pellets at 131 ± 16 kg CO_2eq/MWh of heat (option a) and 131 ± 16 kg CO_2eq/MWh of heat (option b); industrial heating with combustion of SRC wood pellets at 136 ± 8 kg CO_2eq/MWh of heat (option a) and 136 ± 8 kg CO_2eq/MWh of heat (option b); and power only generation by combustion of Miscanthus pellets of 282 ± 25 kg CO_2eq/MWh of electricity.

Ref. No. 12: Details of LCA Study/Calculation Tool/Database/Review: Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration Comparing the Energy Balance, Greenhouse Gas Emissions and Economics, by P. Spath and M. Mann, Report No. BB04.4010; National Renewable Energy Laboratory: Golden, CO, USA, 2004. DOI: n/a
Stated LCA Purpose, and Defined LCA Goal and Scope: National application of carbon capture and storage (CCS) technology to power generators in the US as a means of reducing national emissions of GHG. Cradle to grave LCA of coal, natural gas and biomass based power generation systems with and without CO_2 sequestration. The study compares the global warming potential and the energy balance of these systems to investigate the consequences related to the introduction of CCS on GHG emissions and resource efficiency.
Technological Coverage: This analysis examined power generation for two fossil-based technologies, coal-fired power production and natural gas combined-cycle (NGCC), and two biomass technologies, a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop, and a direct-fired biomass power plant using biomass residue as well as a biomass residue/coal co-fired system.
Technological Assumptions: For the cases where CO_2 is sequestered, the CO_2 is captured via a mono-ethanolamine (MEA) system, compressed, transported via pipeline, and sequestered in underground storage such as a gas field, oil field, or aquifer. The power generation capacity of each system examined was kept constant at 600 MW. For the biomass power systems, it was assumed that several small plants are needed to achieve 600 MW of electric capacity. This is because large transportation distances make biomass power uneconomical at large scales. For the systems that sequester CO_2, lost generation capacity was replaced by adding extra capacity from a natural gas combined-cycle system. Storage of carbon dioxide assumed to be 800m underground, compressor stations situated at 300km intervals and mid US electricity mix for recompression.
Methodological Assumptions: The functional unit is CO_2e/kWh electricity produced. A cradle to grave assessment. Each system includes the upstream processes necessary for feedstock procurement (mining coal, extracting natural gas, growing dedicated biomass, collecting residue biomass), transportation, and any construction of equipment and pipelines. Assumptions regarding all aspects are documented and referenced. Timescale is up to 7 years from publication. Estimated CO_2, CH_4 and N_2O emissions are aggregated suing Global Warming Potentials of 21 kg CO_2eq/kg CH_4 and 310 kg CO_2eq/kg N_2O. A biomass co-firing rate of 15% by heat input was used for the biomass residue/coal fired plant. The biomass is assumed to be produced by urban sources and diverted from normal landfilling and mulching operations. As biomass is diverted from its normal routes of disposal, CH_4 and CO_2 that normally would be produced through decomposition are considered to be avoided. These avoided emissions are taken as a credit in the GHG emissions inventory for the co-fired power generation system. This is also assumed for the direct biomass residue fired plant. Carbon stock changes and land use change are not considered for the biomass-fired IGCC system using a biomass energy crop. Counterfactuals were not considered.
Overview of Transparency: Moderate transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found. Plant with capture and compression: 100 kg CO_2eq/MWh. Pipeline construction: 1 kg CO_2eq/MWh. Recompression: 300km 2 kg CO_2eq/MWh, 600 km 4 kg CO_2eq/MWh, 900 km 5 kg CO_2eq/MWh, 1800 km 11 kg CO_2eq/MWh.

Ref. No. 17: Details of LCA Study/Calculation Tool/Database/Review: Carbon and Energy Balances for a Range of Biofuels Options, by M. A. Elsayed, R. Matthews and N. D. Mortimer, DTI Project No. B/B6/00784/REP, URN 03/836, Resources Research Unit, Sheffield, United Kingdom, 2003. DOI: N/A
Stated LCA Purpose, and Defined LCA Goal and Scope: The aim of the project was "to produce a set of baseline energy and carbon (GHG emissions) balances for a range of electricity, heat and transport fuel production systems based on biomass feedstocks". The LCA goal and scope are not defined.
Technological Coverage: 15 different bioenergy/biofuel pathways (assumed in UK) were analysed, 8 of which were of relevance to this project, and included: large scale combined heat and power (CHP) (combustion) from forestry residue wood chip; small scale CHP (gasification) from short rotation coppice (SRC) wood chip; large scale electricity (combustion) from Miscanthus; large scale electricity (gasification) from forestry residue wood chip; large scale electricity (gasification) from SRC wood chip; ethanol from lignocellulosic processing; small scale heat (combustion) from forestry residue wood chip, and; small scale heat (combustion) from woodland residue wood chip.
Technological Assumptions: CHP (wood chip combustion) based on Masnedo co-firing (straw and wood) plant in Denmark, consuming 32,086 t/a wood chip (25% moisture), with net electrical output rating of 8.2 MW, heat output of 20.8 MW (steam at 522°C and 92 bar) and 55% load factor. CHP (wood chip gasification) based on a modular plant, consuming 17,518 t/a of wood chip (37% moisture), with net electrical output of 2.5 MW, heat output of 6.21 MW (hot water at 90°C) and 55% load factor. Electricity generation (wood chip combustion) based on a simulated plant, consuming 132,808 t/a wood chip (25% moisture), with net electrical output of 20 MW and 65% load factor. Electricity generation (wood chip gasification) based on simulated plant (from extrapolation of a smaller plant), consuming 129,080 t/a wood chip (25% moisture), with net electrical output of 30 MW and 85% load factor. Electricity generation (straw combustion) based on a plant, consuming 112,741 t/a straw (15% moisture), with net electrical output of 20 MW and 65% load factor. Heat production (wood chip combustion) based on plant consuming 89 t/a wood chip (25% moisture), with net heat output of 50 kW and 50% load factor. Lignocellulosic processing of straw based on plant producing 40,000 t/a of ethanol (no input rate or process route given).
Methodological Assumptions: Functional units are 1 oven dry t wood chip (25% moisture), 1 GJ elect., 1 GJ heat and 1 t ethanol. Diverse methodologies were used for different pathways, mostly based upon attributional LCA (e.g. emission allocation for forestry productions based on economic value; no land counterfactual for Miscanthus; etc.). However, SRC and straw pathways used co-product substitution, where appropriate, and reference systems for land use, thereby adopting consequential LCA. The scope covered cradle to final conversion with all GHG emissions disaggregated. GHG emissions for machinery manufacture, maintenance and decommissioning are included (sometimes derived from cost data). Straw incorporation and fallow set-aside (for SRC) are used as land use reference systems. Global Warming Potentials are 24.5 kg CO_2eq/kg CH_4 and 320 kg CO_2eq/kg N_2O. SRC production covers combined harvesting and chipping, or harvesting and baling. For lignocellulosic processing, lignin and non-fermentables provide heat and power, excess electricity (508 kWh/t ethanol) displaces grid supply (credit) and acetic acid (115 kg/t ethanol) is co-produced (credit).
Overview of Transparency: High transparency
Reviewer: Michael Goldsworthy
Headline results: The ranges of GHG emissions for SRC wood chip combustion for electricity = 72 – 101 kg CO_2eq/MWh elect.; SRC wood chip gasification for electricity = 22 –32 kg CO_2eq/MWh elect.; SRC wood chip gasification for CHP = 11 – 22 kg CO_2eq/MWh energy; straw combustion for electricity = 223 - 252 kg CO_2eq/MWh elect.; and lignocellulosic processing of straw = 40 – 54 kg CO_2eq/MWh ethanol.

Ref. No. 21: Details of LCA Study/Calculation Tool/Database/Review: Carbon Impacts of Biomass Consumed in the EU: quantitative assessment, by R. Matthews, N. Mortimer, J.P. Lesschen, T.J. Lindroos, L. Sokka, A. Morris, P. Henshall, C. Hatto, O. Mwabonje, J. Rix, E. Mackie and M. Sayce, Final Report for Project: DG ENER/C1/427, Forest Research, Farnham, United Kingdom, 2015.
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose and defined LCA goal was "to deliver a qualitative and quantitative assessment of the direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU (European Union) under a number of scenarios focussing on the period to 2030, but also extended to 2050, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions". The required LCA scope was to include changes in carbon stocks (trees, litter and soil) and sequestration in forests, and on agricultural land, due to bioenergy use; indirect land use changes for energy crops; counterfactuals of product displacement; and "direct" and "indirect" GHG emissions of relevant bioenergy process chains.
Technological Coverage: Forest management, agricultural land management and land use (change) to supply specified levels of bioenergy are covered. Multiple feedstocks, including, in terms of the current scope, Miscanthus, straw and wood pellets, and biomass conversion technologies, including heat production, electricity and combined heat and power generation, and lignocellulosic processing for ethanol. Material wood products, co-produced with the energy products, and their counterfactuals are also included.
Technological Assumptions: The focus was on solid and gaseous biomass use for heating, electricity and cooling at EU scale. Changes in the whole EU energy system in relation to energy sources and conversion technologies associated with each of the scenarios, including the application of carbon capture and storage were considered. Some of the assumptions are summarised in the report and all details for the bioenergy value chains are documented in the supporting MS Excel workbooks (provided to the European Commission's Directorate-General for Energy as the project client).
Methodological Assumptions: The functional unit is, effectively, the EU in any given future year under specified scenarios, in relation to its contribution to global GHG emissions. Consequential LCA methodology, consistent with this, was applied to evaluate all relevant GHG emissions including those associated with carbon stock changes in forests; with land use changes for energy crops; and with plant construction, machinery manufacture and maintenance. Results were based on estimated CO_2, CH_4 and N_2O emissions which are aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O. LCA was conducted to support the necessary modelling. Scenarios specified levels of bioenergy use and biomass feedstocks involved over the period from 2010 to 2050. Changes in the EU energy system, consistent with 2013 EU PRIMES scenarios, were estimated with the VTT-TIAM model. Biogenic carbon stock changes in EU and other forests supplying biomass feedstocks were evaluated using the CARBINE model. For agricultural biomass sources and energy crops, biogenic carbon stocks were evaluated using the MITERRA-Europe model. Agricultural biomass supply, deployment of energy crops and afforestation activities were constrained to avoid risks of indirect land use change.
Overview of Transparency: Moderate (with access to report only). High transparency (with access to models and workbooks)
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains. Results are presented as global impacts on GHG emissions for each of the scenarios.

Ref. No. 22: Details of LCA Study/Calculation Tool/Database/Review: Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: energy crops, by J. Wiltshire and R. Hughes, Final report for the Department of Energy and Climate Change Project TRN 242/08/2011, London, United Kingdom, December 2011.
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to analyse "the carbon impacts of growing and using a selection of energy crops" for the United Kingdom, and then to compare "these impacts with the carbon impacts associated with the most likely alternative land uses". Although there was no further defined LCA goal and scope, the calculations are consistent with consequential LCA methodology for the energy crops considered.
Technological Coverage: Production of Miscanthus bales, chips and pellets; wheat straw bales; and wood chips and pellets from willow short rotation coppice (SRC) for domestic, commercial and industrial heating (by combustion) plants; combined heat and power (CHP) generation (by combustion) plants; and electricity generation (by combustion) in co-fired and dedicated plants in the United Kingdom.
Technological Assumptions: The ranges of yields were, for Miscanthus = 14.3 – 17.1 t/ha/a at 30% moisture content; for willow SRC = 20.0 - 23.4 t/ha/a at 50% moisture content; and for wheat straw = 1.9 – 4.2 t/ha/a at 25% moisture content. Energy crops were dried by either natural means or diesel fuel heating. Round trip road transport distances ranged from 100 km to 600 km. The range of thermal efficiencies, for domestic heating plants = 90% - 94%; for commercial and industrial heating plants = 88% - 90%; for CHP plants = 54% - 88% with a heat to power ratio of 2.5:1; for co-fired power only plants = 30% - 36%; and for dedicated power only plants = 25% - 36%.
Methodological Assumptions: The functional units were 1 ha/a of land and 1 MWh of energy output at the plants. Consequential LCA methodology was adopted with calculations for separate CO_2, CH_4 and N_2O emissions performed with suitably specified Biomass Environmental Assessment Tool ($BEAT_2$) workbooks. GHG emissions associated with construction of all plants, excluding existing co-firing power only plants, were taken into account. GHG emissions associated with manufacture of all machinery and maintenance of all plants and machinery were included. A reference system, consisting of straw incorporation, was applied to wheat straw provision. Results for Miscanthus and willow SRC were generated without direct land use change (dLUC), and without and with alternative land uses. GHG emissions were aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O.
Overview of Transparency: Low transparency (without supporting workbooks). High transparency (with supporting workbooks)
Reviewer: Nigel Mortimer
Headline Results: The main results were expressed per ha/a of land used for energy crop production. However, results were also provided per unit of energy output from the specified plants. In terms of the current scope, the ranges of GHG emissions, without dLUC and alternative land use were, for Miscanthus pellet commercial and industrial heating = 83 – 169 kg CO_2eq/MWh, CHP = 97 – 202 kg CO_2eq/MWh, co-firing power only = 202 – 331 kg CO_2eq/MWh and dedicated power only = 209 – 389 kg CO_2eq/MWh; and for willow SRC pellet domestic heating = 40 – 151 kg CO_2eq/MWh, commercial and industrial heating = 32 – 140 kg CO_2eq/MWh, co-firing power only = 61 – 479 kg CO_2eq/MWh and dedicated power only = 72 – 461 kg CO_2eq/MWh

Ref. No. 23: Details of LCA Study/Calculation Tool/Database/Review: Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: forests, by R. Matthews, N. Mortimer, E. Mackie, C. Hatto, A. Evans, O. Mwabonje, T. Randle, W. Rolls, M. Sayce and I. Tubby, Project TRN 242/08/2011, Department of Energy and Climate Change, London, United Kingdom, revised and updated 2014.
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose is to assess the potential carbon (GHG) impacts of using different types of bioenergy feedstocks to displace fossil fuels, against the role of forests stocks as carbon stores; and of diverting woody biomass feedstocks from a range of other uses (such as construction) and from end-of-life disposal to bioenergy.
Technological Coverage: Multiple feedstocks were covered, including wood chips, logs, wood pellets and briquettes, from forestry in the UK, represented as three key forestry systems (managed conifer, managed broadleaf and previously unmanaged broadleaf forests). Biomass conversion technologies included small scale heat, power only and combined heat and power (CHP). The focus in this study was as much on the use of wood for the manufacture of material products as on the use of wood for energy.
Technological Assumptions: Biomass supply from forests is considered at the scale of theoretical 1 ha stands of trees, and the use of harvested biomass is then tracked through to end use. Woody biomass is used as energy or as materials, substituting for a range of counterfactuals. Assumptions about forests are summarised in the report withal details being incorporated in MS Excel workbooks to DECC as the project client.
Methodological Assumptions: The functional unit was a theoretical 1 ha stand of trees. Consequential LCA methodology was adopted for consistency with the stated purposes. All relevant GHG emissions were evaluated including those associated with net carbon stock changes in forest; forest management; manufacture and maintenance of plant and machinery; and counterfactual displacement (wood products, bioenergy and fossil fuels). Results were based on estimated CO_2, CH_4 and N_2O emissions which are aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O. The CSORT model was used to simulate biomass carbon (C) flows within forests (annual changes in C stocks in trees litter and soil); the supply of biomass feedstocks for materials and/or bioenergy; and GHG emissions from forestry management, harvesting and extraction. GHG emissions associated with biomass product processing; end use applications; end-of-life disposal (where relevant); and their counterfactuals were calculated using bespoke workbooks. A range of time horizons (20, 40 and 100 years) and fossil fuel displacement options (coal, oil and natural gas) were considered. Results were produced for 282 scenarios for conifer forests, 214 scenarios for managed broadleaf forests and 214 scenarios for restored broadleaf forest, and compared with results for baseline scenarios with no forest harvesting.
Overview of Transparency: Low transparency (with access to report only). High transparency (with access to models and workbooks)
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains. Results are presented for a functional unit of 1 ha of forest for which there were multiple biomass products and bioenergy outputs depending on specific scenarios.

Ref. No. 26: Details of LCA Study/Calculation Tool/Database/Review: Carbon Savings with Transatlantic Trade in Pellets: accounting for market-driven effects, by W. Wang, P. Dwivedi, R. Abt and M. Khanna, Environmental Research Letters, Vol. 10, No. 114019. DOI: 10.1088/1748-9326/10/11/114019
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose of this paper is to calculate the GHG emissions associated with wood pellets, exported from the USA, using either forest biomass only or forest and agricultural biomass combined.
Technological Coverage: Pellets from forestry wood products and from energy crops (Miscanthus and switchgrass) and agricultural residues (corn stover).
Technological Assumptions: No technological details of the bioenergy value chains are presented in the paper.
Methodological Assumptions: The paper addresses major considerations for the evaluation of GHG emissions associated with pellets exported from the USA although it is not, as such, an LCA study. This is achieved using a generalised modelling approach which incorporates the results of specific LCA studies, for which references are provided. However, no details of the methodologies used in these LCA studies are provided so it is not possible to determine whether they have been applied consistently without extensive examination of the original sources. In general, it would appear that consequential LCA methodology has been adopted as counterfactuals are addressed. Carbon stock changes in forests (standing timber, decaying timber and soil), and carbon sequestration and soil N_2O emissions from land used for growing agricultural biomass are taken into account. Quoted GHG emissions associated with wood pellet production range from 41 kg CO_2eq/MWh (using bark as a fuel for drying?) to 184 kg CO_2eq/MWh (using diesel fuel for drying). Additionally, it is noted that CH_4 emissions from storage range from 184 kg CO_2eq/MWh to 731 kg CO_2eq/MWh for forest residues and range from 356 kg CO_2eq/MWh to 882 kg CO_2eq/MWh for sawmill residues. An average estimate of 96 kg CO_2eq/MWh is adopted assuming industry practice of using bark as a fuel for drying and short storage period which reduce CH_4 emissions. It would appear than the GHG emissions associated with the manufacture of machinery and the construction of plants have not been included. The modelling considers 4 different scenarios based on combinations of low and high demand, and forest biomass only and forest and agricultural biomass supply.
Overview of Transparency: Low transparency
Reviewer: Nigel Mortimer
Headline Results: The estimated total GHG emissions associated with the generation of electricity (probably by co-firing) in the UK using wood pellets derived from forests in the USA range from 238 kg CO_2eq/MWh to 279 kg CO_2eq/MWh.

Ref. No. 30: Details of LCA Study/Calculation Tool/Database/Review: Comparative Impact Assessment of CCS Portfolio: Life Cycle Perspective, by B. Singh, A. H. Strømman and E.G. Hertwich, Energy Procedia, Vol. 4, pp. 2486 – 2493, 2011. DOI: 10.1016/j.egypro.2011.02.144.
Stated LCA Purpose, and Defined LCA Goal and Scope: This study evaluates and compares the life cycle impacts of various coal and natural gas electricity generation chains with and without carbon dioxide capture, transport and storage. Results are used to identify the target sites for technology development in the chain to minimise the adverse impacts and the analysis discloses the environmental trade-offs and benefits explicit due to carbon capture and storage (CCS) with different technologies.
Technological Coverage: Natural gas and coal power generation with CCS using three capture techniques: Post-combustion capture with amine-based absorption, pre-combustion capture with selexol absorption and oxyfuel-combustion capture by condensation of flue gas from oxygen fired fuel combustion are considered. Captured CO_2 is then transported by pipeline or ship and tankers; and stored in geological storage, depleted oil and gas fields, or used for enhanced oil recovery (EOR).
Technological Assumptions: All power plants are assumed to have 400MW net electricity output. Net efficiencies of 43.4% and 58.1% are assumed for the coal and natural gas power plant respectively. For the system with CO_2 capture, 90% CO_2 is assumed to be captured. Efficiency losses assumed for post-combustion coal 10.2%, natural gas 8%, pre-combustion IGCC 6.5%, natural gas 7.9%, oxy-fuel coal 11.3%. All assume 500km transport distance. The energy requirements for the capture process are for regeneration of solvent, solvent pumps, flue gas blower, cooling water pumps and carbon dioxide compression. A solvent make-up of 1.6 kg MEA/tCO_2 is needed due to its loss via vaporisation and formation of degradation products. Air emissions and degradation waste from capture process are quantified based on literature. The capture process also removes SO_2, NO_2 and particulates.
Methodological Assumptions: The functional unit is 1 kWh of net electricity produced. System boundaries: foreground system consists of fuel combustion in power plant, CO_2 capture, transport and storage. Other emissions arising from upstream, e.g., the production of fuel (coal/natural gas), absorbent etc. and the emissions from downstream, e.g., waste treatment and disposal are also included in the assessment and infrastructure for power plant and capture unit is accounted as capital investment and attributed to various sectors in US I/O 1998 database. The detailed unit process level information obtained from process model data and the Ecoinvent v2 database is incorporated into the input-output model of the background US economy. The characterisation factors from ReCiPe 2008 method v1.02 are used to estimate the potential environmental impacts of the emissions incurred. A factor of 0.24 1,4-DCB kg eq/kg for human toxicity potential of monoethanolamine (MEA) is used. The environmental impacts are categorized into different mid-point indicators: global warming potential (GWP), terrestrial acidification potential (TAP), fresh water eutrophication potential (FEP), human toxicity potential (HTP), terrestrial ecotoxicity potential (TETP), fresh water ecotoxicity potential (FETP), and marine ecotoxicity potential (METP). Allocation procedures are not clear.
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found.

Ref. No. 32: Details of LCA Study/Calculation Tool/Database/Review: Comparative Life Cycle Environmental Assessment of CCS Technologies, by B. Singh, A. H. Strømman and E. G. Hertwich, International Journal of Greenhouse Gas Control, Vol. 5, Issue No. 4, pp. 911 – 921, July 2011. DOI: 10.1016/j.ijggc.2011.03.012
Stated LCA Purpose, and Defined LCA Goal and Scope: A comparison and evaluation of the life cycle impacts of various coal and electricity generation chains, with and without carbon capture, transport and storage (implicit).
Technological Coverage: Integrated coal gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) power plants, with and without carbon capture and storage (CCS), with world average and best available technology (BAT) net electrical efficiencies considered. Pre-combustion (selexol) and post-combustion (MEA) capture technologies, pipeline transport and under seabed geological storage.
Technological Assumptions: Single electricity generating plants with 400MW net electrical output. Projected, world average and BAT net electrical efficiencies are considered. Extensive details are provided of the technological assumptions. Post capture efficiency 90% for gas and coal, energy penalty coal 10.2% and natural gas 8%. Pre-capture efficiency IGCC 90%, energy penalty 6.5%. Pre-capture efficiency natural gas 85%, energy penalty 7.9%. Oxy-fuel capture efficiency coal 90%, energy penalty 8.8%. Oxy-fuel capture efficiency gas 96%, energy penalty 11.3%
Methodological Assumptions: Hybrid lifecycle assessment using unit process data derived from process model data and Ecoinvent v.2, background data from US economic input-output data, characterisation factors from ReCiPe 2008 v.1.02. A range of environmental impacts are considered including global warming potential. The systems boundary for the foreground system is clearly presented. The function of the product system is power generation and the functional unit 1 kWh of net electricity produced. The foreground system consists of fuel combustion in the power plant, the capture process, transport and storage of carbon dioxide. Other emissions arising from upstream, e.g., the production of fuel (coal/natural gas), absorbent etc. and the emissions from downstream, e.g., waste treatment and disposal are also included in the assessment. Infrastructure for the power plant and capture unit is accounted as capital investment attributed to various sectors in US I/O 1998 database. Allocation procedures are not clear.
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found

Ref. No. 34: Details of LCA Study/Calculation Tool/Database/Review: Comparison of Carbon Capture and Storage with Renewable Energy Technologies Regarding Structural, Economic, and Ecological Aspects in Germany, by P. Viebahn, J. Nitsch, M. Fischedick, A. Esken, D. Schüwer, N. Supersberger, U. Zuberbühler and O. Edenhofer, International Journal of Greenhouse Gas Control, Vol. 1, Issue No. 1, pp. 121 – 133, April 2007. DOI: 10.1016/51750-5836(07)00024-2
Stated LCA Purpose, and Defined LCA Goal and Scope: Integrated assessment in the form of an LCA and a cost assessment combined with a systematic comparison with renewable energies regarding future conditions in the power plant market for the situation in Germany. The intended application being to assess carbon capture and storage (CCS) technologies and renewable energy in a prospective life cycle 2020 with the aim to inform choices for reduction in GHG emissions.
Technological Coverage: Fossil fuel power generation (pulverised hard coal, integrated coal gasification combined cycle and natural gas combined cycle), CCS post-combustion via MEA, pre-combustion via rectisol and oxy-fuel combustion. Geological storage of the carbon dioxide in depleted gas field. The reference renewable technologies are solar thermal and wind power.
Technological Assumptions: National application in Germany as part of meeting GHG reduction commitments and targets. Considers 700MW power plants in western Germany. Compressed carbon dioxide transported via 300km pipeline to onshore depleted gas field.
Methodological Assumptions: The functional unit is 1 kWh delivered to the power grid. It is a prospective assessment and the reference year is 2020 which is when the first commercial plant is expected to be operational. The assessment is cradle to grave, considers extraction of raw materials, their processing and transport, manufacturing of product, use, dismantling and disposal. Covers, GHG, resource depletion, acidic and toxic gases and wastes. LCA data for pipelines etc. are taken from the Umberto database. There is minimal information on LCA related calculation procedures and allocation method not mentioned.
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: Greenhouse gas intensity of CCS (kg CO_2eq/kg stored CO_2): not found. Capture and liquefaction: estimated from graphical data at 16 - 55 kg CO_2eq/MWh depending on fuel type and capture technology.

Ref. No.41: Details of LCA Study/Calculation Tool/Database/Review: ecoinvent version 3, ecoinvent Associates, ecoinvent Centre, Zürich, Switzerland, 2016.
Stated LCA Purpose, and Defined LCA Goal and Scope: This database is normally used in conjunction with SimaPro software with the purpose of undertaking LCA studies, in effect, specified, in terms of goal and scope, by the user. The LCA goal and scope are not defined explicitly as this depends on the particular use of the related LCA software by the user. However, this version of the ecoinvent database offers 3 options of systems models, one of which is consistent with consequential LCA methodology.
Technological Coverage: The only results in the database which are relevant to the current scope appear to be heating from a furnace using wood pellets by combustion. In total, the database contains 12,800 life cycle inventory datasets.
Technological Assumptions: For these particular results, the biomass source for the wood pellets is not known but furnace heating plants (in Europe) are specified with output ratings of 15 kW and 50 kW.
Methodological Assumptions: The functional unit for results in the database are given by specific by units (and geographical area). For these particular results, the functional unit is 1 MJ of heat. For the aggregation of GHG emissions, the Global Warming Potential applied are indicated. Consequential LCA methodology is one option available for preparing results but no further details are published.
Overview of Transparency: Low transparency (without licenced access)
Reviewer: Nigel Mortimer
Headline Results: GHG emissions for wood pellet heating are 15.3 g CO_2e/MJ of heat (15 kW furnace) and 50 kg CO_2eq/MWh of heat (50 kW furnace) based on Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O.

Ref. No. 50: Details of LCA Study/Calculation Tool/Database/Review: Energy Budget and Greenhouse Gas Balance Evaluation of Sustainable Coppice Systems for Electricity Production, by S. Lettens, B. Muys, R. Ceulemans, E. Moons, J. Garcia and P. Coppin, Biomass and Bioenergy Vol. 24, Issue No. 3, pp. 179 – 197, 2003. DOI: 10.1016/S0961-9534(02)00104-6
Stated LCA Purpose, and Defined LCA Goal and Scope: The purpose, goal and scope for the project are not clearly defined. However, the study's objective is to evaluate "the low-input coppice system's ability to efficiently produce bio-energy and to reduce greenhouse gas emissions in comparison to conventional bio-energy crops under Belgium conditions".
Technological Coverage: Three theoretical bio-energy systems were analysed: production of heat and electricity from Miscanthus; production of heat and electricity from SRC willow, and; production of heat and electricity from mixed SRC black alder/sycamore maple/hazel/hornbeam. All systems assumed feedstock cultivation in Belgium. A range of different harvesting scenarios (including cutting and chipping [SRC]; combined cutting and chipping [SRC and Miscanthus]; cutting and baling [Miscanthus]) and conversion systems (fluidised bed gasification [SRC and Miscanthus]; grate combustion [Miscanthus]) were assessed for the bioenergy systems.
Technological Assumptions: One hectare of each system located on sandy loam soil with good water availability over a 100 year time horizon was analysed. Willow is assumed to be coppiced every 3 years and re-established every 25 years. Miscanthus is assumed to be harvested every year and re-established every 10 years. The scale and conversion efficiencies of the conversion systems are not clearly stated.
Methodological Assumptions: ISO standards 14040-14043 were used as a basis for the calculations. CO2Fix was used to estimate net carbon stock changes. The spatial boundary was from cradle-to-plant and included the cultivation, processing and transformation (to heat and electricity) of the bioenergy crop. The temporal boundary of the study is 100 years. The functional unit is one hectare of land used for 100 years. Assumed Global Warming Potentials are not clearly provided. An equivalent amount of heat and electricity produced from fossil fuels [CHP from natural gas and heat from natural gas (boiler)] is used as a reference system, with the spatial boundary covering extraction, processing and transformation. The land used for the bioenergy system is assumed to have previously been fallow, while no extra carbon is assumed to be sequestered in the reference system – only the mean carbon content of the living biomass is therefore included in the counterfactual.
Overview of Transparency: Moderate transparency
Reviewer: Michael Goldsworthy
Headline results: SRC willow gasification (chip harvesting): 1001.1 t CO_2eq/ha/100 years SRC willow gasification (whole stem harvesting): 1059.6 t CO_2eq/ha/100 years SRC willow combustion (chip harvesting): 941.0 t CO_2eq/ha/100 years SRC willow combustion (whole stem harvesting): 996.1 t CO_2eq/ha/100 years SRC mixed coppice gasification (chip harvesting): 521.4 t CO_2eq/ha/100 years SRC mixed coppice gasification (whole stem harvesting): 551.9 t CO_2eq/ha/100 years SRC mixed coppice combustion (chip harvesting): 490.1 t CO_2eq/ha/100 years SRC mixed coppice combustion (whole stem harvesting): 518.8 t CO_2eq/ha/100 years

Ref. No. 55: Details of LCA Study/Calculation Tool/Database/Review: Environmental Impacts of a German CCS Strategy, by P. Markewitz, A. Schreiber, S. Vögele and P. Zapp, Energy Procedia Vol.1, pp. 3763 – 3770, 2009. DOI: 10.1016/j.egypro.2009.02.176
Stated LCA Purpose, and Defined LCA Goal and Scope: To inform policy makers how the replacement of out-dated power plants can be combined with a carbon capture and storage (CCS) strategy, with the aim of reducing GHG emissions from coal fired electricity plants in Germany, and which environmental impacts this will cause now and in the future.
Technological Coverage: CCS post combustion via MEA for hard coal and lignite power plants. Storage method Not clear.
Technological Assumptions: The study examines the power generation of hard coal and lignite-based steam power plants which differ in the year of installation, the conversion efficiency, and in the ability and efficiency to capture CO_2. The plants are characterised either by performance data from existing coal power plants or experts' expectations for the years 2010 and 2020 in Germany. For coal plant, an advanced ultra supercritical (USC, 700°C) power plant is assumed. The lignite plant presents a plant facility with optimized plant engineering, the "BoA concept". The lignite plant4 "BoAPLUS concept" includes pre-drying of lignite by a fluidised bed technology. Energy penalty of fitting with CCS 11.5-14.7%, depending on type of plant.
Methodological Assumptions: Cradle to grave study of fuel (hard coal and lignite) for power generation, with and without CCS. The functional unit is 1 kWh net electricity produced. The assessment includes direct and indirect emissions for coal conditioning, power generation, flue gas cleaning, CO_2 capture and compression, as well as upstream and downstream activities, e.g. the supply of raw and operating materials, waste water treatment or land filling processes. No statement is made regarding the treatment of plant and machinery or allocation processes. The temporal boundary is 1990 to 2030. Characterisation of environmental impacts is based on CML 2001
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found.

Ref. No. 58: Details of LCA Study/Calculation Tool/Database/Review: Environmental Sustainability Analysis of UK Whole-wheat Bioethanol and CHP Systems, by E. Martinez-Hernandez, M. H. Ibrahim, M. Leach, P. Sinclair, G. M. Campbell and J. Sadhukhan, Biomass and Bioenergy, Vol. 50, pp. 52 – 64, 2013. DOI 10.1016/j.biombioe.2013.01.001
Stated LCA Purpose, and Defined LCA Goal and Scope: The goal and scope are not clearly defined. The specific objectives of this study included: (1) assess the environmental impact of the UK wheat ethanol plant as a stand-alone system as well as a whole-wheat system integrated with wheat straw and distillers' dark grain and soluble (DDGS) combined heat and power (CHP) plant using cumulative primary (fossil) energy (CPE), land use, global warming potential in a horizon of 100 years (GWP100), acidification potential (AP), eutrophication potential (EP) and abiotic resources use (ARU) as IC; (2) establish the marginal benefits in terms of GWP100 and primary energy savings, compared to the fossil resources to be replaced, e.g. natural gas for heat and electricity and gasoline for ethanol; and (3) study the relative life cycle inventory (LCI) of DDGS as a commodity to the production of heat and CHP, compared to its usage as animal feed.
Technological Coverage: Wheat cultivated in the UK with the following technological alternatives evaluated: (1) stand-alone ethanol plant to produce wheat ethanol where the residual straw is used in a CHP plant in which heat and power are exported to district and grid systems respectively and DDGS produced is used to produce for animal feed (base case); (2) DDGS as a source of heat for wheat ethanol plant; (3) DDGS as a source of CHP for wheat ethanol plant; (4) straw-based CHP plant supplying energy to ethanol plant and DDGS as an animal feed; and (5) a combination of (2) and (4) wherein selling of DDGS is also considered.
Technological Assumptions: The basis of the conversion plants is 12,000,000 Mg/a of wheat grain and the corresponding amount of excess straw available which is 360,000 Mg/a (after assuming retention of straw cultivated in the soil of 40% to maintain the soil's nutritional value). Plant assumed to run 330 days a year and operate for 10 years. Water recovered from distillation columns is recycled in to the process. For the base case, natural gas is used to supply heat demand. The straw CHP plant has an efficiency of 40%. The CHP plant combusting straw and DDGS under the various alternatives is modelled as an integrated gasification combined cycle (IGCC) plant.
Methodological Assumptions: Methodology is unclear, a single functional unit is not provided and the study quite hard to follow. For the conversion subsystems, the LCI of materials of construction, plant operation and transportation were separately evaluated and combined. For wheat production and cultivation, fossil energy, fertiliser, pesticides and machinery as well as materials of construction were considered as well as emissions from farm to plant. For the ethanol plant, the fossil energy, materials of construction, chemicals, water and enzymes are considered for the hammer milling, liquefaction, saccharification, fermentation, centrifugation, ethanol recovery, and drying. Allocation between wheat grain and straw is by economic values. The wheat ethanol model is a spreadsheet and the results of simulation of biomass IGCC plant for CHP was generated using Aspen Plus. Sensitivity analysis investigated changes to proportion of renewable energy in the electricity mix, percentage renewable fuel in transport fuels and nitrogen fertilisation rates. Global Warming Potentials used (kg CO_2eq/kg): CO_2 = 1, CH_4 = 25, N_2O = 298, and CO = 1.9 (100 year time horizon).
Overview of Transparency: Low Transparency
Reviewer: Paula McNamee
Headline Results: For each scenario (see above); (1) 140 kg CO_2eq/MWh; (2) 291 kg CO_2eq/MWh; (3) 253 kg CO_2eq/MWh; (4) 45 kg CO_2eq/MWh; and (5) 114 kg CO_2eq/MWh.

Ref. No. 62: Details of LCA Study/Calculation Tool/Database/Review: Final Report on Technical Data, Costs, and Life Cycle Inventories of Advanced Fossil Power Generation Systems, by C. Bauer, T. Heck, R. Dones, O. Mayer-Spohn and M. Blesl, Deliverable 7.2, NEEDS (New Energy Externalities Developments for Sustainability), 2008.
Stated LCA Purpose, and Defined LCA Goal and Scope: Fuel cradle to grave life cycle inventories (LCIs) for fossil energy chains for electricity generation and combined heat and power (CHP) plants with current state of the art plants as well as future technologies in order to determine the environmental impact of different power generation technologies and inform decisions on the development of future power generation in Europe. Considers impacts to air, water and land over the next 40 years.
Technological Coverage: Electricity generating technologies considered are lignite, hard coal steam power and integrated gasification combined cycle (IGCC), and natural gas combined cycle. Carbon capture and storage (CCS) technologies include pre, post-capture technologies and oxy-fuel with mineral and geological storage included for future scenarios and based on average conditions in Europe.
Technological Assumptions: It represents a technology roadmap for fossil-fuelled power plants likely to be installed within the next four decades in Europe. The analysis of future technologies includes different concepts for CCS technologies, the three main technologies of CO_2 separation at the power plant, transport of CO_2 by pipeline and storage of CO_2 in generic (non-site-specific) saline aquifers and depleted gas fields. Extensive technical details and assumptions are presented. Efficiency reductions assumed of between 4 and 10% depending on fuel type and technology.
Methodological Assumptions: A series of cradle to grave LCIs of fuel for electricity generation are carried out. The functional unit is 1 kWh of electricity generated in Europe for 2008, 2025 and 2050. Modelling covers the complete fossil energy chains and includes worldwide exploration and production of the fossil energy carriers finally used for electricity generation, their transport to the European power plants as well as operation, construction and dismantling of the plants and disposal of waste. Complete energy chains are split into three sections: fuel supply (upstream chain), power plant infrastructure (construction and dismantling), and power plant operation. In case of energy chains with CCS, transport and storage of CO_2 are further separated. Ecoinvent v1.3 data3 is used for generic background data for LCI modelling and calculation of cumulative LCA results. As the background data represents current conditions which might not be completely applicable for the future time horizons, key aspects of these background processes (e.g. electricity mixes, key materials as well as transport services) are modified according to expected developments in these economic sectors (ESU & IFEU 2008). A full range of impacts to air, water and land are considered. Allocation by exergy for combined heat and power plants.
Overview of Transparency: Moderate transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): Not given. GHG emissions of CO_2 transport and storage on electricity generation are approximately 10 kg CO_2eq/MWh (from graph) based a CO_2 capture efficiency of 90% - 100% (depending on fuel and technology), a transport distance of 200 – 400 km, and a storage depth in depleted gas reservoir of 2500 m.

Ref. No. 63: Details of LCA Study/Calculation Tool/Database/Review: Forest Bioenergy Climate Impact Can Be Improved by Allocating Forest Residue Removal, by A. Repo, R. Känkänen, J.-P. Tuovinen, R. Antikainen, M. Tuomi, P. Vanhala and J. Liski, GCB Bioenergy, Vol. 4, pp. 202 – 212, 2012. DOI: 10.1111/j.1757-1707.2011.01124.x
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose is to estimate the variability of GHG emissions and consequent climate impacts resulting from producing bioenergy from stumps, branches and residual biomass of forest thinning [and felling] operations in Finland, and the contribution of the variability in key factors, i.e. forest residue diameter, tree species, geographical location of the forest biomass removal site and harvesting method, to the emissions and their climate impact.
Technological Coverage: Biomass supply from the forestry system is considered at the scale of representative theoretical areas of Norway spruce, Scots pine and silver birch in either Northern or Southern Finland. The implicit scale is, thus, a notional, representative forest area, or a quantity of biomass supplied by the forest area. Wood chips are produced from either “young stand thinnings” (whole trees or whole stemwood, otherwise thinned to waste) or harvesting residues (branches or stumps, the latter implicitly including major roots. Extraction of harvest residues is assumed to take place at time of thinning or clearfelling in the case of branch wood, and at the time of clearfelling in the case of stumps. The assumed rotation for forest stands appears to be 100 years, but this is not stated explicitly. The study considers the fuel supply chain up to the conversion process. However, the conversion process(es) is not stated explicitly. Conversion involving reasonably large scale heat and electricity generation seems to be considered. It is unclear if the conversion process is represented.
Technological Assumptions: All thinnings or harvest residues extracted are assumed to supply wood chips for ultimate use as bioenergy. Limited information about the representative forest area considered in the study (e.g. tree species composition) is given. The biomass conversion system(s) are not specified, but there is an oblique reference to the combustion of biomass in “power plants”.
Methodological Assumptions: It was intended to include all relevant GHG emissions. However, it is possible that some GHG emissions are not included, e.g. those associated with plant construction, machinery manufacture and maintenance. Carbon sequestration and GHG emissions, i.e., CO_2, N_2O, and CH_4, associated with the extraction, transport and processing of harvest residues and alternative fossil-fuel supply chains, are considered. Fertiliser application in the forest, and the recycling of wood ash, are represented. Total GHG emissions are estimated using Global Warming Potentials of 23 kg CO_2eq/kg CH_4 and 296 kg CO_2eq/kg N_2O. The Yasso07 (litter and) soil carbon model is used to simulate the decay of early thinnings (thinned to waste and left in the forest), branch wood, stumps and roots left in the forest after tree harvesting. The REFUGE model was used to calculate the net impacts of forest bioenergy harvesting on radiative forcing. GHG emissions of counterfactual energy sources (natural gas, heavy fuel oil, coal) are based on national mean emissions factors for Finland.
Overview of Transparency: Moderate transparency
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: For 1, 20, 40 and 100 year time horizons, the approximate annual total GHG emissions from using young thinnings (instead of thinning to waste and leaving them in the forest) are, respectively, 378/378, 259/288, 209/238 and 158/180 kg CO_2eq/MWh (for Southern/Northern Finland). The equivalent results for branch wood are 378/378, 169/194, 130/144 and 76/101 kg CO_2eq/MWh. The equivalent results for stumps (and implicitly major roots) are 378/378, 331/346, 259/288 and 202/216 g CO_2eq/MWh. For comparison, the GHG emissions factors quoted for natural gas, oil and diesel, and coal are, respectively, 281, 320 and 396 kg CO_2eq/MWh.

Ref. No. 64: Details of LCA Study/Calculation Tool/Database/Review: Forest Bioenergy or Forest Carbon? - assessing trade-offs in greenhouse gas mitigation with wood-based fuels, by J. McKechnie, S. Colombo, J. Chen, W. Mabee and H. L. MacLean, Environmental Science and Technology, Vol. 45, pp. 789 - 795, 2011. DOI: 10.1021/es1024004
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to demonstrate the integration of LCA and forest carbon modelling to assess the total GHG emissions of forest-based bioenergy options and to determine how emissions reductions associated with bioenergy are impacted when forest carbon is taken into account. Although not stated clearly at the outset, there was the aim to assess the GHG emissions associated with the use of wood harvested from Canadian forests (residues or whole trees) for bioenergy, compared with the case of leaving the wood in the forest; and it seems that the counterfactual scenario is supposed to represent past and recent practice, and the bioenergy scenario is intended to represent current and potential future developments in practice.
Technological Coverage: Wood pellets produced from two feedstocks: harvest residues (tree tops and branches) and "standing trees" (taken to mean stem biomass of relevant trees harvested for bioenergy), from a forest in the Ontario region of Canada. Biomass conversion technologies consisted of power only generation (co-firing with coal) and ethanol production for transport (E85 blend).
Technological Assumptions: The scale of application was 52,500 km^2 of forest. All additional biomass harvested or extracted in the bioenergy scenarios (electricity generation or ethanol production) is assumed to supply wood pellet mills. Limited supplementary data are given on the forest areas considered in the study (e.g. tree species composition). The scale of the power plants is based on an existing coal fired generating station in the region. Ethanol production is based on model results.
Methodological Assumptions: The functional unit is 1 oven dry t of biomass. It was intended to address all relevant GHG emissions, some may not be included, e.g. those associated with plant and machinery manufacture and maintenance. Carbon sequestration and GHG emissions associated with forest management, harvested bioenergy, and alternative fossil-fuel supply chains are considered. CO_2, N_2O, and CH_4 emissions were calculated separately and aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O. The FORCARB-ON model was used to simulate flows of biomass carbon (C) within forests (annual stocks in trees, litter and soil) and the supply of biomass feedstocks for potential use as wood pellets for use as bioenergy. To the extent covered, GHG emissions associated with forest management, biomass harvesting and bioenergy supply and consumption, were based on bespoke modelling. Bespoke calculations were also undertaken for each specified bioenergy value chain (electricity and ethanol), representing the stages in each chain, the quantities of wood involved, the amounts of bioenergy available from each chain, the calculation of GHG emissions at each stage in the chain, and finally summaries of total GHG emissions for each chain. The calculation of GHG emissions associated with counterfactuals to bioenergy (coal and petrol) appears to have been based on previously published results, i.e. emissions factors.
Overview of Transparency: Moderate transparency (with supplementary data).
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains. Results are presented as total impacts on GHG emissions for the entire studied forest area for each of the forest management scenarios and bioenergy products considered. Some limited results for estimated GHG emissions are presented graphically for scenarios based on harvest residues as the bioenergy feedstock.

Ref. No. 67: Details of LCA Study/Calculation Tool/Database/Review: Global Emissions Model for Integrated Systems (GEMIS) version 4.94, International Institute for Sustainability Analysis and Strategy (IINAS), Darmstadt, Germany, 2016.
Stated LCA Purpose, and Defined LCA Goal and Scope: This calculation tool and database enables users to assemble technologies ("Processes" and "Products") for application of LCA by providing a public domain (open access) life-cycle and material flow analysis model. Users can, effectively, establish the LCA goal and scope by means of the processes they select and the calculation procedures they specify (by accessing "Generic Data" file via double left clicking on one of the relevant "Processes").
Technological Coverage: The calculation tool can be used to represent any technology, including bioenergy value chains, by developing new technological elements and/or adopting existing technological elements that are accessible in the database of existing results which have been recorded from previous IINAS studies or entered by other users (access to the tool encourages this). The nature of technologies is represented by flow charts, which are assembled from existing or new processes, in the "Process Chain" file.
Technological Assumptions: Technological assumptions and details are recorded in the "Generic Data" file and summarised in the "Info" and "Comment" files.
Methodological Assumptions: The functional unit can be specified by the users although most existing results for bioenergy value chain adopt 1 MJ of heat (in fuel, output of the plant, delivered energy, etc.). Where co-products are involved, there is a choice of allocation procedures and "substitution credit" can be selected to be consistent with consequential LCA methodology. Similarly, a choice is available for including or excluding the manufacture and maintenance of plant, equipment and vehicles. Users can incorporate estimated of impacts from direct and indirect land sue change (presumably, the same applies to carbon stock changes in forests). Results for GHG emissions are disaggregated into CO_2, CH_4 and N_2O emissions although total GHG emissions are also reported using selected Global Warming Potentials (default values are 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O).
Overview of Transparency: High transparency
Reviewer: Nigel Mortimer
Headline Results: Based on the application of consequential LCA methodology, estimates of GHG emissions are available for: straw pellets are 17 kg CO_2eq/MWh (EU 2020) and 15 kg CO_2eq/MWh (EU 2030) wood pellets from forest residues are 20 kg CO_2eq/MWh (EU 2020) and 18 kg CO_2eq/MWh; Miscanthus (pellets?) heating are 36 kg CO_2eq/MWh heat (1 MW plant Germany 2010) and 32 kg CO_2eq/MWh heat (5 MW plant Germany 2010) ; straw pellet heating are 26 kg CO_2eq/MWh (15 kW plant Germany 2030); wood pellet (from forest residues) heating are 26 kg CO_2eq/MWh (EU/Germany 2010), 19 kg CO_2eq/MWh (EU/Germany 2020) and 14 kg CO_2eq/MWh (EU/Germany 2030) lignocellulosic processing of straw are 9 kg CO_2eq/MWh ethanol (Germany 2020) and - 0.00972 kg CO_2eq/MWh ethanol (Germany 2030).

Ref. No. 71: Details of LCA Study/Calculation Tool/Database/Review:
Greenhouse Gas Emissions from Four Bioenergy Crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses, by J. Hillier, C. Whittaker, G. Dailey, M. Aylott, E. Casella, G. M. Richter, A. Riche, R. Murphy, G. Taylor and P. Smith, Global Change Biology Bioenergy, Vo. 1, No. 4, pp. 267 – 281, 2009. DOI: 10.1111/j.1757-1707.2009.01021.x

Stated LCA Purpose, and Defined LCA Goal and Scope:
The purpose, goal and scope for the project are not clearly defined. However, the study's objective is to "study currently representative systems for the four bioenergy crops [Miscanthus, SRC poplar, winter wheat and oilseed rape], in order to consider soil-related emissions in the context of full LCAs and, hence, explore the relative GHG savings that could be achieved with each crop".

Technological Coverage:
Four different theoretical bioenergy pathways were analysed: co-firing of Miscanthus bales; co-firing of SRC billets; production of ethanol from winter wheat, and production of fatty acid methyl ester (FAME) from oilseed rape. Though full processing emissions were accounted for, the focus of the LCA was on changes in soil carbon turnover. All systems assumed feedstock cultivation in England and Wales.

Technological Assumptions:
Miscanthus was assumed to be cultivated using no fertiliser. SRC was assumed to be cultivated using only pig slurry as land input. Yields were calculated using spatially explicit datasets (e.g. sunlight/water availability, temperature etc.) for the entirety of England and Wales. Miscanthus is assumed to be combusted at 15% moisture (lower heating value of 15.1 GJ/t) while SRC assumed to be combusted at 30% moisture (lower heating value of 12.1 GJ/t).

Methodological Assumptions:
The scope of the LCA covers cradle-to-plant, including emissions from farm machinery construction and land use change. Global Warming Potential values for aggregating GHG emissions are based on a 100-year time horizon (25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O). Soil N_2O emissions were calculated in accordance with IPCC Tier 1 guidelines. Changes in soil carbon were calculated based on conversion of three different types of land: arable land; grassland and forest/semi-natural land. Land use change emissions are calculated based on comparison to continued management of the land under its previous usage, annualised over 20 years. Further indirect implications of land use change, such as compensation for reduced supply, are not considered. For the biofuel supply chains, emissions are allocated across products and co-products based on their economic value. Thus, while counterfactuals are assumed for the land used, they are not for co-products (attributional LCA is instead used). An equivalent amount of coal energy is used as the reference system for Miscanthus and SRC. An equivalent amount of energy provided by diesel and petrol were used as the reference systems for oilseed rape FAME and wheat ethanol respectively.

Overview of Transparency: Low transparency

Reviewer: Michael Goldsworthy

Headline results:
Net emissions for replacing arable land with Miscanthus: -4 t Ceq/ha/a
Net emissions for replacing arable land with SRC poplar: -4 t Ceq/ha/a
Net emissions for replacing grassland with Miscanthus: -4 t Ceq/ha/a
Net emissions for replacing grassland with SRC poplar: -3 t Ceq/ha/a

Ref. No. 72: Details of LCA Study/Calculation Tool/Database/Review: Greenhouse Gas Performance of Heat and Electricity from Wood Pellet Value Chains – based on pellets for the Swedish market, by J. Hansson, F. Martinsson and M. Gustavsson, Biofuels, Bioproducts and Biorefining Journal, Vol. 9, Issue No. 4, pp. 378 – 396, July/August 2015. DOI: 10.1002/bbb.1538
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was policy development in the EU regarding sustainability criteria for solid biomass/biofuels. The LCA goal was to assess the greenhouse gas (GHG) emissions for heat and electricity from selected wood pellet value chains and the associated potential emissions reduction in relation to fossil fuels. The LCA scope consisted of evaluation of energy use and associated GHG emissions for 9 different wood pellet value chains for heat and/or power production in Sweden (including pellets from Sweden, Latvia, Russia, and Canada).
Technological Coverage: Processes included for each pellet value chain analysis: (1) raw material production and collection, (2) pellet production, (3) transportation of raw material and pellets, (4) conversion to electricity and/or heat.
Technological Assumptions: Stand-alone pellet production is assumed for all cases. A lower heating value of pellets is assumed to be 4.81 kWh/kg at a moisture content of about 8% in all the cases studied. The pellets are assumed to be used in small-scale (0-10 MW thermal) and large-scale (21-50 MW thermal) combined heat and power (CHP) plants. A thermal net conversion efficiency of 86% is assumed for the conversion to district heating only. Average electricity to heat ratio of 0.28 for small-scale and 0.43 for large-scale plants are used. Average electrical efficiencies of 21% and 29% are given for small-scale and large-scale CHP plants, respectively.
Methodological Assumptions: The functional unit is 1 MJ of pellets in fuel terms (and not in heat and electricity terms). GHG emissions from silviculture, logging and sawmill operations related to residues like shavings or sawdust (considered secondary biomass) used as feedstock, are not considered since emission accounting for these raw materials starts with the collection process. Upstream emission after collection primarily due to transportation are included in the GHG balances. Transport to end users includes truck/train transport from pellet plants and sea transport. It also includes handling and storage of wood pellets in port and handling of the pellets at the energy conversion (CHP) plants. GHG emissions from the use of biomass (e.g. from the burning of pellets) are not considered in this study. Wood pellet production includes the use of electricity (for drying, milling, pressing and cooling, and handling and storage as well as removing fines and the use of fuel for drying the raw material. GHG emissions from the use of diesel in machines used for pellet production are also included but not explicitly shown. GHG emissions from the construction and decommissioning of the power plants, the running of the plant and ash management are not included. Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O are used. Uptake and release of carbon by existing forests is not included. Carbon stock changes due to direct land-use change (dLUC) or indirect land-use change (iLUC) are not considered. The total GHG emissions for the pellet value chains are allocated between heat and electricity production using exergy which means that specific results the outputs from the CHP plants are derived using attributional and not consequential LCA methodology.
Overview of Transparency: Low transparency
Reviewer: Maha Elsayed
Headline Results: The total factory-gate GHG emissions at the conversion facility for the wood pellet value chains studied, range between 7 - 90 kg CO_2eq/MWh for Swedish pellets at the lower end, and Russian pellets using natural gas for drying the raw material at the higher end.

Ref. No. 75: Details of LCA Study/Calculation Tool/Database/Review: Hydrogen Production via Biomass Gasification—a lifecycle assessment approach, by C. Koroneos, A. Dompros and G. Roumbas, Chemical Engineering and Processing, Vol. 47, pp. 1261 – 1268, 2008. DOI: 10.1016/j.cep.2007.04.003
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was to reduce GHG emissions for mitigation impacts (possibly as a means of informing policy makers about sustainability). The LCA goal was to assess the environmental feasibility and efficiency of producing hydrogen from biomass via two processes with a defined LCA scope of (1) gasification of agricultural residues followed by reforming of the syngas and (2) gasification followed by electricity generation and electrolysis.
Technological Coverage: Gasification of cotton, olive cake, rice and corn harvest residues to produce syngas and then hydrogen via steam reforming or use syngas to generate electricity in a combined heat and power (CHP) plant and hydrogen via electrolysis.
Technological Assumptions: National scale application of systems to be placed in agricultural areas in Greece.
Methodological Assumptions: Material and energy balances are used to quantify emissions, resource depletion and energy consumption of all processes between biomass acquisition, transportation, processing of raw materials into useful products and the final disposal of all products and by-products. Impacts assessed: greenhouse gas (GHG) emissions, acidification, eutrophication, heavy metals, carcinogenesis, winter smog and summer smog. Classification of the inventory data to impact categories made using the Eco-Indicator 95 methodology. It is assumed that the biomass-gasification-power plant produces all the electricity required for electrolysis and liquefaction steps without need of additional power source. The gasification steam reforming plant requires additional electricity due to compression requirements that involve the steam reforming and PSA processes. The overall energy efficiency of the electrolysis process is taken to be 77%. Construction materials data were taken from GEMIS 2001.
Overview of Transparency: Low transparency (no access to GHG emissions calculations)
Reviewer: Maha Elsayed
Headline Results: Energy inputs to electrolysis process = 4.2 MJ/MJ of hydrogen (93% renewable, 7% non-renewable) and steam reforming process = 2.4 MJ/MJ of hydrogen (54% renewable, 46 % non-renewable). Greenhouse gas emissions for electrolysis process = 72 kg CO_2eq/MWh of hydrogen and steam reforming process = 504 kg CO_2eq/MWh of hydrogen.

Ref. No. 82: Details of LCA Study/Calculation Tool/Database/Review: Indirect Carbon Dioxide Emissions from Producing Bioenergy from Forest Harvest Residues, by A. Repo, M. Tuomi and J. Liski, GCB Bioenergy, Vol. 3, pp. 107 – 115, 2011. DOI: 10.1111/j.1757-1707.2010.01065.x
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to introduce an approach to calculate [the biogenic carbon] emissions from using logging residues for bioenergy production [compared with leaving the logging residues in the forest], and to estimate this emission at a typical target [level] of harvest residue removal for boreal Norway spruce forest in Finland.
Technological Coverage: Biomass supply from the forestry system is considered at the scale of a representative theoretical area of Norway spruce in Southern Finland. The implicit scale is, thus, a notional, representative forest area, or a quantity of biomass supplied by the forest area. Wood chips are produced from harvesting residues with two possible feedstocks, branches and stumps (implicitly including major roots). Extraction of harvest residues is assumed to take place at time of clearfelling, i.e. around 81 to 100 years. The study considers the fuel supply chain up to the conversion process (power generation). It is unclear if the conversion process is represented.
Technological Assumptions: The scale of application is specified in terms of the representative forest area considered. All harvest residues extracted are assumed to supply wood chips for ultimate use as bioenergy. Limited information about the representative forest area considered in the study (e.g. tree species composition) is given in this paper. The paper refers to the combustion of biomass in a "power plant", and gives emissions in kg CO_2eq/MWh produced, however it is not specified whether this is in terms of energy input to the plant, or output from it, and if the latter the efficiency assumed.
Methodological Assumptions: The study has aimed to include all relevant GHG emissions. However, it is possible that some GHG emissions are not included, e.g. those associated with plant construction, machinery manufacture and maintenance. Carbon sequestration and GHG emissions, i.e., CO_2, N_2O, and CH_4, associated with the extraction, transport and processing of harvest residues and alternative fossil-fuel supply chains, are considered. Fertiliser application in the forest, and the recycling of wood ash, are represented. The Global Warming Potentials used to aggregate separate GHG emissions are not stated explicitly. The Yasso07 (litter and) soil carbon model is used to simulate the decay of branchwood, stumps and roots left in the forest after tree harvesting. GHG emissions of counterfactual energy sources (natural gas, oil and diesel, coal) are based on national mean emissions factors for Finland, which are around those generally quoted for delivered fuel in the UK.
Overview of Transparency: Moderate transparency
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: The total GHG emissions as a result of extracting harvest residues and using them for bioenergy depend on the time horizon from the start of practice. For 1, 20, 40 and 100 years after starting the practice, the approximate annual total GHG emissions from using average-sized branches (diameter of 2 cm) are, respectively, 349, 169, 130 and 90 kg CO_2eq/MWh. The equivalent results for stumps (and implicitly major roots) are 349, 281, 241 and 158 kg CO_2eq/MWh.

Ref. No. 86: Details of LCA Study/Calculation Tool/Database/Review: LCA of a Biorefinery Concept Producing Bioethanol, Bioenergy, and Chemicals from Switchgrass, by F. Cherubini and G. Jungmeier, International Journal of Life Cycle Assessment, Vol. 15, pp. 53 – 66, 2010. DOI: 10.1007/s11367-009-0124-2
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was assessing sustainability (possibly for policy-makers) in terms of mitigating climate change and enhancing energy security. The LCA goal was life cycle assessment of a biorefinery converting switchgrass (a lignocellulosic crop) into ethanol, bioenergy, and biochemicals (phenols). The LCA scope was assessment of input and output flows occurring along the production chain- biomass cultivation, harvesting, processing, transport, conversion, and final use of products, and elaboration of issues such as land use change effects and soil N_2O emissions.
Technological Coverage*:* Feedstock is pellets from switchgrass. Cultivation consists of sowing, tilling, spreading of fertilisers, harvesting, and baling, followed by drying and pellet production. Biorefinery processes include pellets pre-treatment, enzymatic cellulose hydrolysis, fermentation and distillation of sugars to ethanol. Anaerobic digestion of wastewater is used to produce biomethane. Process residues are treated by flash pyrolysis of lignin (phenols) for heat and power production) and pyrolytic char recovery.
Methodological Assumptions: The functional unit is 1 t of dry feedstock. The system boundary includes all input and output flows occurring along the full chain for planting and harvesting the crops, processing the feedstock into biofuel, transporting and storing of feedstocks, distributing, and final use of biofuels. Material and energy inputs required to produce switchgrass pellets to be used as feedstocks in biorefinery is listed. Heat and electricity needs are completely met by combustion of lignin and residues. LCA software tool SimaPro 7 used for modelling, and the CML method (CML 2 baseline2,000 V. 2.03) is used to produce results in other environmental categories. Manufacturing of auxiliary materials is accounted for. For land use change, a payback time (or effect time) considered in this assessment is 20 years. The cultivation of switchgrass is on set-aside land. In the first 20 years, the biorefinery system benefits of atmospheric CO_2 sequestration in soil organic carbon; after 20 years, the soil reaches a new equilibrium and the effects of land use change does not occur subsequently. N_2O emissions from land estimated using default emission factors (IPCC 2006). A default value of 10 g CH_4/kg N for the emission of CH_4 from agricultural land is used. A carbon sequestration rate of 0.6 t C/ha.a in 20 years is assumed. Switchgrass yields are assumed to be 16 t dry/ha. The soil organic content (SOC) of set-aside land is calculated using the IPCC factors.
Overview of Transparency: Moderate transparency
Reviewer: Maha Elsayed
Headline Results: In the first 20 years, the biorefinery releases 60 kt CO_2eq/a and requires 10.8 PJ/a of primary energy, of which 0.81 PJ/a is fossil energy based on treatment of 477 kt dry/a of switchgrass and an average yield of 16 t dry/ha/a. 33.6% of the original energy content of the feedstock is recovered in the final products.

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Ref. No. 89: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment (LCA) of an Integrated Biomass Gasification Combined Cycle (IBGCC) with CO_2 Removal, by M. Carpentieri, A. Corti and L. Lombardi, Energy Conversion and Management, Vol. 46, pp. 1790 – 1808, 2005. DOI: 10.1016/j.enconman.2004.08.010
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated aim of this paper was to "assess the environmental impact, on a life cycle horizon, of biomass utilisation in energy production" by examining an integrated biomass-gasification combined cycle (IBGCC) plant with CO_2 removal, and to compare this with an integrated coal gasification combined cycle (ICGCC) plant with CO_2 removal. The LCA goal and scope are not defined adequately.
Technological Coverage: Generation of electricity from an IBGCC plant using biomass derived from "energy crops" consisting of wood (form of feedstock unspecified) from poplar short rotation coppice (SRC) probably grown in Italy.
Technological Assumptions: Very little information is provided on how the biomass feedstock is grown and in what form it is provided to the IBGCC plant. However, it has a specified moisture content of 15% and a lower heating value of 5.0 kWh/kg. The main technical focus of the paper is on the IBGCC plant specifications and operational parameters. The main components of the plant concern biomass gasification, syngas cleaning and syngas combustion in gas turbines. CO_2 is removed pre-combustion by chemical absorption using DEA and MDEA. It is assumed that 80% of the CO_2 is removed. The net thermal efficiency of the IBGCC plant with CO_2 removal is 33.94% and its assumed operating life is 15 years.
Methodological Assumptions: Functional unit consists of the production of 1 MJ of energy (presumably electricity). The LCA biomass feedstock (wood from poplar SRC) cultivation, harvesting, drying and transportation, and IBGCC plant construction, operation, maintenance and dismantling. However, contributions from the manufacture of agricultural machinery and the construction of agricultural buildings for SRC wood production are assumed to be negligible and are not taken into account. The values of Global Warming Potential adopted in calculations are not specified. Results are broken down by contributions from biomass production (including "negative CO_2 emissions" from carbon sequestration during growth) and transportation; and construction, operation, maintenance and dismantling (including "avoided GHG emissions" due to recovered metals and materials displacing new production) of IBGCC plant with CO_2 removal.
Overview of Transparency: Low transparency
Reviewer: Nigel Mortimer
Headline Results: Biomass production (including carbon sequestration) of – 821 kg CO_2eq/MWh; biomass transport of 43 kg CO_2eq/MWh; IBGCC plant construction of 0.9 g CO_2eq/MWh; IBGCC plant operation of 184 kg CO_2eq/MWh; IBGCC plant maintenance of 0.104 kg CO_2eq/MWh; and IBGCC plant dismantling of – 0.018 kg CO_2eq/MWh giving a total of – 594 kg CO_2eq/MWh.

Ref. No. 90: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment of a Hypothetical Canadian Pre-combustion Carbon Dioxide Capture Process System, by L. Piewkhaow, C. W. Chan, A. Manuilova, M. Wilson and P. Tontiwachwuthikul, Carbon Management, Vol. 5, Nos. 5 – 6, pp. 519 – 534, 2014. DOI: 10.1080/17583004.2015.1039251
Stated LCA Purpose, and Defined LCA Goal and Scope: The objective of this study is to identify the technology that offers the most positive environmental effects by evaluating and comparing the environmental performance of a hypothetical Saskatchewan lignite integrated gasification combined cycle (IGCC) - based electricity generating station (with and without the CO_2 capture process) and the competing pulverised lignite coal electricity stations (with and without CO_2 capture).
Technological Coverage: Lignite IGCC-based electricity generation plant with and without the pre-combustion CO_2 capture process and the competing lignite pulverised coal electricity generating plant with and without post combustion CO2 capture. 90% CO_2 removed by MEA for the conventional lignite coal fired electricity generating system with a 33% reduction in electricity output and 95% of the CO_2 is absorbed by the selexol solvent for the IGCC system with an 18% reduction in electricity output.
Technological Assumptions: Single electricity generating plant.
Methodological Assumptions: The majority of the data used was specific to Western Canada. The life cycle impact assessment model used was the 'Tool for Reduction and Assessment of Chemical and other Environmental Impacts' (TRACI). The assessment is cradle to gate for electricity generation and the functional unit is 1 MWh net electricity generated. The allocation procedure and the values for Global Warming Potentials used are not clearly stated. The assessment includes material and fuel production, transport, electrical generating station construction and decommissioning, capture and compression of CO_2, products and by-products, landfilling of slags and wastes. The assessment considers the lifetime of the plant to be 50 years.
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found.

Ref. No. 91: Details of LCA Study/Calculation Tool/Database/Review:
Life Cycle Assessment of a Pulverized Coal Power Plant with Post-combustion Capture, Transport and Storage of Carbon Dioxide, by J. Koornneef, T. van Keulen, A. Faaij and W. Turkenburg, International Journal of Greenhouse Gas Control, Vol. 2, No. 4, pp. 448 – 467, October 2008, (TCCS-4: The 4th Trondheim Conference on CO_2 Capture, Transport and Storage). DOI: 10.1016/j.ijggc.2008.06.008.
Stated LCA Purpose, and Defined LCA Goal and Scope: An assessment of the environmental impact and trade-offs associated with deploying carbon capture and storage (CCS) technology in supercritical pulverised coal fired electricity supply chains which differ in their year of installation, conversion efficiency and ability to capture carbon dioxide on a cradle to grave basis now and in the future. In particular, the assessment considers the broader impacts on the environment and human health of deploying CCS technology in the Netherlands.
Technological Coverage: Pulverised coal fired electricity supply chains with and without CCS. The chain with CCS comprises post-combustion CO_2 capture with mono-ethanolamine, compression, transport by pipeline and storage in a geological reservoir. The two reference chains represent sub-critical and state-of-the-art ultra-supercritical pulverised coal fired electricity generation.
Technological Assumptions: Individual power plants are located in the Netherlands. Case 1: the reference case represents the average sub-critical pulverised coal fired power plant operating in the Netherlands in the year 2000. Case 2: a state-of-the-art ultra-supercritical pulverised coal fired power plant as proposed by several companies to be installed in the coming years (2011–2013) in the Netherlands. This power plant can be considered best available technology at present. Case 3: a state-of-the-art coal fired power plant, equal to case2, equipped with post-combustion capture chemical absorption of CO2 with mono-ethanolamine (MEA). Assumes 90% CO2 removal and an efficiency loss of 11%.
Methodological Assumptions: The function of the product system is electricity generation and the functional unit 1kWh electricity generated. Cradle to grave studies for the years 2005, 2010 and 2050 are presented. Where possible life cycle emissions for the Netherlands are used. The study considers the full life cycle including CO_2 transport and storage; the effect of implementing CO_2 capture on the direct emissions of the power plant, including additional waste formation and the reaction of flue gas constituents with the solvent; the assessment of the impact on the environment other than climate change when implementing CCS; assessment of direct and indirect process environmental impacts based on process data including the determination of environmental impact of the infrastructure for CO_2 capture, compression, transport and injection. The CML 2 baseline 2000 V2.03 impact assessment method is used to characterise environmental interventions and subsequently estimate the potential environmental impacts. After characterisation, the normalised impact scores are obtained by dividing the score for an impact category by the total of that category in a reference region in a certain year. The reference region is the Netherlands in1997. The outcomes are not weighted. Sensitivity analysis is performed to disclose the impact of assumptions made and the uncertainty of input data on the result of the comparison. The allocation procedures used are not clear.
Overview of Transparency: Moderate transparency.
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found. Carbon dioxide transport compression energy: 111 kWh/t CO_2, injection compression energy: 7 kWh/t CO_2 and infra structure requirements for CCS: 0.006% of total emissions.

Ref. No. 94: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment of Biomass Chains: wood pellet from short rotation coppice using data measured on a real plant, by F. Fantozzi and C. Buratti, Journal of Biomass and Bioenergy, Vol. 34, No. 12, pp.1796 – 1804, December 2010. DOI: 10.1016/j.biombioe.2010.07.011
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was for addressing policy (EU Directive) and sustainability. The defined LCA goal was to assess the environmental impacts, of wood pellet utilisation for heat energy production. The defined LCA scope was the overall process, from field growth to ash disposal, considering impacts on global warming, acidification, eutrophication, toxicity and resource depletion.
Technological Coverage: The technology consists of agricultural operations and manufacturing processes for the production of pellets from short rotation coppice (poplar), followed by combustion of pellets in a domestic boiler of pellets.
Technological Assumptions: Poplar cultivation considered with yield equal to 20 t/ha/a (dry basis), with a cultivation cycle of eight years. The impact of land occupation due to pelleting plant was considered for an occupied area of 1 ha. i.e. land occupied for (8 years) of land for forestry cultivation (0.0437 m^2/MJ/a) and a transformation of land from unknown utilisation to forestry cultivation (0.00546 m^2). Energy and mass flows for pelleting was obtained from an existing Italian plant; combustion of wood pellets in a domestic boiler (22kW).
Methodological Assumptions: The functional unit is 1 MJ of heat output. Energy and environmental analysis was carried out using SimaPro 7.0 and adopting the EcoIndicator 99 model for the evaluation of the global burden; analysis with EPS 2000 and EDIP methodologies - the Cumulative Energy Demand (CED) methods are used. The impacts of machinery manufacturing, mass and energy flows (boiler, pipes for heat distribution inside the building, heat accumulator, storage silo and the pellet extraction system) and infra-structures (weights of machinery) and materials used in the pellet chain were taken into account. The method used to attribute environmental burdens to the co-product was the displacement method (system expansion or use of counterfactuals), in which to the primary product is assigned the total environmental burden minus credits due to the environmental burdens avoided as a result of co-product displacement of alternative products elsewhere. Dismantling and recycling of machinery and infra-structures were not considered.
Overview of Transparency: Moderate transparency (all impacts aggregated and there is no breakdown for GHG emissions)
Reviewer: Maha Elsayed
Headline Results: Using (EcoIndicator 99) values in multi-Point, total impacts of pellet chain = 3185.40 µP, climate change = 64.4 µP, and fossil fuels = 933.2 µP.

Ref. No. 97: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment of Carbon Dioxide Capture and Storage from Lignite Power Plants, by M. Pehnt and J. Henkel, International Journal of Greenhouse Gas Control, Vol. 3, No. 1, pp. 49 – 66, January 2009. DOI: 10.1016/j.ijggc.2008.07.001
Stated LCA Purpose, and Defined LCA Goal and Scope: To perform an integrated analysis of the effect of carbon capture and storage (CCS) technology on feedstock demand and GHG emissions for lignite power plant.
Technological Coverage: CCS for several lignite power plant technologies examined. Includes post-combustion, pre-combustion and oxyfuel capture processes as well as subsequent pipeline transport and storage of the separated CO_2 in a depleted gas field. Configurations considered are conventional pulverised coal power plant with amine post-combustion CO_2 capture, integrated coal gasification combined cycle (IGCC) power plant, IGCC with selexol pre-combustion carbon dioxide capture and oxyfuel power plant with carbon dioxide capture.
Technological Assumptions: The technology is single power plants operating at extrapolated efficiencies in 2020. Assumed efficiencies are 46% for pulverised coal, for pulverised coal plus CCS, 1368 kJ electrical energy equivalent are required per tonne of carbon dioxide removed. Amount of MEA to make up for the capture of 1 t carbon dioxide is 1.5 kg. The efficiency of IGCC plant is assumed to be 48% and a percentage drop of around 5% is incurred by the addition of CCS. The efficiency of the oxyfuel plant is the same as for pulverised coal power plant and assumes 92% carbon dioxide separation efficiency. Transport to storage is 325 km via pipeline, the CO_2 being compressed at source with an energy requirement of 116 kWh/t CO_2. Storage is in exhausted coal and gas seams but leakage from storage is not considered.
Methodological Assumptions: The assessment is a predictive assessment for plants operating in 2020. The model is implemented in UMBERTO. Emissions factors are derived through detailed literature analysis and are largely based on European data. IPCC 2007 100 year Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O are used. The functional unit is 1 kWh electricity produced by lignite fired power stations. The analysis covers the full fuel cycle from the mining of lignite to the storage of the carbon dioxide released from power generation in coal and gas seams. The assessment includes construction and decommissioning of plant and infrastructure. The only product is electricity and, hence, no allocation is carried out. Sensitivity and uncertainty analysis is performed and consideration is given to the effects of scaling up CCS to a global level.
Overview of Transparency: High transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found. Approximately 1% of total global warming impact is due to carbon dioxide transport and storage (compression allocated to power plant).

Ref. No. 99: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment of Gas Power with CCS - a study showing the environmental benefits of system integration, by I. S. Modahl, C. A. Nyland, H. L. Raadal, O. Kårstad, T. A. Torp and R. Hagemann, Energy Procedia Vol. 4, pp. 2470 – 2477, 2011. DOI: 10.1016/j.egypro.2011.02.142.
Stated LCA Purpose, and Defined LCA Goal and Scope: The purpose of the study was to give input to Statoil strategy development by comparing the environmental impacts of four different gas power plant scenarios, including one scenario based on system integration.
Technological Coverage: Gas and biomass power plant, carbon capture and storage (CCS) post combustion via MEA and geological storage in spent gas field.
Technological Assumptions: Statoil in 2007 carried out an LCA of a possible future Tjeldbergodden gas power plant case, including CO_2 capture, transport and storage. Scenarios include: A reference gas power plant without CCS; CCS-1: gas power plant with CCS, separate gas fuelled steam boiler for amine regeneration; CCS-2: gas power plant with CCS, separate biofuel steam boiler for amine regeneration and CCS-3; gas power plant with CCS, steam from steam turbine for amine regeneration (system integration). The power plant was designed with two gas turbines of 262 MW nominal each in addition to one steam turbine of 328 MW nominal. The net power production was 832 MW for the reference scenario and 789 MW for the scenarios CCS-1 and CCS-2. For scenario CCS-3 the net power was 702 MW. The net efficiency of the power plant was 59.1% in the reference scenario, 44.8% in the CCS-1 and CCS-2 scenarios and 50.0% in the CCS-3 scenario.
Methodological Assumptions: Function of the product system is power generation and the functional unit 1 TWh electricity generated at Tjeldbergodden gas power plant and delivered to the grid. It is a cradle to grave study covering GHG and other environmental impacts for foreground and background systems including infrastructure. Allocation procedures and GWPs are not clear.
Overview of Transparency: Low transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found. GHG emissions associated with CCS ranges between 137 and 155 kg CO_2eq/MWh.

Ref. No. 102: Details of LCA Study/Calculation Tool/Database/Review:
Life Cycle Assessment of New Willow Cultivars Grown as Feedstock for Integrated Biorefineries, by M. Krzyzaniak, M. Stolarski, S. Szczukowski and J. Tworkowski, Bioenergy Research, Vol. 9, pp. 224 - 238, 2016. DOI: 10.1007/s12155-015-9681-3
Stated LCA Purpose, and Defined LCA Goal and Scope: The primary goal of the LCA was to "determine the environmental impact of the production of seven new cultivars of willow grown [in a 3-year harvest cycle] in a commercial plantation [in Poland] for use in an integrated biorefinery". The study also had additional goals of analysing the impact of transport distance on environmental impact, and identifying the processes with the most negative impact on the environment.
Technological Coverage: Wood chip production from willow short rotation coppice. Final conversion of wood chip in an integrated biorefinery was not considered in the LCA.
Technological Assumptions: Seven different willow cultivars were assessed, grown in a 10.5 ha commercial willow plantation in Lezany, Poland. Plant harvests were undertaken on a 3-year cycle, with 7 harvests assumed to occur over the crop rotation. The site offered poor soil quality (slightly loamy sand and light loamy sand) and was generally dry due to rapid drainage. The 'forecrop' for the site was triticale (wheat-rye hybrid). Willow was chipped at the plantation using a single stage harvester.
Methodological Assumptions: The functional unit was 1 t of dry wood chip. The scope of the LCA covers cradle-to-factory gate emissions. Machinery construction/maintenance emissions were outside the system boundary. Transport distances for the wood chip of 25 km, 50 km and 100 km were analysed. LCA results are provided both with inclusion of carbon sequestration in plant biomass and without. The global warming potential of GHGs is based on a 100-year time horizon (though specific values are not provided). Other environmental impacts were included in the LCA, including eutrophication, acidification, abiotic depletion, freshwater aquatic ecotoxicity and terrestrial ecotoxicity. While sequestration of carbon in plant biomass and accumulation of soil organic carbon was included in the LCA, this was not compared to site characteristics prior to planting, nor compared to any reference system. Therefore, direct land use change emissions are only partially accounted for, while indirect land use change emissions are not considered. SimaPro 7.3.2. was used to undertake the LCA.
Overview of Transparency: Low transparency
Reviewer: Michael Goldsworthy
Headline results: For a 25 km transport distance, GHG emissions for wood chips are: with average cultivar yield = 35.97 kg CO_2eq/dry t (with carbon sequestration) and 107.66 kg CO_2eq/dry t (without carbon sequestration); with lowest yielding cultivar = 97.33 kg CO_2eq/dry t (with carbon sequestration) and 229.95 kg CO_2eq/dry t (without carbon sequestration); and with highest yielding cultivar = 19.01 kg CO_2eq/dry t (with carbon sequestration) and 70.33 kg CO_2eq/dry t (without carbon sequestration)

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Ref. No. 104: **Details of LCA Study/Calculation Tool/Database/Review:** Life Cycle Assessment of Selected Technologies for CO_2 Transport and Sequestration, by C. Wildbolz, Diploma Thesis No. 2007MS05, Swiss Federal Institute of Technology Zurich, Departement Bau, Umwelt und Geomatik Institute of Environmental Engineering (IfU), Switzerland, July 2007.
Stated LCA Purpose, and Defined LCA Goal and Scope: A comparison of the options using life cycle inventory (LCI) of the transport and storage options of supercritical CO_2 in fulfilment of the requirements of a Master's thesis.
Technological Coverage: Transport and storage of CO_2 captured from energy production. Transport options considered are onshore pipeline with and without recompression unit. The storage options are in deep saline aquifers and depleted gas fields. The focus is on the determination of the LCI data. A model is presented and the model parameters compared with values found in literature for existing CO_2 transport and storage projects.
Technological Assumptions: The carbon capture and storage (CCS) is chain is covered by application of data for the post-combustion capture process to a current best pulverised coal power plant in 2007 using data for borehole drilling projected to 2030. Extensive details are given of the assumptions regarding dimensions, flows, equipment and materials required. Transport by pipeline of 200 km (no compression station after power plant) and 400 km (one compression station after power plant) are considered.
Methodological Assumptions: The comparison of the options is done using SimaPro software at the life cycle impact assessment level using Eco-indicator 99 and IPCC 2001 GWPs for a 100 year time horizon. Impacts are presented in terms of kg stored CO_2 and kWh net electricity output from the power plant. The system boundary excludes capture but includes transport and storage, infrastructure and upstream and downstream emissions using research data available in 2007. Allocation procedures are not clear.
Overview of Transparency: Moderate transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): transport (200 km) and storage in depleted gas field (2500 m depth) is approximately 0.016 kg CO_2eq/kg stored CO_2 (estimated from graph), transport (400km) and storage in depleted gas field (2500 m depth) is approximately 0.018 kg CO_2eq/kg stored CO_2 (estimated from graph).

Ref. No. 105: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Assessment of Wheat Straw as A Fuel Input for District Heat Production, by R. Parajul, Master Thesis, Department of Development and Planning, Aalborg University, Aalborg, Denmark, 2013
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was to maximise the use of renewable energy in Denmark (by informing policy-makers and addressing sustainability). The LCA goal was to assess the environmental impacts of wheat straw as a fuel alternative in a combined heat and power (CHP) plant used for district heating (DH). The LCA scope concerns the life cycle impacts of DH system using wheat straw combustion in a CHP plant, for comparison with natural gas and imported wood pellets. Impact categories evaluated consisted of non-renewable energy (NRE) use, global climate change impact (GWP) over a 100 year time horizon, acidification potential (AP), and aquatic and terrestrial eutrophication potential (EP).
Technological Coverage: Wheat straw pellets, produced in Denmark, are used as fuel in a CHP plant with DH. This is compared with imported wood pellets, from timber supplied by forests in Latvia, for use a fuel in a CHP plant with DH.
Technological Assumptions: Wheat straw pellets, obtained after straw baling and handling, pre-treatment, chopping and pelletising in Denmark. The CHP plant has a thermal efficiency of 60% and produces 25% electricity and 35% heat. 1 t of straw (at 85% dry matter) is associated with the co-production of the net electricity equivalent to 827 kWh.
Methodological Assumptions: The functional unit is 1 MJ of heat. Consequential LCA methodology adopted. No land use changes considered. Straw removal impacts are taken into account through a reduction in soil fertility and leaching of nitrates, phosphates and potash, and loss of soil carbon sequestration (assessed over 100 years). No plant construction, machinery and maintenance included. Management of fly ash and bottom ash is considered as a substitute for chemical fertilisers. All the material and fuel inputs required in the energy conversion processes are modelled using SimaPro 7.3.3 software.
Overview of Transparency: Moderate transparency
Reviewer: Maha Elsayed
Headline Results: The removal of 1 t of straw leads to an increase GHG emissions of 135 kg CO_2e as a consequence of applying fertilisers and limitation of soil carbon sequestration. The energy inputs to produce fertilisers to replace the straw which has not been incorporated alone covers 100% of total non-renewable energy use (185 MJ/t straw). For DH with a straw-fired boiler, the non-renewable energy use is 0.134 MJ/MJ of heat and GHG emissions are 85 kg CO_2eq/MWh of heat. For DH with a straw-fired CHP plant, the non-renewable energy use is 0.090 MJ/MJ of heat and GHG emissions are 93 kg CO_2eq/MWh of heat. In comparison with a coal-fired power plant for marginal electricity generation, the net non-renewable energy use is – 1.23 MJ. MJ of heat and the net GHG emissions are – 312 kg CO_2eq/MWh of heat.

Ref. No. 110: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Environmental Impact Assessment of Biochar-based Bioenergy Production and Utilization in Northwestern Ontario, Canada, by K. Homagain, C. Shahi, N. Luckai and M. Sharma, Journal of Forestry Research, Vol. 26, pp.799-809, August 2015. DOI: 10.1007/s11676-015-0132-y
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was to assess the net energy balance, GHG emissions and associated environmental impacts of a biochar-based bioenergy system and its utilisation as a soil amendment to sequester carbon. The scope covered Impact categories including damage to human health, damage to ecosystem quality, damage to resources and, specifically, global climate change.
Technological Coverage: Slow pyrolysis of wood pellets produced from harvest waste, sawmill waste and woody biomass in a managed forest (spruce, pine, poplars, birch). Wood processing consists of chipping/grinding, drying and pelletising.
Technological Assumptions: Biomass produced from Northwestern Ontario forests. Wood pellets to be used in an electricity generation plant that is being converted from coal to biomass.
Methodological Assumptions: The functional unit is 1 t of biochar (and 1 MW of equivalent electricity that is generated) produced from woody biomass processed into wood pellets. System boundary includes biomass collection, transportation, storage, processing and pyrolysis with/without land application of biochar. Ecoinvent 99 and SimaPro 8.1 LCA software are used for input materials, equipment, processes and emissions. Land application of biochar is used to sequester carbon. A weight loss of 10 % is assumed during transportation and application. Storage of biochar is not considered in this study, assuming that it will be applied to land immediately after production. A product yield of bio-oil 35 %, syngas 30 % and biochar 35 % by weight of dry feedstock was assumed. Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O are used. Only GHG emissions from construction of pyrolysis plant is listed (from "Energy and Carbon Modelling of Biomass Systems: conversion plant and data updates" by M. A. Elsayed and N. D. Mortimer, 2001).
Overview of Transparency: Moderate transparency
Reviewer: Maha Elsayed
Headline Results: Energy input is 18402.07 MJ/t dry feedstock (without land application of biochar), and 18994.43 MJ/t dry feedstock (with land application of biochar). GHG emissions are 767.43 kg CO_2eq/t dry feedstock (without land application of biochar) and 780.75 kg CO_2eq/t dry feedstock (with land application of biochar). Also primary fossil energy input and GHG emissions per t of biochar are calculated. Energy balance results show that about 1 GJ more energy is consumed when biochar is applied to the land. However, GHG emissions change from a source (-215 kg CO_2eq) to a sink (68 kg CO_2eq) when land application of biochar is included.

Ref. No. 111: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Evaluation of Emerging Lignocellulosic Ethanol Conversion Technologies, by S. Spatari, D. M. Bagley and H. L. MacLean, Bioresource Technology, Vol. 101, Issue No. 2, pp. 654 -667, January 2010. DOI: 10.1016/j.biortech.2009.08.067.
Stated LCA Purpose and Defined LCA Goal and Scope: The LCA purpose was to address climate change and energy security issues associated with personal transportation, possibly for informing policy-makers and to assist development. The LCA goal was to undertake well-to-(plant) gate LCA comparing the technological features and life cycle environmental impacts of near- and mid-term ethanol bioconversion technologies in the USA. The LCA scope covered energy and material inputs, and environmental emissions associated with biomass feedstock (corn stover and switchgrass) production and transport, and ethanol conversion.
Technological Coverage: Ethanol bioconversion technologies of lignocellulosic (corn stover and switchgrass) with major processes consisting of pre-treatment, hydrolysis, and fermentation.
Technological Assumptions: Eight near-term (2010) and two advanced mid-term (circa 2020) lignocellulosic ethanol conversion technologies, with daily output ratings of 2000 dry t of ethanol, in USA are investigated. All combustible portions of the biomass that are not converted to ethanol are converted to electricity which is sold to the grid.
Methodological Assumptions: The functional unit is 1 litre of ethanol produced per hour. Energy and material inputs and environmental emissions associated with feedstock production (fertilisers, herbicides, and fuel to operate harvesting equipment) and transport, and ethanol conversion are evaluated. A model for corn stover collection assumes that 50% of this residue is removed for ethanol production and 50% remains in the soil for maintaining soil organic carbon and minimising erosion. The 1997 IPCC Tier 1 procedure is used to estimate soil N_2O emissions. Co-product allocation is used to divide emissions between the corn stover collected and that remaining in the field. For switchgrass, it is assumed that CO_2 sequestration amounts to 53,500 g/dry t. The additional CO_2 uptake is associated with the cultivation of switchgrass when grown on cropland. Primary energy inputs and emissions associated with process chemicals used in ethanol conversion are included as well as addition fuel for operating forklifts. Technical and environmental metrics developed for the ethanol bioconversion technologies examined. Results for near-term technologies are presented both as stochastic and point estimates based on Monte Carlo and Aspen simulation results. Energy is recovered for steam and electricity production (conversion of biomass to electricity assumed to range between 13% and 47%) from lignocellulosic fractions not converted to ethanol. System expansion is adopted applying a credit for the surplus co-product electricity. Plant construction, machinery and maintenance are not taken into account. Air pollutant emissions consisting of CO, NO_X, SO_x, and NMOG are assessed. GHG emissions are not disaggregated into CO_2, CH_4 and N_2O.
Overview of Transparency: Moderate transparency (no access to GHG emissions calculations but conversion processes discussed in detail)
Reviewer: Maha Elsayed
Head Line Results: Estimated primary fossil energy inputs range from 1.6 MJ/l to 2.7 MJ/l and GHG emission range from 180 g CO_2eq/l to 205 g CO_2eq/l.

Ref. No. 112: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle GHG Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage, by N. A. Odeh and T. T. Cockerill, Energy Policy, Vol. 36, No. 1, pp. 367 – 380, January 2008. DOI: 10.1016/j.enpol.2007.09.026.
Stated LCA Purpose, and Defined LCA Goal and Scope: Evaluation of life cycle greenhouse gas emissions from power generation with carbon capture and storage (CCS) to inform policy.
Technological Coverage: Supercritical pulverised coal (super-PC); natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC), with and without MEA CCS. Geological storage in depleted gas field. Comparisons are made with sub-critical PC plants. All coal plant is assumed to be equipped with NO_x, particulates and SO_2 removal processes. The NGCC plant has NO_x control.
Technological Assumptions: Considers power plants located on the east Coast of the UK. The power generation capacity for all non CCS cases is kept at 500 MW with a 75% load factor. Reduction in efficiency of plant with CCS: 5.6-18.2%, increase in fuel consumption with CCS (g/kWh) 15-30%.
Methodological Assumptions: Cradle to grave evaluation of electricity generation with and without CCS. The functional unit is 1 kWh net generated. Upstream and downstream processes are included for all activities including material and fuel production, transport, plant construction, fuel handling, power generation pollutant removal, CCS, decommissioning and waste transport and disposal. SimaPro is used to make the assessments and data are derived from Ecoinvent for western Europe and UK input/output tables. 100 km is assumed as the transport distance for coal and materials, and 300 km for CO_2 transport. Sensitivity analysis is carried out for key parameters and the outcomes presented. Allocation procedures are not clear.
Overview of Transparency: Moderate transparency
Reviewer: Anna Evans
Headline Results: GHG emissions of CCS (kg CO_2eq/kg stored CO_2): not found.

Ref. No. 113: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Impacts of Biomass Electricity in 2020: scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK, by A. L. Stephenson and D. J. C. MacKay, URN 14D/243, Department of Energy and Climate Change, London, United Kingdom, July 2014.
Stated LCA Purpose, and Defined LCA Goal and Scope: The one of the aims of this report is to estimate the greenhouse gas emission intensities (in kg CO_2eq/MWh delivered energy) of using pellets derived from wood biomass sources in North American forest for electricity generation in the UK, accounting for the impacts omitted by the European Commissions' Renewable Energy Directive methodology (by including emissions or sequestration from carbon stock changes on the land, foregone carbon sequestration, and indirect impacts). The LCA goal is not defined further. The LCA scope is not defined further than specification of the bioenergy pathways.
Technological Coverage: Electricity generation by dedicated power only plants in the United Kingdom from combustion of wood pellets derived from roundwood, pulpwood, forest residues, deadwood from natural disturbances and sawmill residues, variously, from forests and plantations, managed under different practices, as relevant, in South United States of America, and East and Pacific Canada (combinations amount to 29 scenarios, taking into account selected counterfactuals).
Technological Assumptions: Information on all technological assumptions are provided in the Biomass Emissions and Counterfactuals (BEAC) model which consists of an MS Excel workbook. Default values of data are embedded in this model for the scenarios considered are too extensive to list here.
Methodological Assumptions: The functional unit for this LCA study is 1 MWh of delivered electricity (at the power plant). BEAC model adopts consequential LCA methodology which takes into account carbon stock changes, direct land use changes, land use displacement (in effect, indirect land use change) and counterfactuals (especially in the case of products previously used for other [usually material] purpose being diverted to bioenergy use). Available time horizons consist of 20, 40 and 100 years. GHG emissions associated with the manufacture of plant, machinery and vehicles are not included. Results are aggregated into total GHG emissions using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O.
Overview of Transparency: High transparency (when accessing the BEAC model)
Reviewer: Nigel Mortimer
Headline Results: Ranges of GHG emissions for electricity at the power plant based on the combustion of imported wood pellets derived from: sawmill residues = – 17 to + 121 kg CO_2eq/MWh; forest residues = – 14 to + 826 kg CO_2eq/MWh (40 year time horizon) and – 14 to + 536 kg CO_2e/MWh (100 year time horizon); deadwood from natural disturbances = – 7 to + 531 kg CO_2eq/MWh (40 year time horizon) and – 7 to + 241 kg CO_2eq/MWh (100 year time horizon); roundwood from increased harvesting of naturally-regenerated timberland = + 1270 to + 3988 kg CO_2eq/MWh (40 year time horizon) and + 766 to + 5174 kg CO_2eq/MWh (100 year time horizon); roundwood from existing plantations = - 2504 to + 1692 kg CO_2eq/MWh (40 year time horizon) and - 78 to + 949 kg CO_2eq/MWh (100 year time horizon); wood for bioenergy displacing non-bioenergy uses = + 144 to + 1893 kg CO_2eq/MWh (40 year time horizon) and + 127 to + 1761 kg CO_2eq/MWh (100 year time horizon); new plantations on naturally-regenerated timberland in South United States of America = - 185 to + 870 kg CO_2eq/MWh (40 year time horizon) and + 62 to + 561 kg CO_2eq/MWh (100 year time horizon); and new plantations on abandoned agricultural land = - 2093 to + 1526 kg CO_2eq/MWh (40 year time horizon) and - 263 to + 929 kg CO_2eq/MWh (100 year time horizon).

Ref. No. 114: Details of LCA Study/Calculation Tool/Database/Review: Life Cycle Impacts of Forest Management and Wood Utilization on Carbon Mitigation: knows and unknowns, by B. Lippke, E. Oneil, R. Harrison, K. Skog, L. Gustavsson and R. Sathre, Carbon Management, Vol. 2, pp. 303 - 333, 2011. DOI: 10.4155/CMT.11.24
Stated LCA Purpose, and Defined LCA Goal and Scope: This is a review paper with the objective to show the extent to which recent research findings on life cycle carbon accounting across all stages of processing, from cradle-to-grave, can identify opportunities for carbon mitigation improvement, which can contribute to global carbon objectives and national energy independence objectives. This is not a single, defined LCA study, as such. The review includes discussion of differences in results generated by attributional and consequential LCA (CLCA) studies. Implicitly, there is greater focus on CLCA as the ultimate purpose, given the stated objective of the review.
Technological Coverage: Forest management to produce multiple feedstocks, including bark, sawdust, slabwood, sawmill residues and woodchips, from forestry, used for electricity generation. Material wood products, co-produced with energy products, are included (there is no particular focus on bioenergy in this paper). There is a particular focus on evidence from, and relevance to, the USA and Sweden.
Technological Assumptions: Electricity generation, but no details on specific technologies. Also includes use of mill waste for internal energy use, displacing natural gas.
Methodological Assumptions: Primarily a review paper of techniques but considers five examples of different forest management and wood use strategies which are modelled using a combination of attributional life cycle inventories as input data to CLCA. The strategies consider different options for substitution of harvested wood products and bioenergy. The modelled examples use life cycle inventories from the CORRIM database. Forest management activities, including timber removal and forest regeneration are modelled using the Forest Vegetation Simulator (FVS) within the large-scale simulation framework of the Landscape Management System software. Forest carbon cycle modelling includes stem wood, branches, dead and dying litter and roots.
Overview of Transparency: Low transparency
Reviewer: Geoff Hogan, Ewan Mackie and Robert Matthews
Headline Results: A summary of results for the five examples of forest management and wood use strategies are difficult to interpret because they are presented unconventionally. However, the results suggest that active management of forests and use of wood for materials and bioenergy achieves greater mitigation of GHG emissions compared with maximising the conservation of carbon stocks in forests, by between 2.9 and 9.7 t Ceq/ha/a. These results are characterised as low confidence principally owing to the unconventional method of presentation and consequent difficulties in applying the results in other contexts.

Ref. No. 126: Details of LCA Study/Calculation Tool/Database/Review: Multi Criteria Evaluation of Wood Pellet Utilization in District Heating Systems, by S. Ghafghazi, PhD Thesis, The University of British Columbia, Vancouver, Canada, 2011
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was addressed to policy makers /stakeholders for increasing the use of bioenergy and achieving GHG emissions reductions. The LCA goal was to determine the life-cycle environmental impacts of utilising wood pellet in district heating (DH) and to compare these with DH using natural gas (and recovered sewer heat and geothermal heat). The LCA scope covers heating technology, system efficiency, capital investment, operating costs, system emissions with impacts including effects on human health, ozone layer depletion, effects on aquatic and terrestrial ecosystems (eco toxicity, acidification, nitrification/eutrophication), global warming, non-renewable energy consumption, and mineral extraction.
Technological Coverage: Wood pellets are derived from Canadian sawmills residues (sawdust), involving stemwood harvesting, transportation, sawmill operations and pelletising) and used for DH production (by combustion on a grate burner, gasifier and powder burner).
Technological Assumptions: An existing DH plant, supplied by wood pellets, sewer heat or natural gas, has a base load heat output rating of 2.5 MW and a peak heat output rating of 10 MW peak output (supplied by natural gas). 1.56 t of sawdust are used to produce 1 t of wood pellets. Sawdust is transported, on average, a distance of 27 km by trucks to wood pellet producing plants. 0.267 t of sawdust is used as a drying fuel in the pellet plant to produce 1 t of wood pellets. 253 kg of wood pellets, with a calorific value of 5.28 kWh/kg, are required to produce 1 MWh heat based on a thermal efficiency of 75% for the DH boiler.
Methodological Assumptions: The functional unit is 1 MWh of heat produced at the DH plant. Fuel production and transportation (road and rail including storage), electricity generation and transmission, and DH plant operation and dismantling are taken into account. Land use is not considered. Major materials used for DH plant construction (only some parts), as well as landfilling or recycling of materials after DH plant dismantling. It appears than the manufacture of trucks and trains used for fuel transportation are not included. SimaPro v7.0 software is used.
Overview of Transparency: Moderate transparency
Reviewer: Maha Elsayed
Headline Results: Non-renewable energy requirements are estimated to be 208 MJ/MWh of heat using wood pellets compared with 4390 MJ/MWh of heat using natural gas. Total GHG emissions are estimated to be 39 kg CO_2eq/MWh of heat using wood pellets compared with 240 kg CO_2eq/MWh of heat using natural gas.

NORTH ENERGY

Ref. No. 128: Details of LCA Study/Calculation Tool/Database/Review: Potential Effects of Intensive Forestry on Biomass Production and Total Carbon Balance in North-Central Sweden, by B. C. Poudel, R. Sathre, J. Bergh, L. Gustavsson, A. Lundström and R. Hyvönen, 2012 Environmental Science and Policy, Vol. 15, pp. 106 – 124, 2012. DOI: 10.1016/j.envsci.2011.09.005
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose is to calculate the potential climate change mitigation feedback effect due to the resulting increased carbon stock and increased use of forest products. The LCA goal and scope are: (i) to estimate the increased biomass availability and the potential to use the additional forest production to substitute for non-renewable materials and fuels, (ii) to estimate the effects of biomass removals on the carbon stock in living tree biomass and forest soils, (iii) to quantify the emissions due to forest operations and emissions (CO_2, N_2O, and CH_4) associated with fertilizer production and use, and (iv) to quantify the overall carbon balance of each scenario based on the changes in carbon stock in forest biomass, forest soils and wood products, and the avoided fossil emissions due to biomass substitution.
Technological Coverage: Three scenarios and a reference scenario (representing current practice), with varying levels of forest management and supply of multiple feedstocks from forestry in north-central Sweden (5.4 Mha total area, 4.3 Mha available for production), from stemwood harvesting or whole-tree harvesting (including branches, foliage and tops), with allocation between material wood products and bioenergy for electricity generation. The biomass conversion technology is power only generation. The focus as much on the use of wood for material products as on the use of wood for energy.
Technological Assumptions: The scale of application is specified in terms of the forest area considered. All biomass harvested or extracted in the scenarios is assumed to be used in the building sector, substituting for a range of counterfactuals, or as bioenergy, substituting for coal or natural gas in electricity generation. A summary information (e.g. tree species composition, growth rates, age distributions) is provided. Details of power plants are not given.
Methodological Assumptions: The functional unit is, in effect, the specified forest area. Although it was intended to include all relevant GHG emissions, it is possible that some are not included, e.g. those associated with plant and machinery manufacture and maintenance. Carbon sequestration and GHG emissions (certainly in the case of fertiliser inputs, not explicitly stated in the case of other inputs), associated with forest management, wood products, bioenergy, and alternative material and fossil-fuel supply chains are considered. GHG emissions are aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O. The time period is from 2010 to 2109, broken down into 10-year time steps. Three different models are used to quantify forest net primary production (BIOMASS model), forest production and harvest potential for each scenario (HUGIN) and litter and soil carbon (Q-model). GHG emissions associated with forest management, biomass and bioenergy supply and consumption, processing of biomass products and their counterfactuals (to determine substitution impacts) are calculated from previously-published values for GHG emissions factors of wood biomass products and counterfactuals. Allowances are made for changes in heating efficiencies of buildings due to substitution of material wood products for counterfactuals. GHG emissions associated with the disposal at end-of-life of material wood products and their counterfactuals are not included assuming wood construction products will last longer than the chosen time horizon.
Overview of Transparency: Low transparency
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains. Results give total impacts on GHG emissions for the forest area for each management scenarios, for which there are multiple material and bioenergy products.

Ref. No. 137: Details of LCA Study/Calculation Tool/Database/Review: Scottish Government Biomass Incentives Review: best use of wood fibre, R. Matthews, N. Mortimer, E. Mackie, C. Hatto, A. Evans, O. Mwabonje, T. Randle, W. Rolls, M. Sayce and I. Tubby, Forestry Commission Research Report, Edinburgh, United Kingdom, 2012.
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to determine (1) whether there are priority applications for the substantial and sustainable yet ultimately limited source of biomass supply in Scotland; and (2) whether it is better to use specific types or sources of wood for heating, or in combined heat and power (CHP) generation or in power only plants, or for the manufacture of wood-based materials.
Technological Coverage: Multiple feedstocks, including wood chips, logs, wood pellets and briquettes, from forestry in Scotland, represented as a single characteristic forest type, consisting of coniferous forests already under management for production of timber and/or wood fuel. Biomass conversion technologies include small scale heat, power only and combined heat and power (CHP). The focus was as much on the use of wood for the manufacture of material products as on the use of wood for energy.
Technological Assumptions: Biomass supply from the forestry system is considered at the scale of theoretical 1 ha stands of trees, and the use of harvested biomass is then tracked through to end use. The implicit scale is, thus, 1 ha of forest area, or a quantity of biomass supplied by the forest area. Biomass is used as energy or as materials, substituting for a range of counterfactuals. Details of assumptions about the forestry system are given in the report, details of the technological assumptions are only provided in workbooks.
Methodological Assumptions: The functional unit is 1 ha of forest. All relevant GHG emissions including those associated with plant and machinery manufacture and maintenance are covered. Carbon sequestration and GHG emissions associated with forest management, wood products, bioenergy and alternative material and fossil-fuel supply chains are considered. Results were based on estimated CO_2, CH_4 and N_2O emissions which are aggregated using Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O. The CSORT model is used to model the flows of biomass carbon (C) within forests (annual changes in C stocks in trees, litter and soil), and the supply of biomass feedstocks for potential use as types of material or bioenergy. Supply chain emissions up to the forest gate are also modelled using CSORT. Processing GHG emissions associated with biomass products and their counterfactuals are calculated using bespoke MS Excel workbooks. Full LCA calculations of GHG emissions associated with biomass and bioenergy supply and consumption, including end-of-life disposal of wood materials, were based on bespoke workbooks in conjunction with the outputs produced by the CSORT model. Calculations covered each specified chain for the generation of bioenergy or the provision of wood products from sawlogs, roundwood, bark and branchwood representing the stages in each chain, the quantities of wood involved, the amounts of bioenergy or wood products available from each chain, the calculation of GHG emissions at each stage in the chain, and finally summaries of total GHG emissions for each chain. A similar approach was adopted for the calculation of GHG emissions associated with counterfactuals to biomass and bioenergy products; results for counterfactual products were then compared with those for the biomass and bioenergy products.
Overview of Transparency: Low transparency (with access to report only). High transparency (with access to models and workbooks)
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains. Results are presented for a functional unit of 1 ha of forest for which there were multiple biomass products and bioenergy outputs depending on specific scenarios.

Ref. No. 147: Details of LCA Study/Calculation Tool/Database/Review: The Climate Effect of Increased Forest Bioenergy Use in Sweden: evaluation at different spatial and temporal scales, by O. Cintas, G. Berndes, A. L. Cowie, G. Egnell, H. Holmström and G. I. Ågren, WIREs Energy Environment, 2015. DOI: 10.1002/wene.178
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to: (1) describe common methodological choices and assumptions in assessments of GHG balances for bioenergy systems that use biomass from long-rotation forestry as feedstock; (2) clarify how these choices and assumptions influence assessment outcomes; and (3) discuss the GHG and associated climate effects of increasing forest harvest for energy use. The stated purpose covers some but not all aspects of the defined LCA goal explicitly.
Technological Coverage: A range of scenarios based on theoretical and "real" forest areas relevant to Sweden, variously involving supply of wood chips from branchwood, stumps and stemwood, and bark, used for heat, power or combined heat and power (CHP) with district heating (DH), with some material used for energy within the sawmill or pulp plant – i.e. combusted for heat. Material wood products, co-produced with the energy products, are included.
Technological Assumptions: Forestry systems are considered in terms of theoretical single stands, theoretical "landscapes" and based on forest inventory data for forest areas regarded as forming the catchments for three Swedish cities for the supply of wood bioenergy. Only limited information is given about detailed technological assumptions, e.g. assumed thermal efficiencies of heat only (89%), power only (38%) and CHP (85%) plants.
Methodological Assumptions: The functional unit is 1 ha of forest. The results are presented in terms of carbon (C) balances, "CRF" (Cumulative Radiative Forcing), and global mean temperature change (ΔT). Carbon sequestration and GHG emissions, i.e., CO_2, N_2O, and CH_4, associated with wood products, bioenergy, and alternative fossil fuel supply chains are considered when calculating CRF and ΔT, but other climate forcers, such as albedo, black and organic carbon aerosols, and ozone precursors, are outside the scope of this paper. The calculation of CRF and ΔT refers to recommendations and Global Warming Potentials from the IPCC 5th Assessment Report. Changes in biogenic forest carbon stocks are modelled in detail. The model output is used to quantify, on an annual basis, (1) the C stored in the forest (trees, litter and soil), forest products, and atmosphere pools; (2) the C emissions associated with changes in these C pools; and (3) the avoided emissions of fossil C. In addition, the supply chain emissions for wood products and fossil fuels are added so that GHG emissions can be obtained. Results are presented as C stock changes in the different pools. The CAfBio model is used to model the flows of biomass C within the forest industry and society where the forest products are used. Supply chain emissions are based on Ecoinvent 2.0 and calculated with the GABI software.
Overview of Transparency: Low transparency
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No relevant LCA results presented for individual bioenergy value chains. However, results in terms of cumulative net changes of GHG emissions per ha of forest over time horizons of 100 and 300 years (one and three forest rotations, respectively), indicating the times by which net GHG emissions reductions are achieved.

Ref. No. 148: Details of LCA Study/Calculation Tool/Database/Review: The Comparative Life Cycle Assessment of Power Generation from Lignocellulosic Biomass, by X. Shen, R. R. Kommalapati, and Z. Huque, Sustainability, Vol. 7, pp. 12974 – 12987, 2015. DOI: 10.3390/su71012974
Stated LCA Purpose, and Defined LCA Goal and Scope: The LCA purpose was to address the reduction of GHG emissions and increase the use of renewable energy in the USA (possibly for informing policy makers and promoting sustainability). The LCA goal was to evaluate power generation from lignocellulosic biomass and to compare the effects of using different feedstocks, transportation, and power generation technologies. The LCA scope covered evaluation of different models of LCA to identify the environmental impacts of different types of lignocellulosic biomass during the whole process of power generation through energy, supply consumption and GHG emissions. i.e. from biomass plantation to waste releases in power plants.
Technological Coverage: The lignocellulosic biomass considered consisting of bales of Miscanthus and switchgrass; chips and pellets from forestry residues and poplar and willow short rotation coppice (SRC); and bales and pellets from agricultural residues (corn stover, rice straw and wheat straw), used for electricity generation by direct combustion in dedicated combined heat and power (CHP) plants; co-firing with coal on power only plants; and gasification for gas turbine power only plants.
Technological Assumptions: No specific details are provided relative to the results presented. Generalised data are provided for the production of various biomass feedstocks and the specification of biomass power plants.
Methodological Assumptions: The functional unit consists of the daily operation of a 1 MW plant (but the daily outputs of electricity and/or heat, where relevant, are not specified). The system boundary extends from biomass plantation, transportation, pellet production, power generation and ends at waste released from power plants. Neither environmental impacts of land-use change, either direct or indirect, nor impacts resulting from establishing new infrastructure for power plants are taken into account. Emissions analysis is limited to parameters available in GREET.net 2014 (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, 2014 version), using the mode of “well-to-pump” in simulations. VOC, CO, NOx, PM10 and PM2.5, and the GHG emissions were investigated.
Overview of Transparency: Low transparency
Reviewer: Maha Elsayed
Headlines Results: Results are presented for the daily emissions of CO_2, CH_4, N_2O and GHGs from “electricity generation” (type of power plant not indicated) from Miscanthus, switchgrass, forest residues, and poplar and willow SRC. These results could not be reconciled as daily CO_2 emissions exceed daily GHG emissions.

Ref. No. 151: Details of LCA Study/Calculation Tool/Database/Review: The Environmental and Economic Sustainability of Potential Bioethanol from Willow in the UK, by A.L. Stephenson, P. Dupree, S.A. Scott and J.S. Dennis, Bioresource Technology, Vol. 101, pp. 9612 – 9623, 2010. DOI: 10.1016/j.biortech.2010.07.104	
Stated LCA Purpose, and Defined LCA Goal and Scope: This study investigates the environmental and economic sustainability of a potential operation in the UK in which ethanol is produced from the hydrolysis and subsequent fermentation of coppice willow. The goal and scope of the study are not clearly defined.	
Technological Coverage: Willow grown and cultivated in the UK and Poland (base case = the land was previously idle uncultivated land), pre-treatment (mechanical comminution and steam explosion with 0.5wt% sulphuric acid), detoxification of pre-treated steam with calcium hydroxide, simultaneous saccharification and fermentation for production of ethanol and lignin by-product, product recovery, blending and distribution, waste water treatment, combustion of lignin by-product.	
Technological Assumptions: Data for common practice and cultivation of willow was taken from the literature (mainly Defra sources). As no second-generation ethanol plant in commercial operation at the time of writing, the process information was taken from literature (2000 t/day plant from corn stover producing 2 x 10^5 tonnes ethanol per annum) and assumes saccharification and fermentation process occur simultaneously.	
Methodological Assumptions: The functional unit is 1 t of ethanol which has been blended to a given fractional volume with conventional, fossil, derived gasoline, delivered to a filling station in the UK and combusted in a typical, compact sized car. The control volume encompasses all the stages directly used to produce ethanol (cultivation of willow and conversion to ethanol) and the background system which comprises the homogenous markets providing the materials and energy used by the foreground system. Performed according to ISO 14040 and 14044 with the aid of Gabi 4 software. Cradle to grave analysis from cultivation of the willow to combustion in a car engine. The study uses the EDIP 2003 methodology and reports GHG emissions as kg CO_2e/t ethanol over a time horizon of 100 years as well as the fossil energy requirements. The base case scenario assumes land used for growth of crops had previously been idle cultivated land thus would not cause any direct or indirect greenhouse gas emissions. Carbon sequestration calculations (i.e. carbon sequestered by the willow during growth) were based on the model by Grogan and Matthews (2001). The system expansion allocation method was used where surplus electricity was generated from the combustion of the lignin by-product where it was assumed the electricity generated would displace the corresponding amount from the national grid. Allocation by energetic content was used in the sensitivity analysis. Results were compared with fossil-based gasoline, using literature values.	
Overview of Transparency: Moderate transparency	
Reviewer: Paula McNamee	
Headline Results: GHG emissions for base case scenario: production in UK = – 217 kg CO_2eq/t ethanol, giving 88% saving compared to fossil-derived gasoline on an energy basis (emissions factor of 305 kg CO_2e/MWh), or 37 kg CO_2eq/MWh; production in Poland = - 342 kg CO_2eq/t ethanol (85% saving compared to fossil-derived gasoline on an energy basis) or 46 kg CO_2eq/MWh. Fossil energy requirements for base case scenario: production in UK = – 5.2GJ/t ethanol (83% saving compared to fossil-derived gasoline on an energy basis); production in Poland = - 6.3 GJ/t ethanol (85% saving compared to fossil-derived gasoline on an energy basis)	

Ref. No. 152: Details of LCA Study/Calculation Tool/Database/Review: The Influence of Organic and Inorganic Fertiliser Application Rates on UK Biomass Crop Sustainability, P. Gilbert, P. Thornley and A. B. Riche, Biomass and Bioenergy Vol. 35, pp. 1170 – 1181, 2011. DOI: 10.1016/j.biombioe.2010.12.002
Stated LCA Purpose, and Defined LCA Goal and Scope: The purpose is to examine the LCA of current agronomic practice in the UK for short rotation coppice (SRC) willow and Miscanthus energy crop production and investigate how variations in fertiliser sources (in particular, sewage sludge) and application rates affect the resultant GHG emissions. The paper also evaluates the rationale for any impact of different LCA allocation approaches on the final results for GHG emissions, and eutrophication and acidification potentials. The goal of this study was to determine the environmental impacts for large-scale biomass cultivation under UK conditions, using different fertiliser options for crop nutrition. Sewage sludge application was investigated and compared to the use of an inorganic fertiliser equivalent and an option for no fertiliser control. Direct emission allocation from sewage sludge was also investigated as to whether emissions should be attributed to the wastewater treatment companies or the grower.
Technological Coverage: SRC Willow and Miscanthus grown on previously arable crop land. Ground preparation, planting (willow at a 15,000 cuttings/ha density), harvesting and restoration, transport and delivery of biomass (1MJ).
Technological Assumptions: SRC cultivated within a 25 km radial catchment area on previously arable crop land. SRC yield of 30 odt/ha at 50% moisture content. Natural drying reduces moisture content to 30% after 30 days. Miscanthus yield of 14 odt/ha with an as received moisture content of 25%. (Although not investigated in depth, the study does briefly mention that using sewage sludge in an incineration with energy recovery system alongside waste would result in greater CO_2 eq savings however could result in higher impacts on human ecotoxicity.)
Methodological Assumptions: Functional unit of1 MJ biomass which has been delivered 90 km to the end-user (25 km maximum radius to end-user, with 50 km round-trip and 1.8 tortuosity factor (to compare with 1MJ natural gas). System boundary only up to the delivery of the fuel. In accordance with ISO 14040. SimaPro 7.1 was used to determine the environmental impacts of different rates of fertiliser application and resultant emission allocations. Ecoinvent was used as a reference for the life-cycle inventory data and for impact assessment methodology. Cradle to gate analysis which covers cultivation to delivery of fuel to end user. Co-product function is a 'waste disposal function' and so the environmental impacts associated with the application of sewage sludge must be apportioned correctly. Allocation of emissions from sewage sludge fertiliser performed in the sensitivity analysis for whereby 0% of emissions were attributed to the grower, 30% to the grower and 100% to the grower. GWP (100) is determined for each emission allocation options (as well as acidification and eutrophication potentials for each option). Study assumes use of arable land with no carbon credit or penalty for land-use change. Sensitivity analysis investigates changes to N_2O emissions factor (from 0-3%) and crop yield improvement (+/- 25%).
Overview of Transparency: High Transparency
Reviewer: Paula McNamee
Headline Results: SRC willow: (1) no fertiliser = 187 kg CO_2eq/MWh; (2) inorganic fertiliser = 184 kg CO_2eq/MWh; (3a) sewage sludge (0% to grower) = 187 kg CO_2eq/MWh; (3b) sewage sludge (30% to grower) = 187 kg CO_2eq/MWh; and (3c) sewage sludge (100% to grower) = 184 kg CO_2eq/MWh. Miscanthus: (1) no fertiliser = 202 kg CO_2eq/MWh; (2) inorganic fertiliser = 194 kg CO_2eq/MWh; (3a) sewage sludge (0% to grower) = 198 kg CO_2eq/MWh; (3b) sewage sludge (30% to grower) = 198 kg CO_2eq/MWh; and (3c) sewage sludge (100% to grower) = 194 kg CO_2eq/MWh.

NORTH ENERGY

Ref. No. 155: **Details of LCA Study/Calculation Tool/Database/Review:** The Potential Role of Forest Management in Swedish Scenarios Towards Climate Neutrality by Mid Century, by O. Cintas, G. Berndes, J. Hansson, B. C. Poudel, J. Bergh, P. Börjesson, G. Egnell, T. Lundmark and A. Nordin, Forest Ecology and Management, 2016. DOI: 10.1016/j.foreco.2016.07.015	
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to quantify, by means of modelling, carbon and GHG emissions balances associated with forest management and the production and use of forest products.	
Technological Coverage: Forestry management and the use of wood for electricity, heat and transport fuel production relevant to scenarios used in the 2050 Swedish national roadmap.	
Technological Assumptions: No details of the technological assumptions adopted in modelling are provided in this paper.	
Methodological Assumptions: This paper is not, strictly speaking, an LCA study. Instead, it is implied that relevant results from other LCA studies (not generally referenced) are adopted in the modelling framework, the nature and results of which are the main foci of the paper. However, based on the attention given to displacement effects and the counterfactuals of forest wood products and fuels, it is apparent that the modelling undertaken is consistent with consequential LCA.	
Overview of Transparency: Low transparency	
Reviewer: Nigel Mortimer	
Headline Results: No LCA results presented for individual bioenergy value chains	

Ref. No. 157: Details of LCA Study/Calculation Tool/Database/Review: Understanding the Carbon and Greenhouse Gas Balance of UK Forests, by J. I. L. Morison, R. Matthews, G. Miller, M. Perks, T. Randle, E. Vanguelova, M. White and S. Yamulki, Forestry Commission, Edinburgh, United Kingdom, 2012.
Stated LCA Purpose, and Defined LCA Goal and Scope: This is not an LCA study. This is a review report, with a stated aim to produce a summary of the key information known and not known on the stocks and fluxes of carbon and the fluxes of other greenhouse gases in UK forests, and how they are affected by forest dynamics, management and operations.
Technological Coverage: Forest establishment, management and harvesting in the UK. Limited consideration of biomass use (carbon retained in harvested wood products, high level consideration of substitution impacts).
Technological Assumptions: Carbon dynamics and wood production from example UK forestry systems are considered at the scale of theoretical 1 ha stands of trees, and the use of harvested biomass is then tracked through to allow for carbon retained in wood products. The implicit scale is, thus, 1 ha of forest area, or a quantity of biomass supplied by the forest area. Biomass is used as energy or as materials, substituting for a range of counterfactuals. Details of assumptions about the example forestry systems are provided. However, details of the technological assumptions adopted in modelling are not provided (they were not relevant to this review report).
Methodological Assumptions: The key components of the forestry carbon (C) balance are illustrated: accumulation of C in trees (and the influence of stand management), stocks of C in litter, in soil, and in harvested wood products (HWP) and the C impacts of substitution by wood products for fossil fuel intensive materials. The potential impacts of stand management on the development of C stocks and sequestration over time are explored by referring to results from the CSORT forest carbon accounting model for five different woodland type/management combinations. Soil carbon stocks are illustrated for seven main soil groups using data from the UK BioSoil Network of soil carbon monitoring plots. The impacts of the utilisation of harvested wood for substitution for other products in a range of applications, including fuel, are illustrated using results from the CARBINE and CSORT forest carbon accounting models.
Overview of Transparency: High transparency
Reviewer: Geoff Hogan, Ewan Mackie, Robert Matthews
Headline Results: No LCA results presented for individual bioenergy value chains

Ref. No. 159: Details of LCA Study/Calculation Tool/Database/Review: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: Well-to-Tank Appendix 4 – version 4.0 description, results and pathway input data per pathway, by R. Edwards, J.-F. Larivé, D. Rickeard and W. Weindorf, Technical Report by the Joint Research Centre of the European Union, Ispra, Italy, July 2013. DOI: 10.2788/40526
Stated LCA Purpose, and Defined LCA Goal and Scope: The stated purpose was to establish the GHG emissions balances for different production routes to fuels for road transport powertrains in order to answer the following questions: “what are the alternative uses for a given resource and how can these best be used; and what are the alternative pathways to produce a certain fuel and which of these hold the best prospects?”
Technological Coverage: A very large range of technologies including pathways for conventional and future fossil fuel, nuclear, bioenergy and other renewable energy for providing fuels (liquid fuels, hydrogen and electricity) for passenger road transport vehicles. Relevant bioenergy pathways consisted of production of heat only, electricity only, combined heat and power (CHP), and ethanol from forest residues, poplar and willow short rotation coppice (SRC) and wheat straw.
Technological Assumptions: European Union (EU) forest residues and SRF supplies wood pellets for heat only (combustion in small- and large-scale boilers), and wood chips for electricity only (combustion in dedicated 11.5 MW plant and coal co-fired plant, and 10 MW and 200 MW Integrated Gasification Combined Cycle [IGCC] plants) and CHP (combustion in small- to medium-scale plant) generation, and lignocellulosic ethanol production (Simultaneous Saccharification and Co-Fermentation [SSCF] plants with surplus electricity exports). EU wheat straw supplies bales rather than pellets for lignocellulosic ethanol production (SSCF plant with surplus electricity export).
Methodological Assumptions: The functional units are 1 MJ of electricity and 1 MJ of ethanol delivered to end users (but results are available at plant). Consequential LCA methodology is applied. All co-products are addressed with substitution credits. Carbon stock changes in forest and land use change with SRC are not evaluated. GHG emissions associated with the manufacture of machinery and the construction of plant are not taken into account. Workbooks provide results disaggregated into CO_2, CH_4 and N_2O. Aggregated results use Global Warming Potentials of 25 kg CO_2eq/kg CH_4 and 298 kg CO_2eq/kg N_2O.
Overview of Transparency: High transparency (workbooks for calculations with detail and assumptions provided)
Reviewer: Nigel Mortimer
Headline Results: GHG emissions for heat at boiler using wood pellets from forest residues range from 15 kg CO_2eq/MWh heat to 22 kg CO_2eq/MWh heat; and from SRC range from 23 kg CO_2eq/MWh heat to 31 kg CO_2eq/MWh heat. GHG emissions for heat at CHP plant using wood chips from forest residues are 0.4 kg CO_2eq/MWh heat; and from SRC are 5 kg CO_2eq/MWh heat. GHG emissions for electricity at dedicated plant using wood chips from forest residues are 24 kg CO_2eq/MWh electricity; and from SRC are 50 kg CO_2eq/MWh electricity; at coal co-fired plant using wood chips from forest residues are 29 kg CO_2eq/MWh electricity; and from SRC are 40 kg CO_2eq/MWh electricity; at 10 MW IGCC plant using wood chips from forest residues are 15 kg CO_2eq/MWh electricity; and from SRC are 39 kg CO_2eq/MWh electricity; at 200 MW IGCC plant using wood chips from forest residues are 19 kg CO_2eq/MWh electricity; and from SRC are 27 kg CO_2eq/MWh electricity; and at CHP plant using wood chips from forest residues are 6 kg CO_2eq/MWh electricity; and from SRC are 17 kg CO_2eq/MWh electricity. GHG emissions for ethanol at lignocellulosic plant using wood chips from forest residues are 64 kg CO_2eq/MWh ethanol; from SRC are 76 kg CO_2eq/MWh ethanol; and from wheat straw are 27 kg CO_2eq/MWh ethanol.

APPENDIX G: BIOENERGY LCA DATA COMPENDIUM

Figure G1 Recording Guidance from the Bioenergy LCA Data Compendium

Types of Data
This Data Compendium records, in suitable worksheets. the values of data used in the life cycle assessment workbooks developed for the specified bioenergy value chains in this particular project. These data are separated into two distinct categories: country/region-specific parameters and operational input datasets.
Country/region-specific Parameters
These data are relevant to specific countries or regions within countries. They mainly refer to the particular sources and essential characteristics of biomass feedstocks, or the necessary details of logistics related to the transport of biomass feedstocks in their different forms.
Operational Input Datasets
These combinations of data, in the form of consistent datasets, are related to particular activities which form parts of the specified bioenergy value chains. In many instances, it will be necessary to derive the relevant values of data within these datasets from basic data and, in order to assist with this, suitable formulae are embedded within the appropriate worksheets.
Worksheet Codes
Given the very large numbers of parameters and datasets that need to be recorded in their relevant worksheets, a simple coding system has been adopted and its details have been summarised accordingly. For convenience, codes covering similar parameters or datasets have been grouped together.
Selecting Likely Minimum and Likely Maximum Values
The data recorded in each worksheet are intended to reflect the possible range between the likely minimum and likely maximum values. The selection of data from referenced sources to achieve this will depend, ultimately, on experience and judgement. However, for the operational input datasets, the most important data, in terms of their contribution to greenhouse gas emissions, will be those which generate likely minimum and likely maximum values for fuel or electricity consumption. Hence, these data should determine the selected datasets. Furthermore, it is most probable that likely minimum values will reflect the larger machines or vehicle available, and the likely maximum values will reflect the smaller machines or vehicles available, based on assumed economies of scale. It is possible that entirely complete datasets might not be available in all instances, in which case values of data from other sources may be entered, especially if they result in relatively minor contributions to estimated greenhouse gas emissions (e.g. annual maintenance factors).
Notes and References
Space is provided for adding notes relating to values of specific data as well as for recording references (using reference codes relevant to each particular worksheet) which must be documented fully in each worksheet.
Additional Data Entry Guidance
Further guidance on data entry is provided in the form of notes that are specific to a given worksheet.
Average Values
The worksheets are set up to calculate arithmetic averages of values for specified data from the likely minimum and likely maximum values.
Data for Bioenergy Value Chain Worksheets
The data and their average values which will eventually be transferred over to the bioenergy value chain worksheets for use as default values are indicated in **bold** font. All other data and values are in normal font.

Figure G2 List of Worksheet Codes and their Bioenergy Value Chain Elements with Completed Datasets (excluding the worksheets containing the results of CARBINE modelling of forests)

Code	Bioenergy Value Chain Element
CFC-CAW	Conventional Forest (Conifer), Canada, Western Region
CFC-SBS	Conventional Forest (Conifer), Scandinavia and Baltic States
CFB-UK	Conventional Forest (Broadleaf), United Kingdom
CFC-UK	Conventional Forest (Conifer), United Kingdom
CFC-USNW	Conventional Forest (Conifer), United States of America, Northwestern Region
CFB-USSE	Conventional Forest (Broadleaf), United States of America, South/Southeastern Region
CFP-USSE	Conventional Forest (Pine), United States of America, South/Southeastern Region
PFP-USSE	Plantation Forest (Pine), United States of America, South/Southeastern Region
SRFB-UK	Short Rotation Forest (Broadleaf), United Kingdom
SRFC-UK	Short Rotation Forest (Conifer), United Kingdom
SRFB-US	Short Rotation Forest (Broadleaf), United States of America
SRFC-US	Short Rotation Forest (Conifer), United States of America
FYO	Forestry Operations
SRFO-UK	Short Rotation Forest Operations, United Kingdom
SRFO-US	Short Rotation Forest Operations, United States of America
SRCP-BE	Short Rotation Coppice (Poplar), Belgium
SRCW-BE	Short Rotation Coppice (Willow), Belgium
SRCP-FR	Short Rotation Coppice (Poplar), France
SRCW-FR	Short Rotation Coppice (Willow), France
SRCP-NL	Short Rotation Coppice (Poplar), the Netherlands
SRCW-NL	Short Rotation Coppice (Willow), the Netherlands
SRCP-PO	Short Rotation Coppice (Poplar), Poland
SRCW-PO	Short Rotation Coppice (Willow), Poland
SRCP-UK	Short Rotation Coppice (Poplar), United Kingdom
SRCW-UK	Short Rotation Coppice (Willow), United Kingdom
SRCO-EU	Short Rotation Coppice Operations, Europe

Code	Bioenergy Value Chain Element
MC-UK	Miscanthus, United Kingdom
MCO-UK	Miscanthus Operations, United Kingdom
WS-UK	Wheat Straw, United Kingdom
WSO-UK	Wheat Straw Operations, United Kingdom
TRTL-CAW	Timber Road Transport Logistics, Canada, Western Region
TRTL-SBS	Timber Road Transport Logistics, Scandinavia and Baltic States
TRTL-UK	Timber Road Transport Logistics, United Kingdom
TRTL-USNW	Timber Road Transport Logistics, United States of America, Northwestern Region
TRTL-USSE	Timber Road Transport Logistics, United States of America, South/Southeastern Region
TRT-EU	Timber Road Transport, Europe
TRT-NA	Timber Road Transport, North America
SMRTL-CAW	Sawmill Co-product Road Transport Logistics, Canada, Western Region
SMRTL-SBS	Sawmill Co-product Road Transport Logistics, Scandinavia and Baltic States
SMRTL-UK	Sawmill Co-product Road Transport Logistics, United Kingdom
SMRTL-USNW	Sawmill Co-product Road Transport Logistics, United States of America, Northwestern Region
SMRTL-USSE	Sawmill Co-product Road Transport Logistics, United States of America, South/Southeastern Region
SMRT-EU	Sawmill Co-product Road Transport, Europe
SMRT-NA	Sawmill Co-product Road Transport, North America
WCRTL-BE	Wood Chip Road Transport Logistics, Belgium
WCRTL-FR	Wood Chip Road Transport Logistics, France
WCRTL-NL	Wood Chip Road Transport Logistics, the Netherlands
WCRTL-PO	Wood Chip Road Transport Logistics, Poland
WCRTL-UK	Wood Chip Road Transport Logistics, United Kingdom
WCRT-EU	Wood Chip Road Transport, Europe

Code	Bioenergy Value Chain Element
MCRTL-UK	Miscanthus Chip Road Transport Logistics, United Kingdom
MCRT-UK	Miscanthus Chip Transport, United Kingdom
SBRTL-UK	Wheat Straw Bale Road Transport Logistics, United Kingdom
SBRT-UK	Wheat Straw Bale Road Transport, United Kingdom
WCS-L	Large-scale Wood Chip Storage
MCS-L	Large-scale Miscanthus Chip Storage
SCS-L	Large-scale Straw Bale Storage
TC-LS	Large-scale Stationary Timber Chipping
WCD-L	Large-scale Wood Chip Drying
MCD-L	Large-scale Miscanthus Chip Drying
SBD-L	Large-scale Wheat Straw Bale Drying
WCM-L	Large-scale Wood Chip and Sawmill Co-product Milling
MCM-L	Large-scale Miscanthus Chip Milling
SBM-L	Large-scale Wheat Straw Bale Milling
WP-L	Large-scale Wood Pelletising
MP-L	Large-scale Miscanthus Pelletising
SP-L	Large-scale Wheat Straw Pelletising
PTIL-BE	Pellet Inland Waterway Transport Logistics, Belgium
PTIL-FR	Pellet Inland Waterway Transport Logistics, France
PTIL-NL	Pellet Inland Waterway Transport Logistics, the Netherlands
PTIL-UK	Pellet Inland Waterway Transport Logistics, United Kingdom
PTIL-US	Pellet Inland Waterway Transport Logistics, United States of America
PTI-EU	Pellet Inland Waterway Transport, Europe
PTI-US	Pellet Inland Waterway Transport, United States of America

Code	Bioenergy Value Chain Element
PTRL-BE	Pellet Road Transport Logistics, Belgium
PTRL-CA	Pellet Road Transport Logistics, Canada
PTRL-FR	Pellet Road Transport Logistics, France
PTRL-NL	Pellet Road Transport Logistics, the Netherlands
PTRL-PO	Pellet Road Transport Logistics, Poland
PTRL-UK	Pellet Road Transport Logistics, United Kingdom
PTRL-US	Pellet Road Transport Logistics, United States of America
PTR-EU	Pellet Road Transport, Europe
PTR-NA	Pellet Road Transport, North America
PTTL-BE	Pellet Rail Transport Logistics, Belgium
PTTL-CA	Pellet Rail Transport Logistics, Canada
PTTL-FR	Pellet Rail Transport Logistics, France
PTTL-NL	Pellet Rail Transport Logistics, the Netherlands
PTTL-PO	Pellet Rail Transport Logistics, Poland
PTTL-UK	Pellet Rail Transport Logistics, United Kingdom
PTTL-US	Pellet Rail Transport Logistics, United States of America
PTT-EU	Pellet Rail Transport, Europe
PTT-NA	Pellet Rail Transport, North America
PTSL-BE	Pellet Ship Transport Logistics from Belgium to United Kingdom
PTSL-CAW	Pellet Ship Transport Logistics from Canada, Northwestern Region, to United Kingdom
PTSL-FR	Pellet Ship Transport Logistics from France to United Kingdom
PTSL-NL	Pellet Ship Transport Logistics from the Netherlands to United Kingdom
PTSL-PO	Pellet Ship Transport Logistics from Poland to United Kingdom
PTSL-UK	Pellet Ship Transport Logistics around United Kingdom
PTSL-USNW	Pellet Ship Transport Logistics from United States of America, Northwestern Region, to United Kingdom
PTSL-USSE	Pellet Ship Transport Logistics from United States of America, South/Southeastern Region, to United Kingdom
PTS-EU	Pellet Ship Transport, Europe
PTS-NAE	Pellet Ship Transport, North America, Eastern
PTS-NAW	Pellet Ship Transport, North America, Western

Code	Bioenergy Value Chain Element
MP-SHO	Small-scale Heat Only Production with Miscanthus Pellet-fired Boiler
SP-SHO	Small-scale Heat Only Production with Wheat Straw Pellet-fired Boiler
WP-SHO	Small-scale Heat Only Production with Wood Pellet-fired Boiler
MP-MHO	Medium-scale Heat Only Production with Miscanthus Pellet-fired Boiler
SP-MHO	Medium-scale Heat Only Production with Wheat Straw Pellet-fired Boiler
WP-MHO	Medium-scale Heat Only Production with Wood Pellet-fired Boiler
MP-MCHP	Medium-scale Miscanthus Pellet-fired Combined Heat and Power Generation
SP-MCHP	Medium-scale Wheat Straw Pellet-fired Combined Heat and Power Generation
WP-MCHP	Medium-scale Wood Pellet-fired Combined Heat and Power Generation
MP-LCHP	Large-scale Miscanthus Pellet-fired Combined Heat and Power Generation
SP-LCHP	Large-scale Wheat Straw Pellet-fired Combined Heat and Power Generation
WP-LCHP	Large-scale Wood Pellet-fired Combined Heat and Power Generation
MP-EO	Miscanthus Pellet-fired Electricity Only Generation
SP-EO	Wheat Straw Pellet-fired Electricity Only Generation
WP-EO	Wood Pellet-fired Electricity Only Generation
MP-EO-CC	Miscanthus Pellet-fired Electricity Only Generation with Carbon Capture
SP-EO-CC	Wheat Straw Pellet-fired Electricity Only Generation with Carbon Capture
WP-EO-CC	Wood Pellet-fired Electricity Only Generation with Carbon Capture
MP-EDH	Miscanthus Pellet-fired Electricity Generation and District Heating
SP-EDH	Wheat Straw Pellet-fired Electricity Generation and District Heating
WP-EDH	Wood Pellet-fired Electricity Generation and District Heating
MP-EDH-CC	Miscanthus Pellet-fired Electricity Generation and District Heating with Carbon Capture
SP-EDH-CC	Wheat Straw Pellet-fired Electricity Generation and District Heating with Carbon Capture
WP-EDH-CC	Wood Pellet-fired Electricity Generation and District Heating with Carbon Capture

Code	Bioenergy Value Chain Element
MP-GH	Hydrogen from Miscanthus Pellet Gasification
SP-GH	Hydrogen from Wheat Straw Pellet Gasification
WP-GH	Hydrogen from Wood Pellet Gasification
MP-GH-CC	Hydrogen from Miscanthus Pellet Gasification with Carbon Capture
SP-GH-CC	Hydrogen from Wheat Straw Pellet Gasification with Carbon Capture
WP-GH-CC	Hydrogen from Wood Pellet Gasification with Carbon Capture
MP-GHDH	Hydrogen and District Heating from Miscanthus Pellet Gasification
SP-GHDH	Hydrogen and District Heating from Wheat Straw Pellet Gasification
WP-GHDH	Hydrogen and District Heating from Wood Pellet Gasification
MP-GHDH-CC	Hydrogen and District Heating from Miscanthus Pellet Gasification with Carbon Capture
SP-GHDH-CC	Hydrogen and District Heating from Wheat Straw Pellet Gasification with Carbon Capture
WP-GHDH-CC	Hydrogen and District Heating from Wood Pellet Gasification with Carbon Capture
MP-GE	Electricity Only Generation from Miscanthus Pellet Gasification
SP-GE	Electricity Only Generation from Wheat Straw Pellet Gasification
WP-GE	Electricity Only Generation from Wood Pellet Gasification
MP-GE-CC	Electricity Only Generation from Miscanthus Pellet Gasification with Carbon Capture
SP-GE-CC	Electricity Only Generation from Wheat Straw Pellet Gasification with Carbon Capture
WP-GE-CC	Electricity Only Generation from Wood Pellet Gasification with Carbon Capture
MP-LPE	Ethanol from Lignocellulosic Processing of Miscanthus Pellets
SP-LPE	Ethanol from Lignocellulosic Processing of Wheat Straw Pellets
WP-LPE	Ethanol from Lignocellulosic Processing of Wood Pellets
CS	Carbon Storage
ASH-TR	Ash Transport by Road
ASH-DIS	Ash Disposal to Landfill
SN2O-AF	Soil Nitrous Oxide Emissions from Artificial N Fertiliser Application
SN2O-AR	Soil Nitrous Oxide Emissions from Agricultural Residue Incorporation

Code	Bioenergy Value Chain Element
NGH	Existing Natural Gas-fired Heating
BFB	Burning Forest Biomass
BWW	Burning Waste Wood

Figure G3 Colour Coding of Cells in Worksheets of the Bioenergy LCA Data Compendium

Cells available for entering data values have a light blue background =	
Cells which are not available for entering data values because they contain formulae have a rose background =	
Cells which contained values of data linked to the Emissions Factor Database have a light green background =	

Figure G4 Example of a Country/Region-Specific Parameter Worksheet from the Bioenergy LCA Data Compendium

ETI CARBON LIFE CYCLE ASSESSMENT EVIDENCE ANALYSIS: Bioenergy LCA Data Compendium							
Specific Parameters for Production of Miscanthus Chips at Plantation in United Kingdom							
Parameters	Units	Minimum Value	Notes and Source of Data	Maximum Value	Notes and Source of Data	Derived Average Value	Data Entry Guidance
Rhizome Planting Rate (for establishment)	**kg/ha**					**0**	Values of specific parameters for complete datasets. The production cycle covers establishment, harvesting and grubbing out. The yield is annualised over the rotation duration.
Nitrogen Fertiliser Application Rate (for establishment)	**kg N/ha**					**0**	
Phosphate Fertiliser Application Rate (for establishment)	**kg P_2O_5/ha**					**0**	
Potash Fertiliser Application Rate (for establishment)	**kg K_2O/ha**					**0**	
Lime Application Rate (for establishment)	**kg $CaCO_3$/ha**					**0**	
Manganese Application Rate (for establishment)	**l $MnSO_4$/ha**					**0**	
Herbicide Application Rate (for establishment)	**kg a.i./ha**					**0**	
Production Cycle	**a**					**0**	
Miscanthus Yield (annualised over production cycle)	**green t/ha.a**					**0**	
Miscanthus Moisture Content	**%**					**0**	
Miscanthus Milne Higher Heating Value (oven dry, ash free)	**MJ/t oven dry**					**0**	
Miscanthus Ash Content (oven dry)	**%**					**0**	
Miscanthus Hydrogen Content (oven dry)	**%**					**0**	

Figure G5 Example of an Operational Input Dataset Worksheet from the Bioenergy LCA Data Compendium

ETI CARBON LIFE CYCLE ASSESSMENT EVIDENCE ANALYSIS: Bioenergy LCA Data Compendium							
Input Datasets for Miscanthus Operations, United Kingdom							
Input Datasets	Units	Minimum Value	Notes and Source of Data	Maximum Value	Notes and Source of Data	Derived Average Value	Data Entry Guidance
Establishment Operations							Values for a complete dataset reflecting
Fuel Consumption Calculation Procedure (Power Rating or Fuel Rate)		Power Rating		Power Rating			a specific machine or group of machines
Power Rating of Machinery	kW						with each dataset representing a derived
Thermal Efficiency of Machinery	%						minimum or maximum value of the unit
Diesel Fuel Consumption Rate	l/h						diesel fuel consumption which is
Density of Diesel Fuel (off-road vehicles)	kg/l	0.840	Average of 0.835 to 0.845 kg/l	0.840	Average of 0.835 to 0.845 k		determined either using the power
Net Calorific Value of Diesel Fuel	MJ/kg	43.0	Default value of 43.00 MJ/kg fo	43.0	Default value of 43.00 MJ/k		rating of the machinery or its fuel
Productivity of Machinery	ha/h						consumption rate. The derived unit
Derived Unit Diesel Fuel Consumption for Establishment Operations	**MJ/ha**	#DIV/0!		#DIV/0!		#DIV/0!	manufacturing requirement is specified
Weight of Machinery	t						either in t or £(2004). The annual
Purchase Price of Machinery	£(2004)						maintenance factor is percentage of
Working Life of Machinery	a						machine purchase price. The derived
Annual Utilisation of Machinery	h/a						unit maintenance requirement is
Derived Unit Manufacturing Requirement of Establishment Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	specified either in t or £(2004).
Derived Unit Manufacturing Requirement of Establishment Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Annual Maintenance Factor of Machinery	%/a						
Derived Unit Maintenance Requirement of Establishment Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Derived Unit Maintenance Requirement of Establishment Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Cut and Chip Harvesting Operations							Values for a complete dataset reflecting
Fuel Consumption Calculation Procedure (Power Rating or Fuel Rate)		Power Rating		Power Rating			a specific machine or group of machines
Power Rating of Machinery	kW						with each dataset representing a derived
Thermal Efficiency of Machinery	%						minimum or maximum value of the unit
Diesel Fuel Consumption Rate	l/h						diesel fuel consumption which is
Density of Diesel Fuel (off-road vehicles)	kg/l	0.840	Average of 0.835 to 0.845 kg/l	0.840	Average of 0.835 to 0.845 k		determined either using the power
Net Calorific Value of Diesel Fuel	MJ/kg	43.0	Default value of 43.00 MJ/kg fo	43.0	Default value of 43.00 MJ/k		rating of the machinery or its fuel
Productivity of Machinery	ha/h						consumption rate. The derived unit
Derived Unit Diesel Fuel Consumption for Cut and Chip Harvesting Operations	**MJ/ha**	#DIV/0!		#DIV/0!		#DIV/0!	manufacturing requirement is specified
Weight of Machinery	t						either in t or £(2004). The annual
Purchase Price of Machinery	£(2004)						maintenance factor is percentage of
Working Life of Machinery	a						machine purchase price. The derived
Annual Utilisation of Machinery	h/a						unit maintenance requirement is
Derived Unit Manufacturing Requirement of Cut and Chip Harvesting Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	specified either in t or £(2004).
Derived Unit Manufacturing Requirement of Cut and Chip Harvesting Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Annual Maintenance Factor of Machinery	%/a						
Derived Unit Maintenance Requirement of Cut and Chip Harvesting Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Derived Unit Maintenance Requirement of Cut and Chip Harvesting Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Grubbing-out Operations							Values for a complete dataset reflecting
Fuel Consumption Calculation Procedure (Power Rating or Fuel Rate)		Power Rating		Power Rating			a specific machine or group of machines
Power Rating of Machinery	kW						with each dataset representing a derived
Thermal Efficiency of Machinery	%						minimum or maximum value of the unit
Diesel Fuel Consumption Rate	l/h						diesel fuel consumption which is
Density of Diesel Fuel (off-road vehicles)	kg/l	0.840	Average of 0.835 to 0.845 kg/l	0.840	Average of 0.835 to 0.845 k		determined either using the power
Net Calorific Value of Diesel Fuel	MJ/kg	43.0	Default value of 43.00 MJ/kg fo	43.0	Default value of 43.00 MJ/k		rating of the machinery or its fuel
Productivity of Machinery	ha/h						consumption rate. The derived unit
Derived Unit Diesel Fuel Consumption for Grubbing-out Operations	**MJ/ha**	#DIV/0!		#DIV/0!		#DIV/0!	manufacturing requirement is specified
Weight of Machinery	t						either in t or £(2004). The annual
Purchase Price of Machinery	£(2004)						maintenance factor is percentage of
Working Life of Machinery	a						machine purchase price. The derived
Annual Utilisation of Machinery	h/a						unit maintenance requirement is
Derived Unit Manufacturing Requirement of Grubbing-out Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	specified either in t or £(2004).
Derived Unit Manufacturing Requirement of Grubbing-out Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Annual Maintenance Factor of Machinery	%/a						
Derived Unit Maintenance Requirement of Grubbing-out Operations (weight-based)	**t/ha**	#DIV/0!		#DIV/0!		#DIV/0!	
Derived Unit Maintenance Requirement of Grubbing-out Operations (price-based)	**£(2004)/ha**	#DIV/0!		#DIV/0!		#DIV/0!	

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