UK ENERGY RESEARCH CENTRE

LIFE CYCLE ASSESSMENT IN THE BIOENERGY SECTOR:

DEVELOPING A SYSTEMATIC REVIEW

Working Paper

21st January 2008:
REF: UKERC/WP/FSE/2008/002

Rebecca Rowe, Dr. Jeanette Whitaker, Jennifer Chapman, David Howard and Professor Gail Taylor

Sponsored by:
UKERC and TSEC-BIOSYS

This document has been prepared to enable results of on-going work to be made available rapidly. It has not been subject to review and approval, and does not have the authority of a full Research Report.

THE UK ENERGY RESEARCH CENTRE

Operating at the cusp of research and policy-making, the UK Energy Research Centre's mission is to be the UK's pre-eminent centre of research, and source of authoritative information and leadership, on sustainable energy systems.

The Centre takes a whole systems approach to energy research, incorporating economics, engineering and the physical, environmental and social sciences while developing and maintaining the means to enable cohesive research in energy.

To achieve this we have developed the Energy Research Atlas, a comprehensive database of energy research, development and demonstration competences in the UK. We also act as the portal for the UK energy research community to and from both UK stakeholders and the international energy research community.

www.ukerc.ac.uk

THE FUTURE SOURCES OF ENERGY (FSE) THEME OF UKERC

UKERC's FSE research programme is weighted towards networking UK research programmes, including carbon capture and storage, fuel cells, solar PV, bioenergy and wave and tidal power. The key objective is to enable and integrate coherent and interlocking programmes of world-class research.

THE ENVIRONMENTAL SUSTAINABILITY (ES) THEME OF UKERC

Environmental Sustainability is a research and networking theme within UKERC. The over-arching goal of Environmental Sustainability is to develop and demonstrate an approach that can be used to appraise consistently the relationships between the environment and all fuel cycles.

Executive Summary

The UK and EU have pledged to increase the utilisation of biomass in the energy sector, for both heat and power generation, and liquid transport fuels, with the aim of reducing greenhouse gas (GHG) emissions and helping to achieve reduction targets. It is therefore necessary to critically assess complete bioenergy production chains to:

- ensure GHG and energy balances of production process are favourable
- identify areas within each production chain which are particularly inefficient, energy intensive, or emit high concentrations of GHGs
- highlight research and development (R&D) needs within the field

In order to fulfil these objectives, this study has reviewed hundreds of life cycle assessments (LCAs) relevant to the UK. Studies covered a range of bioenergy production systems within the sector, including seven broad methods of liquid transport fuel production and four sources of feedstock for heat and power production from biomass. These include bioenergy chains which are currently used commercially within the UK as well as those in R&D stages.

The study has used a systematic selection and analysis procedure to assess each LCA, collating data on the energy and GHG balances of liquid transport fuels and biomass for heat and power. This consistent approach will produce a dataset which can be used to uniquely compare the energy and GHG balances of these two uses of biomass. The representation of collated LCAs as straightforward visual summaries highlights variations within methodology, system boundaries and reporting.

Although this study is ongoing, several issues relating to the lack of transparency of LCA reporting have already become apparent. Common obstacles to reviewing this subject have been in successfully identifying system boundaries, co-product allocation methods and conversion efficiencies used in the LCAs being analysed. Therefore, a set of recommendations for LCA reporting are listed at the end of this report.

Acknowledgements
Jennifer Chapman, Gail Taylor, David Howard and Jeanette Whitaker were supported by UKERC during the course of this study, whilst Rebecca Rowe is a PhD student within the TSEC-BIOSYS consortium (http://www.tsec-biosys.ac.uk), studying the environmental impacts of SRC willow.

Contents

1. Introduction

The main sources of greenhouse gas (GHG) emissions generated in the UK are from the use of fossil fuels for heat and power and for transport (Figure 1) [3]. The UK Government is committed to decrease UK carbon emissions to a level that is 40% of the 1990 emission level by the year 2050 [1, 2]. In order to meet this target, energy from renewables is likely to increase, with the UK government pledging to increase the proportion of power supplied by alternative sources of energy from 4.2% in 2005 to 10% in 2010 [1, 2]. For transport, the government is promoting alternative transport solutions together with the development of cleaner fuels and low carbon fuels, such as biofuels. To increase the production and use of these fuels the EU and UK have set a target of 5% of liquid fuels to be supplied from biofuels by 2010 within the Renewable Transport Fuels Obligation (RTFO[1]), alongside an EU target of 10% biofuels by 2020.[1]

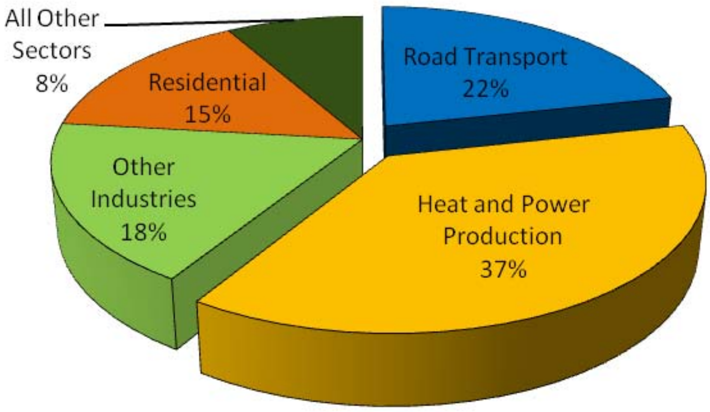

Figure 1: Contribution of different sectors to UK's total greenhouse gas emissions in 2005 [Adapted from 3].

The utilisation of biomass – organic material that has recently been created by living organisms – is presented as a key government strategy for reducing GHG emissions from electricity generation and transport. Using biomass potentially provides low carbon transport fuel, heat and power, as biomass crops assimilate carbon from the atmosphere during growth. Therefore, the carbon released back to the atmosphere when the biomass is combusted is that which has been recently captured and should not raise atmospheric concentrations. However, fossil fuels are used in cultivation, production, processing, transport and use and other GHG emissions arise from processes such as fertiliser production and use and changes in soil carbon stocks. For the targets to achieve their objective, the balance of GHG emissions per unit of energy used must be assessed.

Heat and Power

Biomass crops that are specifically bred and cultivated for the production of energy are termed 'second generation' crops. In the UK, second generation crops include the energy grass Miscanthus and short rotation coppice (SRC) willow and poplar. Second

[1] http://www.dft.gov.uk/pgr/roads/environment/rtfo/

generation crops are already used for power production in numerous locations throughout the UK. The most common method is co-firing with coal, largely because an existing plant will accept the feedstock with little or no conversion; dedicated biomass combustion plants also exist [10]. Biomass gasification, where material is converted to a combustible gas, is an attractive alternative method for bioenergy conversion. The technology is not currently commercially available, but it is being researched by a number of teams. In some cases, a small amount of fossil fuel such as diesel or natural gas is required to assist or initiate combustion in dedicated biomass combustion and biomass gasification plants [11-13].

Combustion is an exothermic reaction, releasing heat that is usually converted into electricity by driving a turbine based generator. The conversion of heat to electricity is inefficient and considerable heat is lost at this stage of power production. This loss of energy can be reduced if the thermal energy is used directly by heating either water or space, which can then be fed into a local or district heating system – that is, the production of combined heat and power (CHP) [11].

To meet Government targets for energy from renewable sources, a significant increase in second generation crop utilisation will be necessary, which would result in significant changes to the UK landscape. In 2006 less than 10,000 ha were used to grow SRC and Miscanthus [4, 5]; this is dramatically less than the predictions of one scenario for 2020, which assumes 70% of all power will be generated from SRC and Miscanthus and estimates that 350,000 hectares will be required for that purpose [6]. For changes of this magnitude it is essential that we assess the potential environmental consequences of bioenergy deployment, by comparing the environmental impacts of cultivating dedicated energy crops with the current land-use practices. The area of arable cultivation in 2007 was approximately 4.5 x 10^6 ha and set-aside occupied 440,000 ha [21].

Transport Fuels

At present, the two major liquid transport fuels produced from biomass in the UK are bioethanol and biodiesel. They are known as ‘first generation’ biofuels as they employ traditional food crops to grow grain and seeds that are fermented or esterified. ‘Second generation’ biofuels use non-food feedstocks and exploit different plant components, including lignocellulose in cell walls, but the conversion processes are not yet mature. Bioethanol is currently produced in the UK by the fermentation and subsequent distillation of sugar from sugarbeet or wheatgrain, and biodiesel is produced by the esterification of rapeseed oil or recycled vegetable oil. Internationally, crops such as sugar cane or maize are used for bioethanol production, and oil palm or soybean for biodiesel production.

The energy and carbon balances for liquid transport fuels from these ‘first generation’ fuels are generally positive compared to fossil fuels. However, these crops were bred for their nutritional content rather than energy content, and only a small part of the plant is used for fuel production. As a result, the process is not very energy efficient [7], and alternative production methods are being explored. Second generation biofuels use lignocellulosic biomass, the fibrous and woody portion of plants, to produce bioethanol, biodiesel and synthetic fuels. Potential feedstocks include Miscanthus, SRC willow and poplar and wheat straw, however, the processes for converting this complex lignocellulosic material are still under development and need to be scaled up for commercial production

To produce ethanol, lignocellulosic biomass may be pre-treated by a combination of physical, chemical and enzymatic steps to yield monomeric sugars, which can then be fermented and distilled [8]. Alternatively, the lignocellulosic biomass can undergo thermochemical conversion to produce bio-oil or syngas. To produce bio-oil, the feedstock is subjected to fast pyrolysis. This bio-oil is then used as a diesel replacement [9]. Syngas can be produced by biomass gasification and then undergoes upgrading by Fischer-Tropsch synthesis to produce synthetic fuel [17].

Bio-oil from fast pyrolysis can also be used in turbines for electricity generation and has a higher energy density than wood chips, making long-distance transport a feasible option, with the further benefit that its waste products are cleaner than those from wood chip combustion [9, 14].

Life Cycle Assessment

The use of bioenergy crops for energy generation and transport fuel production has great potential to reduce GHG emissions if the fuels replace traditional fossil feedstock. However, the use of these crops has recently come under serious criticism, with some groups questioning their true environmental cost [18, 19]. Although there is a large body of research in this area, the environmental costs and benefits associated with bioenergy crops can be difficult to assess because of the complexity of the production systems. One technique which has been used extensively in the literature to compare the energy and GHG balances of bioenergy chains is life cycle assessment (LCA).

LCA is an internationally recognised technique for evaluating the natural resource requirements and environmental impacts from the whole process and materials involved in the manufacture of a product or service [20]. It has been used extensively in the bioenergy sector to investigate the energy and carbon balances of bioenergy chains, and in a smaller number of cases has been used to look at wider environmental impacts. Results from these studies vary quite widely. However, it is often difficult to compare studies from different authors due to lack of transparency in the data and significant differences in the way in which findings are reported. This has resulted in substantial disagreements in the literature as to the relative energy and GHG balances of bioenergy chains.

2. Aims and Objectives

This working paper describes the development of a systematic review of LCAs of bioenergy for heat and power and liquid transport fuels. The aim of this work is to provide a clearer picture of current knowledge on the relative efficiency and energy and carbon balances of a range of bioenergy chains. This uniquely enables a quantitative comparison of the two end uses of bioenergy crops – liquid transport fuels and the generation of heat and power.

The primary objective of this task is to devise a means to cross compare the impacts of different methods of energy production, be it for transport fuel, heat or power. Ultimately, the UKERC FSE and ES themes aim to compare bio-based energy to other systems, such as wave and tidal power, but we will initially be evaluating different bioenergy conversion processes (e.g. gasification, pyrolysis) and feedstocks (e.g. Miscanthus, oil seed rape).

In the long term, the comparison of bioenergy supply chains will include the assessment of a broad range of environmental impacts in a quantitative manner. However, the primary stage and current focus is to review current published data on the energy requirements and GHG outputs for a range of UK bioenergy chains. Data for net GHG emissions and fossil energy utilisation will be converted into comparable formats for solid biomass and liquid biofuels. This will be done for each step of the production process for which data are available, allowing a direct comparison of different feedstocks and conversion processes.

Hundreds of LCAs for bioenergy have been completed throughout Europe and globally [7, 11-16]. Despite the ISO standard [20] for LCA, which defines the assessment procedure, the system boundaries and assumptions which different authors use can vary substantially, for example in the assumptions of crop yield or fertiliser use. These variations in boundaries and assumptions can significantly affect the outcome of the LCA.

In addition not all studies fully report the methods used in calculations, making the comparative value of these studies' findings low. Therefore, the second objective of this paper is to highlight the need for transparent reporting in LCA research and develop a set of guidelines for LCA reporting for the bioenergy sector. These guidelines will include recommendations to ensure data transparency, as well as suggestions for suitable units and parameters which must be included in a bioenergy LCA.

3. Systematic Review Protocol

In order to rigorously assess LCA in the bioenergy sector, a systematic review protocol was devised (Figure 2). This included clearly defined criteria for literature searches and a set of conditions for accepting or rejecting the publications located. For the literature search, a defined set of search terms were agreed (Table 1). Search terms used for each technology differed as a generic list would not cover all publications for each technology. Secondly a list of databases and search engines were identified which covered a range of scientific peer-reviewed journals, grey literature and government reports (Table 2).

At the first stage, papers were selected only by reading the title and abstract, and entered into a preliminary list. Each paper in this list was then read to determine whether the data presented was appropriate. For the paper to be deemed appropriate it had to fulfil certain eligibility criteria:

1. The LCA represents a supply chain that could be considered in the UK
2. Figures are given in mathematically operable formats, i.e. not as percentages or weighted figures, and if expressed in an inappropriate format the original figures from which they were calculated are available
3. The LCA has defined sub-systems and system boundaries

Once the eligible publications were identified, the data could then be analysed.

Search Terms	
Bioenergy for Heat and Power	**Liquid Transport fuels**
Life cycle LCA LC* Externalities Balance +energy +carbon Budget +energy +carbon Footprint +energy (+ biomass, + bioenergy) Balance Impact Cradle to Footprint (+energy +carbon +GHG) Cradle to +energy Cradle to +biomass Footprint +energy +carbon Footprint +energy +carbon	Life cycle LCA LC* Externalities (+ biofuel, + bioethanol, + ethanol, +E85, +biodiesel, +biobutanol) Balance + biofuel Budget + biofuel Impact + biofuel Cradle to + biofuel Footprint + biofuel (+energy, + carbon, +GHG)

Table 1: Search terms identified for the systematic review of bioenergy LCAs (Key search terms were combined with those in brackets below each group).

Database / Search Engine	Weblink
Web of Science	http://wos.mimas.ac.uk/
Science Direct	http://www.sciencedirect.com
ETDE (IEA Energy Technology Data Exchange	http://www.etde.org/
IEA (International Energy Authority documents and publications)	http://www.iea.org/Textbase/publications/index.asp
DTI (Department of Trade and Industry documents and publications)	http://www.dti.gov.uk/publications/index.html
EEA Database	http://reports.eea.europa.eu/GH-07-97-595-EN-C/en
DEFRA	http://www.defra.gov.uk
US DoE documents and publications	http://www.energy.gov http://www.osti.gov/graylit/ http://www.osti.gov/energycitations
National Renewable Energy Laboratory (US)	http://www.nrel.gov/publications/
Copac academic and national library catalogue (UK and Ireland)	http://copac.ac.uk/
Environmental Research Web	http://environmentalresearchweb.org/cws/home
Renewable Energy Association	http://www.r-e-a.net/home.fcm
Institute for Lifecycle environmental assessment (US)	http://ww.ilea.org/
Tyndall Centre	http://www.tyndall.ac.uk/

Table 2: Databases and search engines identified for the systematic review of Bioenergy LCAs.

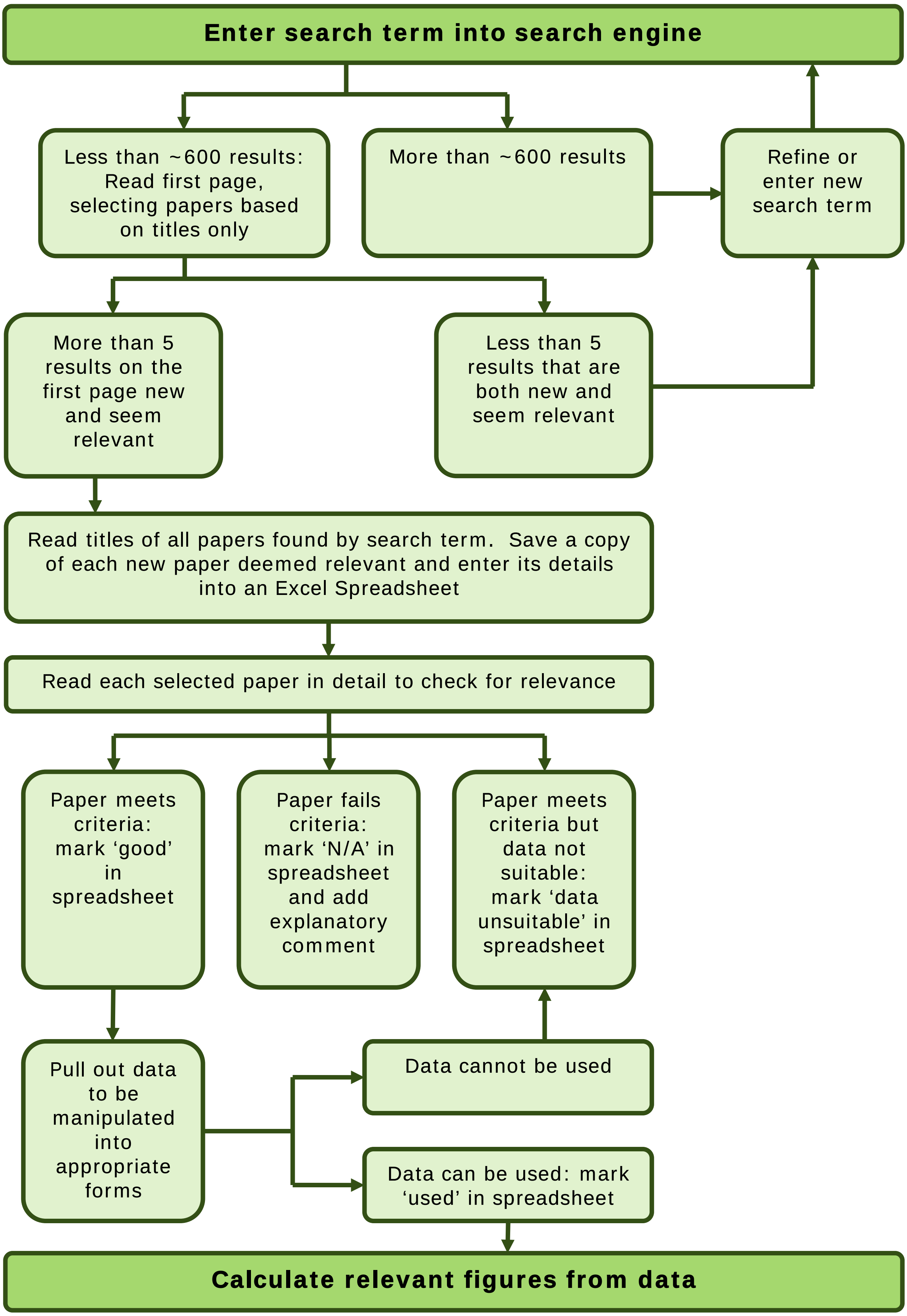

Figure 2: Flow chart explaining the process used to locate appropriate data

4. Data Analysis

Using the refined list of eligible LCAs, data on the energy use and GHG outputs of a range of bioenergy chains were collated. In addition, meta-data on the process steps considered in each paper were recorded.

Biomass for Heat and Power

The outcome of the biomass for heat and power data analysis can be considered in two sections. The first section is a detailed breakdown of the energy requirements and GHG outputs from the separate process steps involved in each production chain before conversion of the biomass into heat or electricity. The second section shows the final energy requirements and GHG outputs for each system after conversion.

Detailed Breakdown

Data collected included primary energy input (MJ), energy output (MJ) and GHG output (g CO_2 equivalents) for each process step of each chain. The energy and GHG data were converted into standard units, and the energy requirement (MJ input / MJ output) and GHG output were calculated.

The data were summarised by recording which factors were considered, the average figure for each process step, and how many papers this average was calculated from. This gives an insight to the stages during the life cycle which are particularly emitting or energy-demanding. The data will be expressed in a defined format (Figure 3). Emissions and energy requirement in these breakdowns are reported on two separate diagrams, as each calculation requires different factors to be considered and so uniting them would overcomplicate the diagram.

The data in the break-downs are taken from a variety of LCAs which do not necessarily quote the same conversion efficiency for each process. Therefore, expressing data in terms of MJ of heat or electricity produced (MJ output) does not give an accurate comparative platform. For that reason, the data at this stage is expressed in terms of MJ of raw energy in the fuel ready for conversion (MJ fuel). That is, emissions are expressed as g CO_2 eq. / MJ fuel and energy requirement is expressed as MJ in / MJ fuel.

The LCAs are generally consistent in their terminology to describe different steps in the process chain although the detail and subcomponents described at each stage differed between authors. The overall complete chain, with sub-processes was derived by examination of all LCAs being studied.

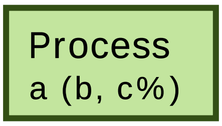

Figure 3: Each process step included for production of energy from the crop, such as crop establishment or plant construction, will be labelled with the following numbers:

a. Average figure for this step in the process – depending on the diagram, this will either be emissions (g CO_2 eq. / MJ fuel) or energy requirement (MJ in / MJ fuel)
b. Number of papers this average has been taken from
c. Percentage of all documents reviewed that include this input, even if they don't give the actual figure to calculate the average from

The complete diagram will therefore show all of the process steps included in the calculation, how many papers have considered them, and the emissions or energy requirement associated with each process step (Figure 4).

The process steps are:

- Ground Preparation
- Crop Establishment
- Crop Maintenance
- Harvesting
- Storage
- Transport to Power Station
- Plant Construction
- Plant Operation
- Plant Dismantling
- Carbon Storage (Emissions figures only)

Each process step is itself made up of a variety of factors. For example, 'Crop Establishment' comprises the divisions 'Nursery Operation', 'Planting', 'Cutback', and 'Weeding'. Therefore, eight diagrams for biomass for heat and power will be produced, with a diagram for energy requirements and a diagram for GHG outputs for each main fuel source – woody crops, grasses, forestry residues and municipal waste – available in the UK.

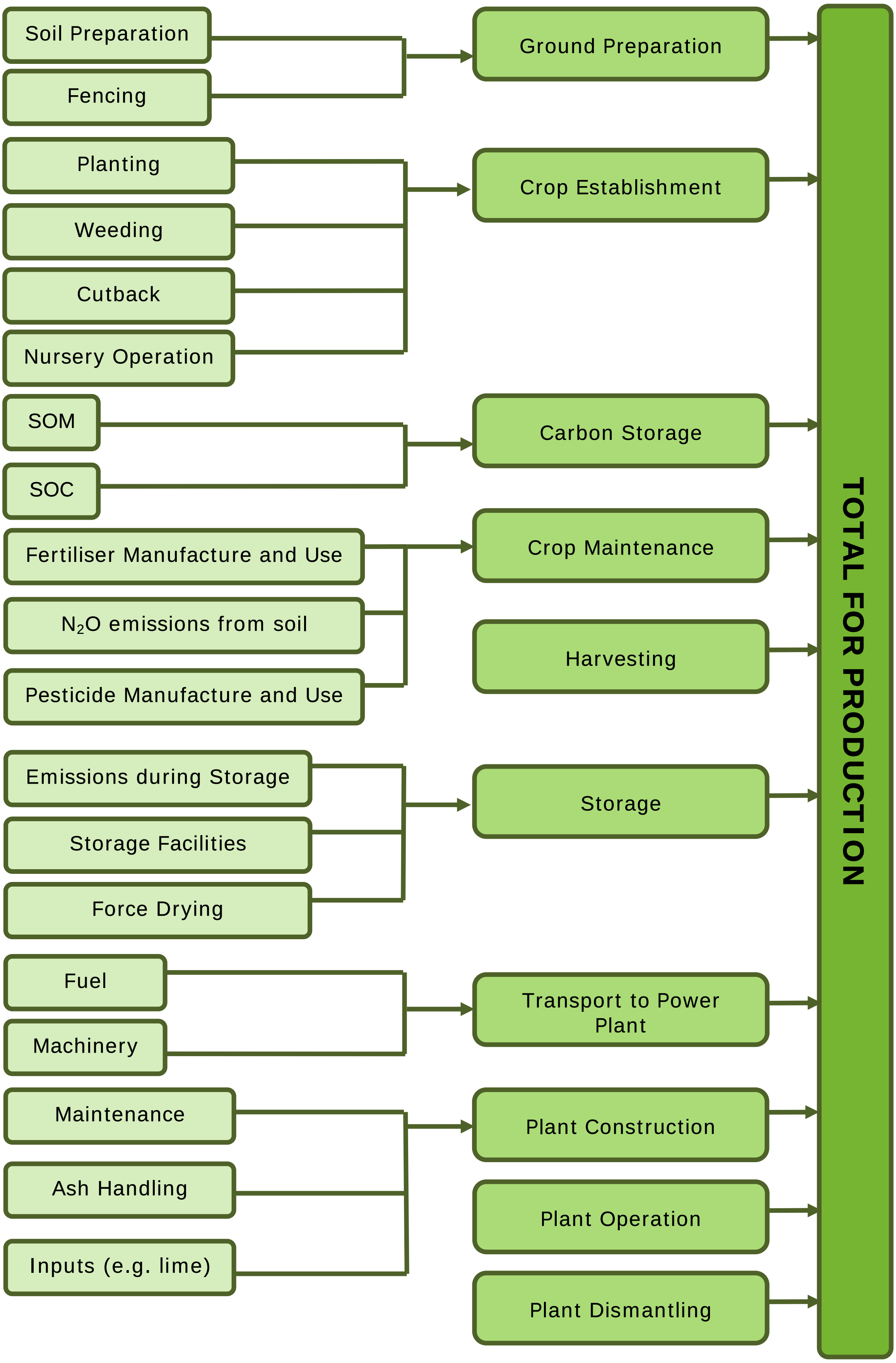

Figure 4: An example of an emissions breakdown diagram for heat and power production, typical of the diagrams to be produced for each bioenergy chain.

Summary Tables after Conversion

The second section of the bioenergy data analysis shows the emissions and energy requirement of each energy production system after conversion, and so g CO_2 eq. and MJ input are expressed in terms of MJ output. This not only shows the final emissions and energy requirements to be expected of each process, and therefore the most energy efficient or emission-limiting conversion routes, but also the effect conversion efficiencies have upon the final figure.

A table for each process will be produced (Table 3), listing the different studies reviewed for that method of conversion, stating the plant type, feedstock and conversion efficiency used in each study, and a final summary row. The summary row averages the findings and states the range of conversion efficiencies used to obtain the average. The methods of conversion considered are biomass gasification, biomass co-combustion with fossil fuels, dedicated biomass combustion and combined heat and power generation.

GASIFICATION			**Conversion efficiency**	**Final Figures**
Author	**Feedstock**	**Plant Details**	**%**	**MJ in / MJ out**
Heller (2004)	SCR willow	NREL Gasifier Willow		
Heller (2004)	SRC willow	EPRI Gasifier Willow		
…	…	…		
Average				

Table 3: The table style being produced for each conversion process.

To calculate these figures, the average yield and energy content of the crop as well as the conversion efficiency used in the LCA must be given. Furthermore, with these figures it is possible to add our own set of assumptions or predictions of yield to forecast how changes in the genotypes of crops used or different land types might affect the emissions or energy balance of each process.

Liquid Transport Fuels

LCAs of transport fuels come in two forms, a “well-to-wheels” and “well-to-tank” approach. The “well-to-wheels” approach includes all energy use and GHG emissions from crop cultivation through to the combustion of the fuel in the vehicle. The “well-to-tank” approach excludes the combustion of the fuel in the vehicle so its system boundary is the point at which fuel arrives at the petrol station. For this review we are using the system boundaries of the well-to-tank approach which ends with the fuel at point of distribution. This enables a comparison of transport fuels with electricity and heat generation prior to transmission through the network.

The collation and illustration of the data for transport biofuels for the different process steps will be the same as that described for LCAs of biomass for heat and power. However, the data analysis and conversion will be slightly different for liquid transport fuels, as only specific parts of the crop are used to produce the fuel, and co-products are generated for use as products or for co-firing. The energy input data and net GHG output data for liquid transport fuels will be expressed in terms of MJ contained in the final fuel (MJ fuel). Therefore, MJ fuel for biomass for heat and power, e.g. energy contained in the wood chips before conversion in the power plant, is equivalent to energy contained in the transport fuel prior to combustion in the vehicle. So energy requirements will be calculated as MJ in / MJ (fuel), and net GHG outputs are calculated as g CO_2 eq. / MJ (fuel).

The analysis will be presented in an identical format to the detailed breakdown diagrams of biomass for heat and power, resulting in a total of seven pairs of diagrams, representing the seven bioenergy chains for liquid transport fuel production which have been assessed:

- Bioethanol from Wheat (grain)
- Bioethanol from Sugarbeet
- Bioethanol from wood
- Bioethanol from Straw (Wheat)
- Biodiesel from Oilseed rape (RME)
- Biodiesel from Recycled Vegetable Oil (VME)
- Fischer Tropsch biodiesel from wood (SRC)

The process steps for each bioenergy chain differ, depending on the feedstock used and the fuel manufactured. The common process steps are:

- Cultivation and harvesting
- Feedstock transport
- Feedstock processing (different for different feedstocks)
- Fuel manufacture (different for bioethanol and biodiesel)
- Plant construction and maintenance
- Fuel storage
- Fuel distribution

For biodiesel, feedstock processing and fuel manufacture includes feedstock drying and storage, oil extraction, oil refining and esterification. To manufacture bioethanol from sugarbeet, the feedstock must be prepared and shredded before undergoing fermentation and distillation. The production chain for bioethanol from wheat is more complicated, as the sugar is not present in the grains in a useable form. Therefore, the feedstock is dried and stored, followed by milling and diffusion, yielding starch. This product is then hydrolysed into monomeric sugars before undergoing fermentation and distillation, and finally dehydration. The procedure for the remaining bioenergy chains similarly vary.

An additional complication in the data analysis of liquid biofuels LCAs is the production and utilisation of co-products from the process e.g. glycerine from biodiesel, and the method by which the energy and GHG outputs from these co-products are allocated. A number of different methods for co-product allocation are used in the literature ranging from no co-product allocation, allocation by price, energy content, or by substitution with the product they might replace. Also some analyses calculate the benefits of using co-products in CHP systems to provide heat and power for the fuel production process, e.g. wheat straw co-fired.

In this analysis of liquid biofuel LCAs we have therefore recorded the method of co-product allocation used, the presence or absence of co-firing and calculated the energy requirements and GHG outputs with and without these allocations (where possible) in order to demonstrate the significance of these allocations on the overall energy and GHG balance of liquid biofuels.

5. Life Cycle Assessment: some considerations for development of guidelines

Proposed Life Cycle Assessment Guidelines	**Justification**
Use defined units that can be mathematically manipulated, such as energy ratio or energy requirement and not weighted values, relative figures or energy savings (without giving original energy/carbon/fossil fuel requirements values!).	The figures of many different studies can be compared using various mathematical means and displayed graphically, allowing cross comparison.
System boundaries must be clearly defined.	Without stating system boundaries it is impossible to determine the value of the final figure and whether it is appropriate for comparison or not.
Conversion efficiency of plants should always be stated, as should yield assumptions and time scale of the study.	This allows the outcome hypothetical scenarios to be easily determined, for example if a different phenotype with higher yield was used, as well as allowing cross comparison between studies.
Do not only give one final figure, but present figures for sub-systems, including productions, utilisation and transport (with defined system boundaries).	For the identification of stages requiring improvement, the simple determination of hypothetical scenario outcomes as well as cross comparison of each stage between processes.
Cite sources for values not calculated and confidence levels on statistics derived	The use of published values is legitimate, but must be transparent.

Table 4: The recommended LCA guidelines are to enable cross comparison between studies, processes and methodology. These guidelines will be re-assessed on completion of the study.

References

1. DTI Publication. 2006. UK Energy in Brief. URN 06/220
2. DTI Publication. 2007. UK Energy in Brief. URN 07/220
3. DEFRA. 2007. 2005 UK climate change sustainable development indicator and greenhouse gas emissions final figures. Ref 24/07, http://www.defra.gov.uk/news/2007/070131a.htm (accessed 30/10/2007)
4. The National Non-Food Crops Centre. 2007. http://www.nnfcc.co.uk/statistics/uk.cfm (accessed 05/10/2007)
5. DEFRA, DTI Publication. 2006. Creating value from renewable materials, a strategy for non-food crops and uses, two year progress report. http://www.defra.gov.uk/farm/crops/industrial/pdf/nfc-progress-0611.pdf (accessed 05/10/2007)
6. Anon. 2004. House of Lords, Science and Technology Committee, 4th report of session 2003-4. Renewable energy: practicalities, Volume I: report. HL Paper 126-I ed. London: The Stationery Office Limited.
7. Righelato, R. and Spracklen, D.V. 2007. Carbon Mitigation by Biofuels or by Saving and Restoring Forest? *Science* 317: 902
8. Wymann, C.E. 2007. What is (and is not) vital to advancing cellulosic ethanol. *Trends in Biotechnology* 25(4): 153-157
9. Biomass Technology Group, BTG. 2001. Pyrolysis produces a clean liquid biomass energy carrier. http://www.btgworld.com/technologies/pdf/leaflet-fast-pyrolysis.pdf (accessed 12/10/2007)
10. Renewable Energy Association, REA. 2006. Map – British Bioenergy: Biomass, Biogas and Biofuels, First Edition.
11. Dubuisson, X. and Sintzoff, I. 1998. Energy and CO_2 balances in different power generation routes using wood fuel from short rotation coppice. *Biomass and Bioenergy* 15 (4/5): 379-390
12. Mann, M.K. and Spath, P.L. 1997. Life Cycle Assessment of a Biomass Gasification Combined-Cycle System. NREL Publication.
13. Carpentieri, M., Corti, A. and Lombardi, L. 2005. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal. *Energy Conversion and Management* 46: 1790-1808
14. Elsayed, M.A., Matthews, R. and Mortimer, N.D. 2003. Carbon and energy balances for a range of biofuels options. DTI Publication, URN 03/836
15. Heller, M.C., Keoleian, G.A., Mann, M.K. and Volk, T.A. 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy* 29: 1023-1042
16. Weiss, M., Patel, M., Heilmeiner, H. and Bringezu, S. 2007. Applying distance-to-target weighing methodology to evaluate the environmental performance of bio-based energy, fuels, and materials. *Resources, Conservation and Recycling* 50: 260-281
17. Royal Society (2008) Sustainable Biofuels: prospects and Challenges. Policy document 01/08.
18. OECD (2007) Biofuels: Is the cure worse than the disease? Round Table on Sustainable Development OECD SG/SD/RT(2007)3

19. Environmental Audit Committee (2008) Are Biofuels Sustainable? Vol 1. HC76-1, House of Commons.
20. ISO (2006) *ISO 14040: 2006 – Environmental management: life cycle assessment – principles and framework*. International Standards Organisation.
21. Defra (2008) Agriculture in the United Kingdom 2007. http://statistics.defra.gov.uk/esg/publications/auk/2007/18%20Whole%20publication.pdf (accessed 07/04/2008)