EVALUATING GREENHOUSE GAS BALANCES AND MITIGATION COSTS OF BIOENERGY SYSTEMS – A REVIEW OF METHODOLOGIES

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Abstract

Replacing fossil-based energy systems with biomass-based ones holds potential to reduce the net emission of greenhouse gases. When analysing such energy systems, systems that give a high and cost-efficient reduction of greenhouse gases, are preferable from a climate change perspective. This report gives a review of methods and approaches for assessment of greenhouse gas mitigation and cost-effectiveness in biomass-based energy systems, identifying methodological strengths and weaknesses. Beneficial methodological approaches should be accurate, transparent and efficient in the assessment of greenhouse gas mitigation potentials and costs.

The approaches most frequently used in project-level studies of greenhouse gas mitigation of biomass-based systems are lifecycle assessments (LCA), performed either with dedicated LCA-software or 'manually' in spreadsheets, and energy systems analysis (ESA) typically performed in spreadsheets. The general aspects which determines the quality of a methodology used for energy system assessments are; 1) accuracy, including the comprehensiveness and consistency of the study, 2) transparency of assumptions and calculations and 3) efficiency, meaning that an appropriate level of detail must be balanced by ease-of-use. These aspects were used as the framework in a standard reporting format for a selection of reviewed published reports.

Some methodological aspects are discussed in greater detail. One aspect of fundamental importance is the baseline, or reference fossil system, against which the biomass-based systems are compared. For an accurate baseline the choice of reference technology should be made carefully, including e.g. future development, market influence and site-specific effects. The functional unit is also fundamental. The same unit should be used in the comparisons between fossil and biomass-based systems and have to be defined accurately. This requires specific considerations in studies of multifunctional systems like cogeneration plants. As in all system analysis the comprehensiveness of the assessment is dependent on how the system boundaries are chosen. The methodological treatment of different time-spans, and the use of different output parameters are discussed, as is the use of sensitivity analysis as a way to increase transparency of the uncertainty associated with the complex analyses.

In energy systems much focus has been on conversion technology, but with the life-cycle perspective most studies include the precluding production stages of the system. Still, the end-use conversion is sometimes not included. Cost assessments often cover only conversion and/or production costs and not the complete life cycle. Costs, however, have also been estimated based on energy prices and from top-down models like input-output analysis. For calculations of investment costs parameters like the interest rate may have large influence on the results. External costs, covering the costs for impact on the ecosystem, have been used in energy system analysis, though the uncertainties in these estimates are relatively high.

Keywords: biomass; cost-efficiency; energy system; greenhouse gases; life-cycle;
methodology; mitigation

Contents

A. Introduction

Climate change is an issue of global concern, and in most scenarios expected to have major impact on ecological and social systems (McCarthy et al. 2001). The anthropogenic emissions of greenhouse gases (GHG; carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], and halocarbons) are considered to be a key factor (Houghton et al. 2001) and, since these emissions to a large extent are the result of energy use, implementation of new energy systems is an important strategy for the mitigation of climate change (Metz et al. 2001).

Diverse biomass energy technologies present considerable potential for the large-scale exploitation of renewable energy sources in the European Union. Additionally, these technologies offer significant prospects for reducing greenhouse gas emissions, which are associated with global climate change. However, in order to assist the promotion of these important technologies, it is essential that there is a wide understanding and appreciation of their greenhouse gas emissions benefits. Consequently, an accurate and user-friendly tool is needed as a routine means of analyzing the greenhouse gas balance and emissions-saving cost-effectiveness of biomass energy technologies. The development of such a tool is the objective of the project “BIOmass-based climate change MITigation through Renewable Energy” (BIOMITRE).

The present report is one of the deliverables from the BIOMITRE Work Package No.1, intended to confirm the basic nature and any deficiencies of the main existing methodologies for evaluating greenhouse gas balances and emissions-saving cost-effectiveness of prominent biomass energy technologies relevant to the European Union.

B. Methods for reviewing

The current review of existing methodologies was made in three steps; collection, indexing and detailed evaluation. This approach was chosen to make the available material useful to other stakeholders by providing a structured framework for dealing with the extensive literature.

B.1. Collection

Literature was mainly collected from international databases. Research networks, as the IEA Task 38, were consulted to ensure that well-known suitable references were not missed in the database searches. The survey included refereed scientific papers, technical reports and books, essentially spanning the last two decades until June 2003. The selection was based on relevance to the BIOMITRE project, i.e. material on various aspects of assessments of greenhouse gas emissions and mitigation costs in biomass based energy systems, with special focus on methodology. Though the scope of the BIOMITRE project is bioenergy in Europe, non-European literature was included in the review for a geographical comprehensiveness of methodological issues. About 500 references were originally collected.

B.2. Indexing

Based on a preliminary screening, some 300 references were selected for a detailed indexing with 21 keywords (Table 1). The keywords were of two types, describing both the relevance to the BIOMITRE project and general methodological characteristics. These references were compiled in a public-access database, searchable with denoted keywords (http://www.joanneum.ac.at/biomitre/).

B.3. Detailed evaluation

A shorter list of references was selected as representative for a detailed evaluation of methodological characteristics. The selection was mainly based on the indexed keywords (Table 1) and on expert knowledge of the BIOMITRE research group. The selected papers typically describe project level applications of analyses of GHG-emissions from bioenergy systems with a life-cycle perspective, including comparisons to fossil fuel references. Cost-assessments in relation to GHG reductions are of high interest to the BIOMITRE project, but since very few references contained such combined approaches, some of the selected papers have no cost assessments.

Table 1. Characteristics considered in the indexing of literature.

Reference characteristics	**Keywords**		
Type of methodological description	Conceptual methodology paper	New model/tool presented	Method described
Objective	Project	Policy	
Energy-system studied	Energy system		
Energy-source studied	Biomass based		
Origin of biomass	Agricultural origin	Forestry origin	Animal origin
	Primary products	Residues/waste	
Energy-use studied	Heat	Electric power	Liquid/gas fuel
Fossil-fuel comparison	Fossil reference		
Parameters considered	GHG	Costs	Effect of GHG-emissions
Process-steps considered	Whole chain of life-cycle	Indirect emissions	

Current methodological approaches were evaluated for their strengths and weaknesses in relation to the objectives for the BIOMITRE project, i.e. evaluating greenhouse gas balances and emissions-saving cost-effectiveness of prominent biomass energy technologies relevant to the European Union. Various criteria for methodological comparisons can be found in the literature (e.g. Baumann and Cowell 1999, Metz et al. 2001, Watson et al. 2000). The list of criteria suggested by Schlamadinger et al. (1997), was found comprehensive and well adapted for assessments within the objectives of BIOMITRE. The importance of accurately defining the reference system was further stressed by Gustavsson et al. (2000), who also provided relevant recommendations. Hence, the current review was largely based on the methodological recommendations from these two papers.

Three categories of key questions were recognized and applied to each method evaluated;

- *Accuracy* of the methodology; considering *comprehensiveness* (functional unit, system boundaries in time and space, reference system etc.) and *consistency* (consistent treatment of actual and reference system, etc.)
- *Transparency* (assumptions clearly shown, use of flow charts and sensitivity analyses)
- *Efficiency* (appropriate level of detail balanced with ease-of-use, comparable output parameters)

The accuracy of the total methodological approach to the scope of the study, is of fundamental importance for any methodological approach. Transparency is important for the identification of used assumptions, etc and for the “user-friendliness” of the approach, including the possibility to understand the usefulness and limitations of the results. The third question, efficiency, partly determines whether the method will be further used or not, since resources for GHG-assessments are likely to remain limited. In practice, efficiency is always balanced against the accuracy and transparency when choosing a methodological approach.

To simplify comparisons of comprehensiveness and consistency in the system definition, a graphical representation based on Schlamadinger et al. (1997) was adopted and somewhat modified (Figure 1). This figure was used as a “checklist” for each review, but the graphical representations of each review are not shown in this report.

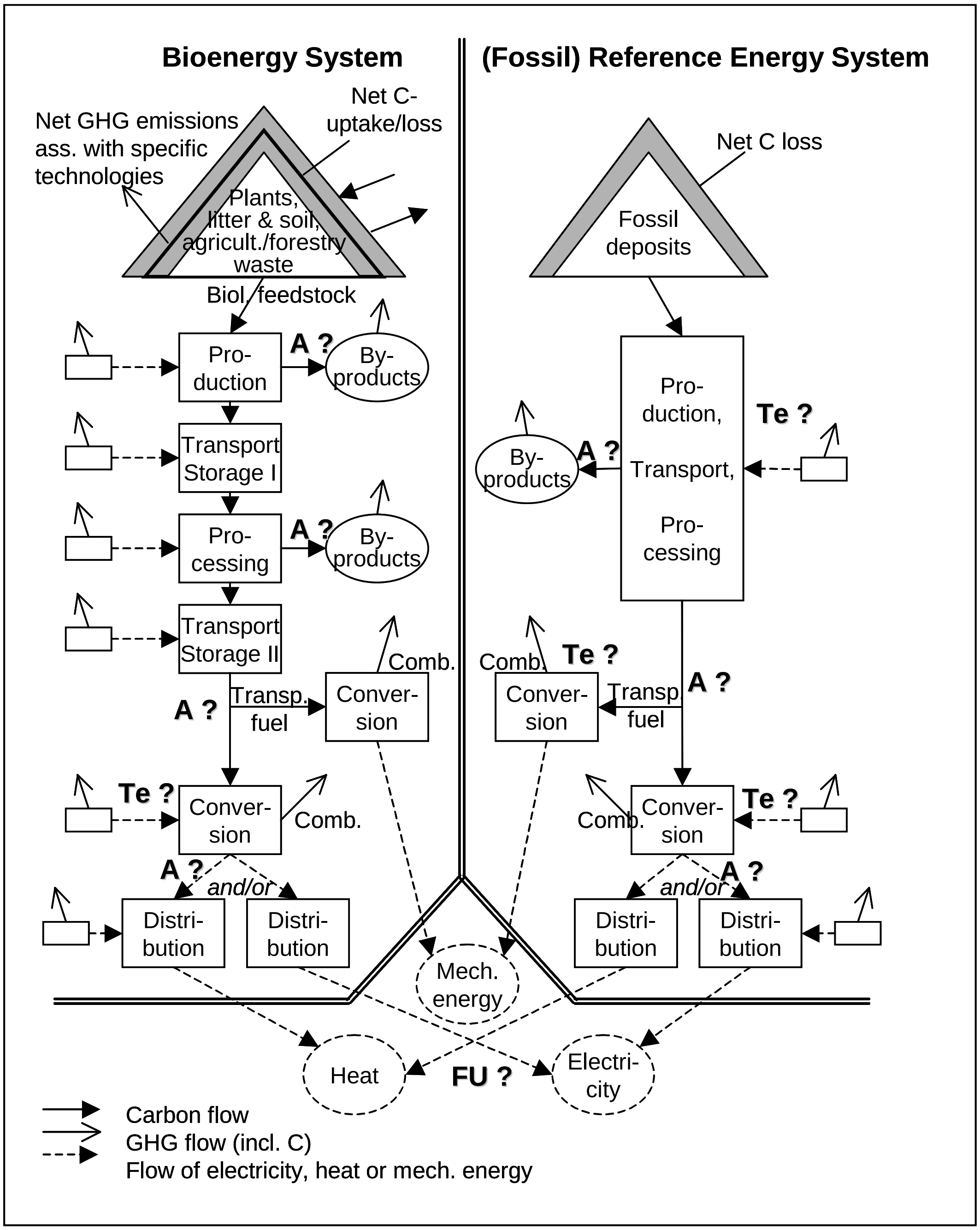

Figure 1. Graphical representation of biomass system and reference system used for characterization of reviewed reports. Question marks indicate examples of points of special methodological interest for allocation method (A?), choice of functional unit (FU?) and choice of technology (Te?). *Based on Schlamadinger et al. (1997)*

B.4. Standard reporting format

The detailed review of selected references was performed and reported according to a standard format, for increased comparability. The reporting format for each reference consist of tables with the following content:

- Title, author; full bibliographic reference
- Objective of study
- Tool/method; name and type of methodology applied
- Functional unit
- Output parameters
- Key citations
- Keywords added for BIOMITRE project
- Main strengths and weaknesses presented under the four categories; comprehensiveness, consistency, transparency and efficiency

C. Results

The papers reviewed in this report, selected as representative examples of methods for assessment of greenhouse gas mitigation potential in bioenergy projects, generally showed large variations in methodological transparency. This makes the papers difficult to compare, though they address similar questions.

The results of reviewed selected papers are presented in a standardized format in Appendix 1. These reports cover the application of four different types of methodological approaches;

- Spreadsheet LCA (Elsayed et al. 2003, Hartmann and Kaltschmitt 1999, Jungk 2000, Kaltschmitt et al. 1997, Mortimer et al. 2003)
- Computerized LCA (Beer et al. 2002, Fritsche 2002, Jungmeier 1999, Jungmeier and Hausberger 2002)
- Energy system analysis (Gustavsson and Karlsson 2002, Karlsson and Gustavsson 2003)
- Other approaches (Groscurth et al. 2000)

In the following text, the general characteristics of these methodological approaches are presented (section C.1), followed by an evaluation of the methodological details (section C.2).

C.1. General methodological approaches

C.1.1. Life cycle assessment (LCA)

The ISO 14040-series for Life Cycle Assessments (ISO 1997, ISO 1998, ISO 2000a, ISO 2000b, ISO 2002) is an international methodological standard for environmental assessments. The ISO status gives good acceptance for LCA-results in society, including business, and an incentive for further methodological development. An LCA consist of four steps; 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation. The ISO-standard has been applied in a large number of assessments of bioenergy systems, but there is still substantial variation among these as to the actual way in which the standard is implemented. This variability is an inherent characteristic of the ISO-standard since it is not constructed as a precisely defined tool, but rather as a set of guidelines for good practice. Some parts of the standard, as e.g. allocation rules (e.g. (Ekvall and Finnveden 2001, Jungmeier et al. 2002)), are still under development.

Spreadsheet LCA

One way to perform an LCA is here referred to as a ‘spreadsheet LCA’. It is characterized by a substantial input from the analyst in constructing spreadsheets containing the full system under study, as the modules of the process tree with their internal relations, the inventory data, the emission databases and the modules for output of results (Elsayed et al. 2003, Hartmann and Kaltschmitt 1999, Jungk 2000, Kaltschmitt et al. 1997, Mortimer et al. 2003). This highly manual approach gives the advantage of good control over methodology and data from the analyst. Another characteristic of spreadsheet LCA is an often comprehensive coverage of the details in the bioenergy systems, and often an ambition to use the most relevant input data available. Impact categories of an LCA often include a range of environmental aspects together with the GHG-emissions, which can be an advantage if the objectives are wider than those of the BIOMITRE project. Taken together, the complexity and variability of a spreadsheet LCA, makes good accuracy possible, but the result is strongly dependent on the skills of the analyst.

Low transparency sometimes precludes the interpretation of reports based on spreadsheet LCA. Large amounts of input data and system assumptions can be hard to present, especially in a compact report format, focused on the results of the study (Kaltschmitt et al. 1997). Transparency can be improved by the presentation of system flow-charts (Hartmann and Kaltschmitt 1999). Jungk (2000) also showed consistent flow charts, and in addition made spreadsheets with data and calculations available on a web-page. Still, it can be cumbersome for the reader to fully understand the complex calculations.

The transparency of the assessments were substantially improved by Elsayed et al. (2003) and Mortimer et al. (2003), without compromising a very detailed coverage of the studied systems. These authors have designed a consistent presentation format, with quantitative flow-charts of the systems under study, accompanied by comprehensive data sheets including detailed explanations of underlying assumptions.

The spreadsheet assessment by the ISO 14040 standard sometimes show a very high ambition in the coverage of flows of material and energy, and in their calculations of greenhouse gas emissions and global warming potential based on generic and well documented IPCC conversion factors (Houghton et al. 1997). However, directives for calculation of costs are not included in the ISO-standard, and costs are usually not presented together with LCA data.

Mortimer at al. (2003) produced estimates of mitigation costs by comparing emission reductions calculated by spreadsheet LCA, with the cost of total governmental subsidies to the bioenergy sector, including all supportive payments to agriculture, grant schemes, market stimulation mechanisms and derogation of fuel excise duties. Such social implementation costs are highly dependent on current policies, which may change substantially over time, but this approach may still be useful for studies of the implementation process. However, the mitigation costs of interest to the BIOMITRE project are those associated with the technology of the energy systems, rather than the social implementation costs.

Computerized LCA-tools

The ISO-standard for life cycle assessments has been incorporated in computerized tools, developed for increased user-efficiency, and with suggested applicability to a range of assessment situations, including bioenergy systems.

GEMIS (currently available in version 4.1 from Öko-Institut, Darmstadt, DE) is a modular tool which evaluates environmental impacts of energy, material and transport systems to all processes involved in an energy system - local, regional and global (Fritsche 1999b). GEMIS software and databases are public domain software and can be downloaded from a web site, free of charge. It was developed for comprehensive assessments of energy systems, covering efficiency, emissions, waste, pollutants, land-use and costs (investment costs, fixed and variable annual costs and externality factors for air and GHG). Hence, the tool has potential for good consistency in comparisons between energy systems and between technical and economic parameters. No parameter for mitigation costs is included, but this can easily be calculated from the outputs on GHG-emissions and costs (Jungmeier and Hausberger 2002).

The usefulness of results published from GEMIS applications is reduced due to a low degree of transparency in the outputs generated by the software and presented in the reports (Jungmeier 1999, Jungmeier and Hausberger 2002). Only non-quantitative flow-charts are shown, data and assumptions for calculations are hidden in the software modules, breakdown into different process stages is not possible and no sensitivity analysis is presented. The benefits from a simple modular approach, appears to be partly lost to a cumbersome editing mode for input of additional data, and a lack of guidance on how to combine the generic modules in an accurate way.

SimaPro (currently sold in version 5.1 by Pré Consultants, Amersfoort, NL) is a computerized LCA-tool, to collect, analyze and monitor environmental information for products and services, with integrated databases and impact assessment procedures (Goedkoop and Oele 2002). Each step is clear and the process tree can be used to display results, showing a high degree of transparency, since calculations are shown alongside each process box. It is possible to view parts of the life cycle at different scales, and to display their contributions to the total score. Functional units definition is incorporated, as is sensitivity analysis. SimaPro has no function for calculations of costs.

Transparency is somewhat reduced in SimaPro as algorithms are not immediately obvious in inventory results compilation, and incorporation of allocation and reference system is not clear. There is no means of checking the completeness of the process chain, or data fitness or quality.

SimaPro was applied to an extensive study on Australian transportation fuels, demonstrating good comprehensiveness and flexibility to appropriate system boundaries, e.g. as transport work (ton km) including end use efficiency, was used as the functional unit (Beer et al. 2002). The potentially high transparency of the tool was not fully adopted in this report, which instead had a rather complex format were assumptions and calculations were hard to find.

C.1.2. Energy system analysis (ESA)

An alternative basis for the calculation of GHG and other emissions is the well-established energy system analysis. In ESA an inventory is made on all direct and indirect use of energy carriers, in specified forms, over the life cycle of the energy system. Compared to a life cycle assessment by ISO 14040 standards, the data inventory of an ESA can be less complicated. The ESA approach for assessments of GHG can be justified by the fact that most of the emissions related to an energy system originate from the use of energy.

In an ESA study of biomass-based systems for residential heating, GHG-emissions were calculated together with costs, including the costs for investments, operation and maintenance (Gustavsson and Karlsson 2002). It was assumed that the price of a fuel reflected its life-cycle cost. This study also included GHG-emissions caused by changes in carbon stocks in the biological system. The ESA approach resulted in a comprehensive system analysis, with consistent treatment of bioenergy system and fossil system, as well as technical and economic system. In a later study the external costs were included by the use of the ExternE dataset (Karlsson and Gustavsson 2003). Mitigation cost were not calculated specifically, but comparative indicators were constructed for energy effectiveness (MWh_{fuel} / MWh_{heat}), emission effectiveness (kg C / MWh_{heat}) and energy cost (€ / MWh_{heat}).

Transparency is good in these energy system analyses, with the systems described in detail, and flow-charts and sensitivity analyses included. The assessments are complex, e.g. in terms of choosing appropriate system boundaries. Similar to some of the LCA-studies described above, calculations were made by spreadsheets developed by the analysts, and accuracy is strongly dependent on the skills of the analyst.

C.1.3. Other approaches

In the BioCosts project a methodology for calculations of costs and environmental effects from bioenergy systems was developed (de Almeida et al. 1998). The approach involved using a combination of tools to make comprehensive comparisons of energy systems possible, with a less detailed data inventory compared to a full LCA. An inventory of direct emissions and costs around the conversion facility was performed as in other lifecycle assessments. But from other parts of the life-cycle estimates were based on statistical data and the input/output model EMI 2.0. The resulting data were used for consistent comparisons of bioenergy systems, including abatement costs (Groscurth et al. 2000). The report has a low degree of transparency in input data, system assumptions and calculations, and data are presented without any kind of sensitivity analysis. A higher transparency would have improved the comparability of results from this study, considering the higher degree of uncertainty in the type of indirect data used.

C.2. Methodological details

C.2.1. Functional unit

In all systems analysis the choice of an appropriate functional unit, as the basis for comparisons, is of major importance (e.g. Ekvall and Finnveden 2001). Special considerations are necessary in studies of systems with more than one output, e.g. energy systems where a combination of heat and electricity (CHP-plants) is co-generated.

Karlsson (2003) estimated GHG-emissions and mitigation costs for a range of biomass-based cogeneration systems under different methodological assumptions (Table 2). The choice of a functional unit was given strong consideration, since the proportion between the products may differ between the studied and the reference system. This can be dealt with by considering one product as the functional unit and the other as a by-product, and then assuming that the difference in generation of the by-product is balanced by another energy system in the reference scenario (allocation by subtraction).

Table 2. Energy systems studied by Karlsson (2003) and the optional functional units and by-product technologies used in the calculations.

System studied	*Reference system*	*Functional unit*	*By-product technology*	
CHP-NGCC	CHP-CST	Heat	Corresponding	NGHWB
CHP-NGCC	CHP-CST	Heat	Cost-efficient	CHWB
CHP-NGCC	CHP-CST	Power	Corresponding	NGCC
CHP-NGCC	CHP-CST	Power	Cost-efficient	CST
CHP-BST/FGC	CHP-CST	Heat	Corresponding	BHWB
CHP-BST/FGC	CHP-CST	Heat	Cost-efficient	CHWB
CHP-BST/FGC	CHP-CST	Power	Corresponding	BST
CHP-BST/FGC	CHP-CST	Power	Cost-efficient	CST
CHP-BIG/CC	CHP-CST	Heat	Corresponding	BHWB
CHP-BIG/CC	CHP-CST	Heat	Cost-efficient	CHWB
CHP-BIG/CC	CHP-CST	Power	Corresponding	BIG/CC
CHP-BIG/CC	CHP-CST	Power	Cost-efficient	CST

BHWB	Wood-fuelled hot-water boiler in district-heating plants
BIG/CC	Biomass integrated gasification/combined cycle in power plants
BST	Wood-chip-fired steam turbine in power plants
CHP	Cogeneration plant (i.e. combined heat and power)
CHP-BIG/CC	Biomass integrated gasification/combined cycle in cogeneration plants
CHP-BST/FGC	Wood-chip-fired steam turbine and flue gas condensation in cogeneration plants
CHP-CST	Coal-fired steam turbine in cogeneration plants
CHP-NGCC	Natural-gas-fired combined cycle in cogeneration plants
CHWB	Coal-fuelled hot water boiling in district-heating plants
CST	Coal-fired steam turbine in power plants
NGCC	Natural-gas-fired combined cycle in power plants
NGHWB	Natural-gas fired hot-water boiler in district-heating plants

The mitigation costs calculated for the different CHP systems were significantly changed by the choice of the main product, heat or electricity (Figure 2). Using electricity as the main product illustrates that the demand for electricity constrain the production of co-generated heat. Using heat as the main product illustrates that the heat demand limits the use of cogeneration systems. This is the typical situation in Europe.

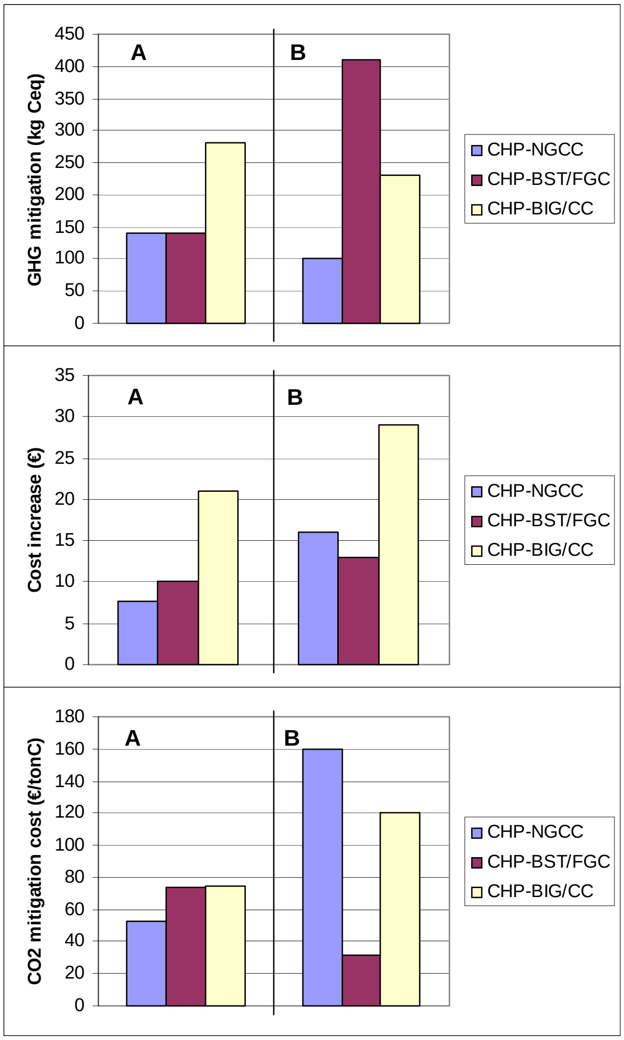

Figure 2. Variation in calculated GHG-mitigation, costs and GHG mitigation costs for three different types of CHP-plants from performing calculations with heat (A) or electricity (B) as the main product. Assumed technologies and abbreviations are shown in Table 2. Bars denote differences between the studied system (CHP-NGCC, CHP-BST/FGC, CHP-BIG/CC) and the CHP-CST reference system.
(Modified from Karlsson, 2003).

Karlsson (2003) also showed results from studies of CHP-plants where the functional unit was defined in a multifunctional way. This method was preferred to the subtraction method due to its transparency, since the subtracted parts of the system must not be shown when the subtraction method is used. Again, this methodological approach gave different mitigation estimates from those shown in Figure 2.

C.2.2. Reference system

In assessments of mitigation effects, a comparison with a reference system, or baseline, is an inherent and central property of the analysis. Accordingly, the choice of reference system has a profound impact on the accuracy of the results, and should be given serious attention (Gustavsson et al. 2000, Schlamadinger et al. 1997).

When options for new investments in energy systems are studied, the biomass and reference system should have the same technology level. Typically, new systems include facilities and infrastructure, which are likely to be used for a long period of time. For retrofit studies, where fuel changes are made in a present infrastructure, the old technology may be the appropriate reference, but the dynamic effects of limited operation time must be considered (Gustavsson et al. 2000). The appropriate choice of technology for the reference system, is discussed in some of the studies (Beer et al. 2002, Faaij et al. 1998, Groscurth et al. 2000, Jungk 2000). Some studies also include a sensitivity analysis describing the importance of chosen technology level (Gustavsson and Karlsson 2002, Jungmeier 1999).

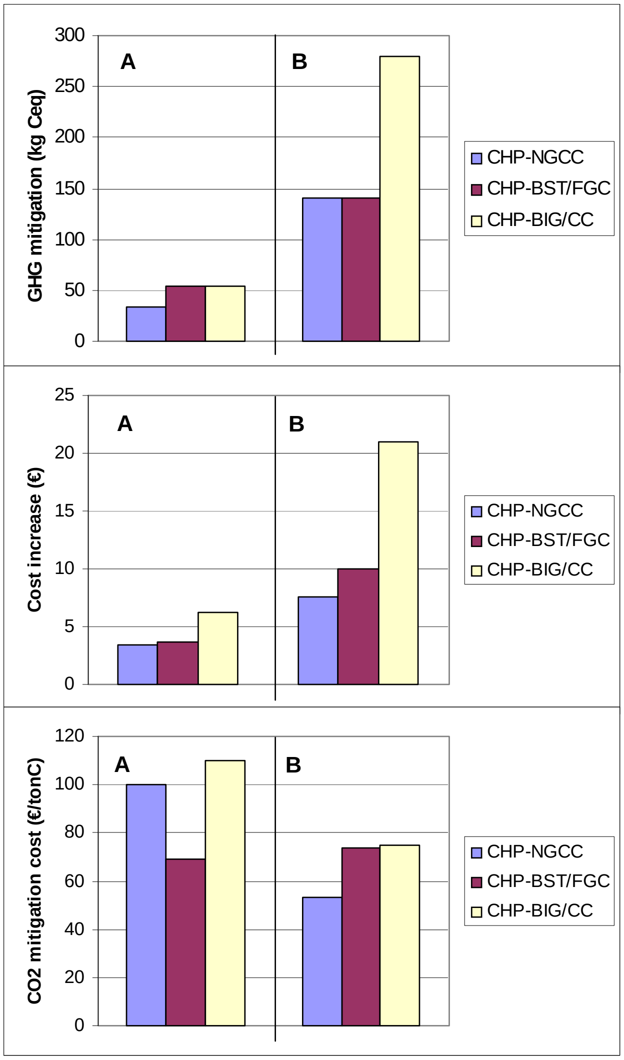

Figure 3. Variation in calculated GHG-mitigation, costs and GHG mitigation costs for three different types of CHP-plants when defining the technology for producing the by-product with corresponding (A) or most cost efficient (B) technology. Assumed technologies and abbreviations are shown in Table 2. Bars denote differences between the studied system (CHP-NGCC, CHP-BST/FGC, CHP-BIG/CC) and the CHP-CST reference system.
(Modified from Karlsson, 2003).

Another reason to carefully consider the choice of technology in the reference system was illustrated by Karlsson (2003), who estimated GHG-emissions and mitigation costs for a range of biomass-based cogeneration systems under different assumptions (Table 2). A coal-fired cogeneration plant with a steam turbine was used as reference system for the mitigation comparison. The implications on the choice of functional unit from a variable balance between generated heat a power in different systems, were discussed above (section C.2.1). However, the balancing by-product could be produced in different ways, and the effect of choosing different technologies in the calculations are shown in Figure 3. This example clearly shows that when ranking different energy systems based on expected GHG-mitigations, the choice of assumed technology in the reference system can significantly affect the calculated performance.

The methodology used for describing the reference system should in general be as similar as possible to the methodology used for the biomass system. It can still be accurate to use generic data for e.g. fossil fuels, if it can be clearly shown that the origin of such a reference is consistent enough with the biomass system. Low transparency in generic reference data could limit the usefulness of some studies (Elsayed et al. 2003, Faaij et al. 1998, Kaltschmitt et al. 1997, Mortimer et al. 2003).

C.2.3. System boundaries

Different authors treat the system boundaries differently, which can reduce accuracy and make comparisons between the studies uncertain. For example, in a study of liquid transportation fuels a comparison was made on the basis of the energy content of the fuel, excluding end-use conversion (Elsayed et al. 2003), while other authors have expanded the system boundaries to include the transportation work in the functional unit (Beer et al. 2002, Jungk 2000, Jungmeier and Hausberger 2002). From a GHG mitigation perspective the question should be how to perform a certain amount of transportation work with a minimum emission of GHG. When end-use conversion efficiency varies between the compared systems, excluding this factor will reduce accuracy of the calculations. Mortimer et al. (2003) suggested that available end-use performance data for liquid biofuels have to improved for meaningful calculations..

C.2.4. Site specificity

Site-specific differences are recognized as important factors for the accuracy of a system analysis. This can be done by using different input data for different regions, and a modular LCA-tool like GEMIS holds data for more than 30 countries (Fritsche 1999a). Site-specific differences also affect the choice of appropriate reference technology as discussed above. Another dimension of site-specificity is the different results that can be obtained if a studied energy system is considered as base-load or peak-load. Especially the costs can be greatly influenced by the high costs associated with the marginal use of a certain fuel only for peak-loads. Gustavsson and Karlsson (2002) showed how the variability can be presented together with the results, when the choice is not unambiguous.

C.2.5. Cost-measurements

In studies of energy systems, assessments of costs in relation to GHG emission are not frequent. This may be due to low availability of useful data and uncertainties, e.g. with reference to site-specific variations. The costs at the conversion facility are the most frequently described, and can often be comprehensive including investment costs, operational costs and costs for maintenance and fuel (Groscurth et al. 2000, Gustavsson and Karlsson

2002, Jungmeier and Hausberger 2002). To calculate costs from other, upstream, parts of the life cycle, like transportation and agricultural production, different methods have been applied.

The GEMIS software have modules including costs for various processes, which have been applied in one study of bioenergy systems (Jungmeier and Hausberger 2002). The accuracy of this approach is hard to evaluate due to the low transparency. SimaPro has no function for cost assessments. A partial cost analysis covering e.g. only agricultural production costs (Jungk 2000) have a limited value, and is not useful for calculations on GHG mitigation costs within the objectives of BIOMITRE.

In energy systems analyses, costs of conversion and distribution were calculated based on investment, operation and maintenance costs, while fuel costs for all energy carriers of the system were based on market prices (Gustavsson and Karlsson 2002). This approach has the advantage of a consistent treatment of data for costs and emissions, based on the same inventory data. It was also used consistently on the biomass and reference systems, further increasing accuracy of the results.

Upstream costs have also been estimated from national input/output statistics (Faaij et al. 1998, Groscurth et al. 2000). This may be seen as a top-down approach for easier data acquisition, but the accuracy of results obtained by this method is difficult to evaluate.

For investment costs the interest rate and estimated life-time used in the calculations can have a large influence on the results. For reasonable transparency the used parameters must be clearly stated, and a sensitivity analysis on the total result under e.g. various interest rates seems justified as good practice.

The costs used in mitigation studies, generally do not include national subsidies or other policy related costs. However, the GHG-mitigation costs could be related to the implementation cost of a certain energy system, and could be considered in addition to other direct costs (Karlsson and Gustavsson 2003, Mortimer et al. 2003). Such cost are of limited value to the BIOMITRE project.

External environmental costs are costs usually not valued in monetary terms by the market. The ExternE project has developed a methodology and databases for estimates of damage costs, including the costs for the impact of anthropogenic climate change (European Commission 1998). External costs have been included in the assessments of bioenergy systems by some authors (ECOTEC 2002, Faaij et al. 1998, Groscurth et al. 2000, Jungmeier et al. 1998, Karlsson and Gustavsson 2003). The results have been used for comparisons to other costs, but the external costs of GHG-emissions, are highly uncertain.

C.2.6. Time dynamics

IPCC has given attention to the importance of time dynamics in calculations of GHG-balances (McCarthy et al. 2001, Watson et al. 2000). However, little attention has been given to the time factor in studies of energy systems on a project level. Gustavsson and Karlsson (2002) discussed the variation over time in decay rates of logging residues when the change in carbon stocks of the biological system was included in studies of biomass based energy systems.

When choosing a time frame for the conversion factors in calculations of CO_2-equivalents, most authors use the data established by IPCC for 100 years, some have used 500 years (Jungk 2000), while some do not show this assumption at all (Groscurth et al. 2000, Kaltschmitt et al. 1997). There is no definite rule to follow, but comparability would be improved if each study was fully transparent in the choice of time frame for GHG calculations.

C.2.7. Mitigation parameters

Generally, mitigation cost is calculated as the ratio between net reductions of GHG emissions and net difference in costs, between the studied and reference system (ΔGHG / Δcosts). For comparative assessments of GHG mitigation by bioenergy systems, a range of different parameters has been used (see “Output parameters” in Appendix 1). Most widely used is a parameter relating the net released CO_2-equivalents to the amount of energy available for end-use (kg CO_2-eq/MJ_{fuel}), generally called GHG-requirement or emission effectiveness. Authors with an interest in an efficient use of finite resources have used GHG-emissions per energy unit of finite origin (i.e. fossil fuels) or GHG-emissions per land area occupied. Others, stressing the efficiency of the energy system, have used parameters denoted energy requirement or energy effectiveness, based on input energy per useful unit of output energy. Employment opportunities have also been considered in relation to bioenergy systems.

The limited number of studies including costs may explain why the number of suggested parameters for costs related to GHG-mitigation is rather low. Production costs have been used (cost/$GJ_{useful\ energy}$) and specific abatement costs (Δcosts/ΔCO_2-eq), while authors focusing on the effect of implementation costs have used the inverse, called GHG-saving cost effectiveness.

C.2.8. Uncertainty

A number of the methodological issues discussed above involve the use of data with variability and uncertainty of a varying degree. Such questions must always be dealt with in studies of energy systems. Comparing different scenarios is one way to handle parts of these uncertainties. Another useful tool is the sensitivity analysis, by which the relative contribution of a certain source of variation is compared to the total result of the study. A parameter with large influence and a significant variation should be given special attention in the interpretation of the results, while a negligible impact could even be a reason to exclude an insignificant parameter completely from the study. Sensitivity analyses were manually performed and actively used by some of the authors (Faaij et al. 1998, Gustavsson and Karlsson 2002, Jungk 2000, Kaltschmitt et al. 1997, Mortimer et al. 2003), and is a feature of the SimaPro software (Goedkoop and Oele 2002).

D. Discussion

The previous sections described the basic nature of the main existing methodologies for evaluating greenhouse gas balances and emissions-saving cost-effectiveness of prominent biomass energy technologies relevant to the European Union. The strengths and weaknesses were also evaluated. In the following sections, suggestions are made on methodological details and general approaches in future studies.

Accuracy is the foremost methodological aspect to consider. Comprehensiveness and consistency are key factors of an accurate methodological approach. System boundaries, in time and space, should be set to include all differences in GHG emission and cost between the bioenergy and the reference system. For example, the functional unit should include end-use efficiency, if it varies between compared systems.

Allocation should as far as possible be avoided by expanding system boundaries to include both main- and by-products.

The best choice of reference system appears to be "the least-cost fossil energy system with the lowest GHG-emissions and minimized environmental impact, fulfilling the same goals as the bioenergy system"(Schlamadinger et al. 1997), but several alternatives may have to be considered.

The methodology used to describe the compared systems, must be consistent and the same technical level should be used in all comparisons. All assumptions and calculations should be shown in a clear and structured way, and for good transparency, flow charts should be used to describe the process-trees of all systems studied, including the reference system.

From an efficiency point of view, details with a small impact on the results in relation to uncertainties of other parameters might be omitted, and the uncertainties of the other parameters should be reduced instead. Scenario studies and sensitivity analysis could be used to investigate the relative importance of a process unit, or the effect of varied assumptions.

Relevant output parameters should be used for comparison of results. For the scope of BIOMITRE the following parameters, suggested by Gustavsson and Karlsson (2002), are suitable ones; Cost efficiency (GHG reduction / costs), Primary energy efficiency (GHG reduction / input of bioenergy), and Biomass efficiency (GHG reduction / biomass input).

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G. Appendices

Appendix 1. Tabular summaries of selected papers

Appendix 1. Tabular summaries of detailed reviews

(Mortimer et al. 2003)

Mortimer, N. D., P. Cormack, M. A. Elsayed, and R. E. Horne. 2003. **Evaluation of the comparative energy, global warming and socio-economic costs and benefits of biodiesel.** 132 pp. Resources Research Unit, Sheffield Hallam University, Sheffield, UK

Objective:	Comprehensive evaluation of the energy use, global warming and socio-economic costs and benefits of producing biodiesel from oilseed rape, compared to “ultra low sulphur diesel”. United Kingdom
Tool/Method:	Spreadsheet LCA (ISO 14040); Indicative costs based on national subsidies
Functional unit:	1 tonne biodiesel at point of distribution
Output units:	Primary energy use, GHG-emissions (CO_2, CH_4 and N_2O), Total government subsidies (£), Impact on rural economy Carbon requirement (kg CO_2 / MJ); Energy requirement (MJ_{in} / MJ_{out}); GHG-requirement (kg CO_2 eq / MJ); GHG saving cost effectiveness (Δkg CO_2 eq / £ subsidies)
Key references	(Kaltschmitt and Reinhardt 1997), (Beer et al. 2002), (Gover et al. 1996), (ECOTEC 2001), (ECOTEC 2002),
Keywords:	method described; project level; energy system; biomass based; agricultural origin; forestry origin; primary product; heat; electric power; liquid/gas fuel; fossil reference; GHG; cost; effect; whole-chain; indirect emissions

(Mortimer et al. 2003)	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Detailed assessment of biomass system + Socio-economic costs included	+ Analysis consistent with Elsayed et al., 2003	+ Flow-charts; consistent and quantitative + All assumptions shown for biofuel system + Sensitivity analysis + Data with error bars + Parameters for effectiveness & resource use	+ Complex material summarized in compound output parameters + Modular approach
Weakness	– No direct/assoc. costs – Technology level not discussed – GHG from conversion not included – End-use efficiency not included – C-stock changes not included	– Low consistency between cost- and technical system – Unclear in relation to generic reference system	– Generic data for ref.-system, no transparency	– High complexity, with all details – Manual calculations
Other comments	o Allocation by price o	o	o	o Illustrative pie-charts to describe role of sub-systems

(Elsayed et al. 2003)

Elsayed, M. A., R. W. Matthews, and N. D. Mortimer. 2003. **Carbon and energy balances for a range of biofuels options - Final report.** 341 pp. Resources Research Unit, Sheffield Hallam University, Sheffield, UK.

Objective:	Comprehensive evaluation of the carbon and energy balances for a range of bioenergy systems in the United Kingdom. The study addresses the production of biodiesel from oilseed rape and recycled vegetable oil, ethanol from lignocellulosics (wheat straw), sugar beet and wheat, and rapeseed oil from oilseed rape, the generation of electricity by combustion of Miscanthus and straw, and the combustion, gasification and pyrolysis of wood chip from forestry residues and short rotation coppice, the supply of heat by combustion of wood chip from forestry residues and woodland management, and the provision of combined heat and power by combustion of wood chip from forestry residues and gasification of wood chip from short rotation coppice.
Tool/Method:	Spreadsheet LCA (ISO 14040)
Functional unit:	1 MJ of electricity, heat or transportation fuel
Output units:	Primary energy use, GHG-emissions (CO_2, CH_4 and N_2O), Carbon requirement (kg CO_2 / MJ); Energy requirement (MJ_{in} / MJ_{out}); GHG-requirement (kg CO_2 eq / MJ)
Key references	(Kaltschmitt and Reinhardt 1997), (Beer et al. 2002), (Matthews and Mortimer 2000), (Hanegraaf et al. 1998), (Jungmeier et al. 1998), (Bullard and Metcalf 2001), (Grant et al. 1995), (Jungmeier 1999), (O'Connor et al. 1999), (Wyman 1994), (Gover et al. 1996), (Schwaiger and Schlamadinger 1998)
Keywords:	method described; project level; energy system; biomass based; agricultural origin; forestry origin; primary products; residue; liquid/gas fuel; electric power; fossil reference; GHG; whole-chain

(Elsayed et al. 2003)	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Detailed assessment of biomass system	+ Highly consistent analyses of biofuel systems	+ Flow-charts; consistent and quantitative + All assumptions shown for biofuel system + Data with error bars + Parameters for effectiveness & resource use	+ Complex material summarized in compound output parameters + Modular approach
Weakness	– No direct/assoc. costs – Technology level not discussed – GHG from conversion not included – End-use efficiency not included – C-stock changes not included	– Unclear in relation to generic reference system	– Low transparency in generic data for ref.-system, – No sensitivity analysis	– High complexity, with all details – Manual calculations
Other comments	o	o Method based on thorough reviewing	o	o

(Kaltschmitt et al. 1997)

Kaltschmitt, M., G. A. Reinhardt, and T. Stelzer. 1997. **Life cycle analysis of biofuels under different environmental aspects.** Biomass & Bioenergy 12: 121-134.

Objective:	Evaluation of environmental potential for biofuels by life-cycle calculations of GHG, acidification and resource use. Exemplified by Rape Methyl Ether (RME) in comparison with diesel fuel in Germany.
Tool/Method:	Spreadsheet LCA (ISO 14040)
Functional unit:	1 ha agricultural land
Output units:	Primary energy (kWh); CO_2-equivalents as CO_2, CH_4 and N_2O; SO_2-equivalents as SO_2, NO_x, NH_3 and HCl. CO_2eq / fossil kWh substituted, CO_2eq / ha (land-area and primary energy input regarded as 'finite resources')
Key references	(ISO 1997), (Kaltschmitt and Reinhardt 1997)
Keywords:	model/tool presented; project level; energy system; biomass based; agricultural origin ;forestry origin; residue; liquid/gas fuel; fossil reference; GHG; whole-chain; indirect emissions

Kaltschmitt et al. 97	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity**
Strength	+ From production (land-use) to conversion + Discussing choice of land-use reference system and leakage	+	+ Biomass system clearly described qualitatively + Parameters for effectiveness	+
Weakness	– No costs – Primary energy in biomass not included (only for 'finite resources') – Infrastructure not included (buildings, roads, machines) – Technology level not discussed – C-stock changes not included	– Unclear consistency	– Flow-charts missing – Primary data not shown – Generic, non-transparent reference system – Sensitivity analysis not quantitative	– High complexity
Other comments	o Allocation to coupled products o Improved details in balance characteristics	o	o	o

(Hartmann and Kaltschmitt 1999)

Hartmann, D., and M. Kaltschmitt. 1999. **Electricity generation from solid biomass via co-combustion with coal; Energy and emission balances from a German case study.** Biomass & Bioenergy 16: 397-406.

Objective:	Evaluation of environmental potential for co-combustion of coal with biomass residues (10% straw or 10% residual wood). Life-cycle calculations of GHG, acidification and resource use in Southern Germany.
Tool/Method:	Spreadsheet LCA (ISO 14040)
Functional unit:	1 kWh electric power
Output units:	Primary energy (kWh); CO_2-equivalents (CO_2, CH_4 and N_2O); SO_2-equivalents (SO_2, NO_x, NH_3 and HCl). CO_2eq / GWh_{el} (greenhouse effect); MWh_{prim} / GWh_{el} (non-renewable energy resource consumption)
Key references	(Kaltschmitt and Reinhardt 1997), (ISO 1997), (ISO 1998), (Hartmann and Kaltschmitt 1999)
Keywords:	method described; project level; energy system; biomass based; agricultural origin; forestry origin; residue; electric power; fossil reference; GHG; whole-chain; indirect emissions

Hartmann & Kaltschmitt 99	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Ref. system carefully described + Conversion plant infrastructure included	+ Very good between biomass and reference systems	+ Flow-charts + Biomass system clearly described qualitatively + Parameters for effectiveness	+
Weakness	– No costs included – Technology level not discussed – C-stock changes not included	–	– No sensitivity analysis – Primary data not shown	– High complexity
Other comments	o	o	o	o Illustrative pie-charts to describe role of sub-systems

(Jungk 2000)

Jungk, N. C. 2000. **Bioenergy for Europe: which ones fit best? - A comparative analysis for the community. Final report.** 184 pp. IFEU – Institut für Energie- und Umweltforschung Heidelberg GmbH (Institute for Energy and Environmental Research Heidelberg).

Objective:	Aims to produce a tool for comparing biofuels with each other and with fossil equivalents, including socio-economic issues. 10 biofuels were investigated; Triticale for co-firing electricity, Willow and Miscanthus for district heating, RME (rape seed oil methyl ester), SME (sunflower oil methyl ester) and ETBE (ethyl tertiary butyl ether) from sugar beet for transport fuel, Traditional firewood and Wheat straw for district heating, Biogas from swine effluent for combined heat and electricity, Hemp gasification for electricity. Case studies from Austria, Denmark, France, Germany, Greece, Italy, The Netherlands and Switzerland.
Tool/Method:	Spreadsheet LCA (ISO14040-43)
Functional unit:	1 MJ_{heat}, 1 kWh_{electr} or 1 km distance driven. 1 ha of land used.
Output units:	Quantitative: Primary energy, GHG, Acidification, Eutrophication, Summer smog, Nitrous oxide Qualitative: Human toxicity, Ecotoxicity, Ecosystem occupation, Harmful rainfall (erosion) Costs: €/GJ useful energy (costs only include production costs in agriculture or farm)
Key references	(ISO 1997, ISO 1998, ISO 2000a, ISO 2000b),
Keywords:	Model/tool presented; method described; project level; energy system; biomass based; agricultural origin; forestry; animal origin; primary product; residue; heat ;electric power; liquid/gas fuel, fossil reference; GHG; costs; effect of emissions; whole-chain

Jungk 00	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Ref. system carefully described + Best available technologies chosen + End-use comparisons	+ Good between biomass and reference systems	+ Consistent flow-charts on biomass and reference systems + Assumptions shown for biofuel system + Data with error bars + Sensitivity analysis	+ National data used + Standardized and well explained presentation of results
Weakness	– Only agricultural/forestry production costs included – Only fossil C considered – C-stock changes not included	– Very low for costs vs. GHG	– All data not shown in paper	– High complexity
Other comments	o Many environmental impacts studied	o Costs not related to GHG	o Full spreadsheets with data and calculations on web-page	o

(Beer et al. 2002)

Beer, T., T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson, and D. Williams. 2002. **Comparison of Transport Fuels - Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles**. 485 pp. Commonwealth Scientific and Industrial Research Organisation, Aspendale, Australia.

Objective:	To calculate life cycle impacts of different processes and products (also incorporating a means of comparison between products) in Australia. Effects considered include GHG-emissions, health related issues, viability and functionality, and other environmental issues. The fuels examined include various diesel fuels, biodiesel and canola oil, gaseous fuels, hydrated ethanol-based fuels, hydrogen and light vehicle fuels with various combinations of ethanol and petrol.
Tool/Method:	SimaPro 5.1. A computerized LCA model (based on ISO 14040-series) with integrated database and impact assessment procedures.
Functional unit:	Transport units (ton·km) alt. total primary energy used (MJ)
Output units:	GWP (IPCC), air quality
Key references	(Goedkoop and Oele 2002), (ISO 1997), (ISO 1998), (ISO 2000a), (ISO 2000b) Databases cited/used include; ETH-ESU (1996), Buwal 250 (1997), Dutch 10 Dataset (2002), Idemat (2001), IVAM (2000), and industry data. Impact assessment methods include; CML2 baseline 2000, EPS 2000, Eco-indicator 99, Ecopoints 97 and EDIP 96.
Keywords:	method described; project level; policy level; energy system; biomass based; animal origin; agricultural origin; primary product; residue; liquid/gas fuel; fossil reference; GHG; effect of emissions; whole-chain; indirect emissions

Beer 02	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Full life-cycle including production, by-products and end-use conversion + Technology level addressed	+ Consistent analysis of biomass and reference systems	+ Assumptions described in text + Uncertainty analysis	+ National databases used
Weakness	– No costs – No assessment of mitigation effectiveness – C-stock changes not included	–	– Limited flow-charts – Hard to overview data and results	– 485 pp report !
Other comments	o System expansion and allocation o Data from Australia	o	o Information present inside the model o Quantitative flow-charts can be produced by software	o Contribution analysis can be produced by software

(Jungmeier 1999)

Jungmeier, G. 1999. **Greenhouse Gas Balance of Bioenergy Systems - a Comparison of Bioenergy with Fossil Fuel Systems.** Pages 9-26 in K. A. Robertson and B. Schlamadinger, eds. IEA Bioenergy Task 25 Workshop. IEA Bioenergy Task 25, Gatlinburg, Tennessee.

Objective:	Life cycle GHG calculations, including land-use change and byproducts, for a range of bioenergy based systems for generation of heat and electricity, in comparison with fossil-based systems in Austria. The study covers 243 bioenergy systems and 96 fossil energy systems, including two different time-frames for technology level.
Tool/Method:	GEMIS ver. 3.1 (ISO14040). A computerized LCA model (based on ISO 14040-series) with integrated database and impact assessment procedures.
Functional unit:	1 kWh_{heat} or 1 kWh_{el} alt. (0,33 kWh_{el} + 0,67 kWh_{heat}) after end-use conversion
Output units:	Primary energy (kWh), GHG (CO_2, CH_4 and N_2O) CO_2eq / kWh
Key references	(Fritsche 1999a), (Schlamadinger et al. 1997)
Keywords:	method described; policy level; energy system; biomass based; agricultural origin; forestry origin; animal origin; primary product; residue; heat; electric power; fossil reference; GHG; whole-chain; indirect emissions

Jungmeier 99	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Full life-cycle, including land-use, byproducts and end-use conversion + Technology & time considered (2 option scenarios)	+ Good consistency bioenergy and reference system	+ Flow-charts	+ Module design enables simple model-construction for many optional systems
Weakness	– No costs (though possible in GEMIS software) – No assessment of effectiveness	–	– Assumptions very unclear in paper (e.g. allocation to byproducts) – No quantities in flow-charts – No sensitivity analysis	– No guidance to which modules were (should be) used
Other comments	o Allocation by substitution	o Unclear consistency due to low transparency	o Information present inside the model	o

(Jungmeier and Hausberger 2002)

Jungmeier, G., and S. Hausberger. 2002. **Greenhouse Gas Emissions of Cars with Bio-fuels in Austria – A Comparison to Cars with Conventional Fuel**. Pages 1128-1131. 12th European Biomass Conference: Biomass for Energy, Industry and Climate Protection. ETA-Florence, Amsterdam, The Netherlands.

Objective:	Life cycle GHG calculations, including land-use change and byproducts, for a range of bio-fuel options, in comparison with fossil-based systems, in Austria. Studied bio-fuels were; vegetable oil, biodiesel, bioethanol, methanol and hydrogen from various biomass sources, including various end-use technologies.
Tool/Method:	GEMIS ver. 4.1 (ISO14040). A computerized LCA model (based on ISO 14040-series) with integrated database and impact assessment procedures, including cost calculations.
Functional unit:	Transportation distance (km) after end-use conversion
Output units:	GHG-emissions (gCO_2eq / km), costs (€/km), GHG mitigation costs (€/tCO_2eq)
Key references	
Keywords:	method described; project level; energy system; biomass based; agricultural origin; animal origin; residue; liquid/gaseous fuels; fossil reference; GHG; costs, whole-chain; indirect emissions

Jungmeier & Hausberger 02	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ Full life-cycle, including land-use, byproducts and end-use conversion + Technology & time considered (2 option scenarios)	+ Good consistency bioenergy and reference system + Good consistency technological and economic system	+ Flow-chart + Mitigation costs	+
Weakness	–	–	– Assumptions very unclear in paper (e.g. allocation to byproducts) – No quantities in flow-charts – No sensitivity analysis	– No guidance to which modules were used
Other comments	o Allocation by substitution o Unclear comprehensiveness due to low transparency	o Unclear consistency due to low transparency	o Information present inside the model	o

(Gustavsson and Karlsson 2002)

Gustavsson, L., and Å. Karlsson. 2002. **A system perspective on the heating of detached houses.** Energy Policy 30: 553-574.

Objective:	Comparison based on primary energy use, emissions and costs (not external) of different energy systems for heating of detached houses. Sweden
Tool/Method:	Energy system analysis; Emissions based on direct and indirect energy carriers; Costs estimated from fuel prices, investments (at 6% discount rate) and O&M costs in conversion systems.
Functional unit:	1 MWh heat at end-user
Output units:	Primary energy use; GHG-emissions (CO_2 and CH_4); hydrocarbons; sulphur oxides (SO_x); nitrogen oxides (NO_x) Direct costs
Key references	(Schlamadinger et al. 1997), (Börjesson 1999), (Gustavsson and Börjesson 1998), (Zetterberg and Hansén 1998), (Hillring 1999), (Ishitani and Johansson 1995)
Keywords:	method described; project level; policy level; energy system; biomass based; forestry origin; primary product; residue; heat; electric power; fossil reference; GHG; costs; effect of emission; whole-chain; indirect emissions

Gustavsson & Karlsson 02	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ C-stock change included + Best known technology in reference system + Base/peak-load included + Detailed ref. system + Sink availability considered	+ High consistency in biomass vs. reference system + High consistency in technical system vs. cost	+ Flow charts + All assumptions described + Data with error bars + Sensitivity analysis	+ Data collection and calculations from generic energy carrier data
Weakness	–	–	– No ‘mitigation-costs’ calculated	– Complicated system
Other comments	o Only emissions related to energy use	o Fuel price assumed to reflect life-cycle costs	o	o

(Karlsson and Gustavsson 2003)

Karlsson, Å. and L. Gustavsson, 2003. **External costs and taxes in heat supply systems.** *Energy Policy* 31: 1541-1560.

Objective:	Comparison based on primary energy use, emissions and costs (incl. external) of different energy systems for heating of detached houses. Effects of tax system. Sweden
Tool/Method:	Energy system analysis; Emissions based on direct and indirect energy carriers; Costs estimated from fuel prices, investments (at 6% discount rate) and O&M costs in conversion systems. External costs (ExternE)
Functional unit:	1 MWh heat at end-user
Output units:	Primary energy use; GHG-emissions (CO_2 and CH_4); hydrocarbons; sulphur oxides (SO_x); nitrogen oxides (NO_x) Direct and External Costs. Energy effectiveness (MWh_{fuel} / MWh_{heat}); Emission effectiveness (kg C / MWh_{heat}); Energy cost (€ / MWh_{heat});
Key references	(European Commission 1998), (Brännström-Norberg et al. 1996), (Gustavsson and Börjesson 1998), (Gustavsson and Karlsson 2002),
Keywords:	method described; policy level; energy system; biomass based; forestry origin; primary product; residue; heat; fossil reference; GHG; costs; effect of emission; whole-chain; indirect emissions

Karlsson & Gustavsson 03	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ C-stock change included + Detailed ref. system + Cost & energy effectiveness + Emission effectiveness	+ High consistency in biomass vs. reference system + High consistency in technical system vs. cost	+ Flow charts + All assumptions described + Data with error bars	+ Data collection and calculations from generic energy carrier data
Weakness	–	–	– No ‘mitigation-costs’ calculated	– Complicated system
Other comments	o System expansion with conversion efficiencies of heat/power plant o Only emissions related to energy use	o Fuel price assumed to reflect life-cycle costs	o	o

(Groscurth et al. 2000)

Groscurth, H.-M., A. de Almeida, A. Bauen, F. B. Costa, S.-O. Ericson, J. Giegrich, N. von Grabczewski, D. O. Hall, O. Hohmeyer, and K. Jorgensen. 2000. **Total costs and benefits of biomass in selected regions of the European Union.** Energy 25: 1081-1095.

Objective:	Comprehensive analysis of economic and environmental performance of bioenergy use for heat and electricity. Seven cases from the EU with specific fossil reference systems analyzed. Systems studied were CHP-plants fed with woody biomass (with/without gasifier), forest residues or with biogas from organic wastes or a diesel engine fed with cold-pressed rapeseed oil.
Tool/Method:	Facility inventories (direct emissions and economy), Input-output Model EMI 2.0 (indirect emissions and economy), LCA (indirect emissions from production of fertilizers), EcoSense within ExternE (external costs).
Functional unit:	1 kWh of electricity or heat after conversion
Output units:	Internal production cost (€/kWh), Specific employment time (1000h/M€ and h/MWh). External costs from human health impact (YOLL-based) Emissions of; air pollutants (g/kWh), GHG (g CO_{2eq}/kWh). Specific abatement costs (Δcost/ΔCO_{2eq})
Key references	(de Almeida et al. 1998), (Hohmeyer and Walz 1992), (European Commission 1995), (Pope et al. 1995), (Patyk and Reinhardt 1997)
Keywords:	Conceptual methodology paper; energy system; biomass based; agricultural origin; forestry origin; animal origin; primary product; residue; electric power; fossil reference; GHG; costs; effect of emission; whole-chain; indirect emissions

Groscurth et al. 00	**Comprehensiveness**	**Consistency**	**Transparency**	**Complexity/efficiency**
Strength	+ GHG and costs + Direct and indirect costs + Technology level discussed + Normalized for regional variations	+ High between emissions and direct costs + High between bioenergy system and reference	+ Abatement costs calculated	+ Efficient use of national I/O-data
Weakness	– C-stock changes not included (alt. land-use?) – Technology level not quantitatively addressed	– Unclear (and varying?) time frame – Indirect costs don't include climate change	– No flow-charts describing system boundaries – No detailed list of assumptions – No primary data shown – No sensitivity analysis	–
Other comments	o Indirect emissions based on material flow statistics o Allocation by energy content (heat & electricity)	o Hard to interpret in detail due to low transparency	o	o Hard to estimate due to low transparency

End