A Comparison of Life Cycle Assessment Studies of Different Biofuels

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Abstract The intensive increase of biofuel demand has pushed the researchers to find a sustainable biofuel production system. LCA is the most accepted tool to assess the sustainability of biofuel production systems. The functional unit, scope, system boundary, reference system, data source, and allocation are the most important steps of an LCA study. Variations in these steps between studies affect the results significantly. Previous studies have shown that different biofuel feedstocks have different environmental burden hot spots, which refer to elevated greenhouse gas (GHG) emissions associated with a specific life cycle stage or facility process. The present chapter is an effort to compare various LCA studies on different biofuels. The well-to-wheel (cradle-to-grave) system is recommended for the assessment of biofuels production system. An LCA study of biofuels can demonstrate their sustainability and can guide the policy makers in adopting the policies for their promotions.

1 Introduction

Biofuels are plant-derived energy sources that can either be burnt directly for heat or converted to a liquid fuel such as ethanol, biodiesel, biogas, biohydrogen (Davis et al. 2009; Nigam and Singh 2011). The global biofuel sector has grown

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A. Singh et al. (eds.), *Life Cycle Assessment of Renewable Energy Sources*,
Green Energy and Technology, DOI: 10.1007/978-1-4471-5364-1_12,

considerably in the recent years, driven primarily by concerns about fossil fuel prices and availability. Large-scale biofuel industries are being promoted to decrease reliance on petroleum in response to an abrupt rise in oil prices and to develop transportation fuels that reduce greenhouse gas (GHG) emissions compared to conventional fuel (IPCC 2007). This growing interest in biofuels is a means of “modernizing” biomass use and providing greater access to clean liquid fuels while helping to address energy costs, energy security, and global warming concerns associated with petroleum fuels. Industrial use of biofuels, particularly in North America and Latin America, has been expanding over the past century (Fernandes et al. 2007). However, the energetic use of biomass also causes impacts on climate change and, furthermore, different environmental issues arise, such as land-use and agricultural emissions, acidification, and eutrophication (Emmenegger et al. 2012; Dressler et al. 2012). Therefore, the environmental and climate benefits of bioenergies must be verified according to life cycle assessment (LCA) methods (ISO 14040 2006; ISO 14044 2006) to make them a sustainable energy source.

The environmental performance of products and processes has become a key issue, which influences some companies to investigate ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving beyond compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. One such tool is LCA. This concept considers the entire life cycle of a product (Curran 1996). Life cycle assessment is a tool for assessing the environmental impacts of a product, process, or service from design to disposal, i.e., across its entire lifecycle, a so-called cradle-to-grave approach. The impacts may be beneficial or adverse depending on a variety of factors most of which has been discussed in great detail in the previous chapters. These impacts are sometimes referred to as the “environmental footprint” of a product or service. The results of an LCA study depend on several factors, e.g., consideration of system boundaries, functional unit, data sources, impact categories, allocation. This chapter is an effort to compare different LCA studies of biofuels to highlight the main unresolved problems in performing an LCA study for biofuel production systems.

2 Role of LCA in Improvement of Biofuels Production System

Modern bioenergy can be a mechanism for economic development, enabling local communities to secure the energy they need, with farmers earning additional income and achieving greater price stability for their production (UNEP/GRID-Arendal 2011). Cultivation of the energy crops has raised concerns due to their high consumption of conventional fuels, fertilizers, and pesticides, their impacts on ecosystems and competition for arable land with food crops. Safeguards are needed and special emphasis should be given to options that help mitigate risks and create positive effects and co-benefits (UNEP/GRID-Arendal 2011). Responding to these challenges effectively requires a life cycle perspective of the biofuel production pathway/system. Since biofuels are considered a major alternative for the future energy demands, several LCA studies were carried out for the enhancement of biofuel production system (Muys and Quizano 2002; Kim and Dale 2009; Chiaramonti and Racchia 2010; Dressler et al. 2012). If biofuels are to become a major alternative to petroleum, it has to be both environmentally and economically advantageous. LCAs of these transitions will require much stronger integration between economists and systems engineers to address what happens during the transition phase when large-scale changes occur in many components of a complex, market driven, technological system (McKone et al. 2011). To achieve the target as per EC Directive 2009/28/EC (EC 2008), i.e., GHG savings of 60 % by 2020, selection of feedstock for considering local factors and land utilization, process technology, and consumption perspective are major steps to be considered under LCA for improvement in production system. LCA studies conducted in the recent past reported the process phases that can be improved by advancing the technology to consider a product as biofuel according to European Directive 2009/28/EC (Watson et al. 1996; Kaltschmitt et al. 1997; CONCAWE 2004; Larson et al. 2006; Larson 2006; Korres et al. 2010). A generalized scheme for LCA of biofuel production is presented in Fig. 1.

By the LCA study of energy crops, Emmenegger et al. (2011) concluded that producing biofuels can reduce the fossil fuel use and GHG emissions when compared to a fossil reference. The focus on GHG emissions of the main regulatory schemes neglects other relevant environmental impacts and may provide the wrong incentives. Thus, water consumption may become a major concern, offsetting the benefits of biofuel use with respect to climate change. McKone et al. (2011) explained the following seven grand challenges that must be confronted to enable LCA to effectively evaluate the environmental footprint of biofuel alternatives.

(a) understanding farmers, feedstock options, and land use
(b) predicting biofuel production technologies and practices
(c) characterizing tailpipe emissions and their health consequences
(d) incorporating spatial heterogeneity in inventories and assessments
(e) accounting for time in impact assessments
(f) assessing transitions as well as end states
(g) confronting uncertainty and variability

Dressler et al. (2012) conducted LCA study of biogas from maize at three different sites and find a variation in results due to local factor suggesting consideration of local and regional factors before selecting energy crops. In a study with biofuel from grass, Korres et al. (2010) consider that agronomy and digester use are the biggest issues for controlling the GHG savings.

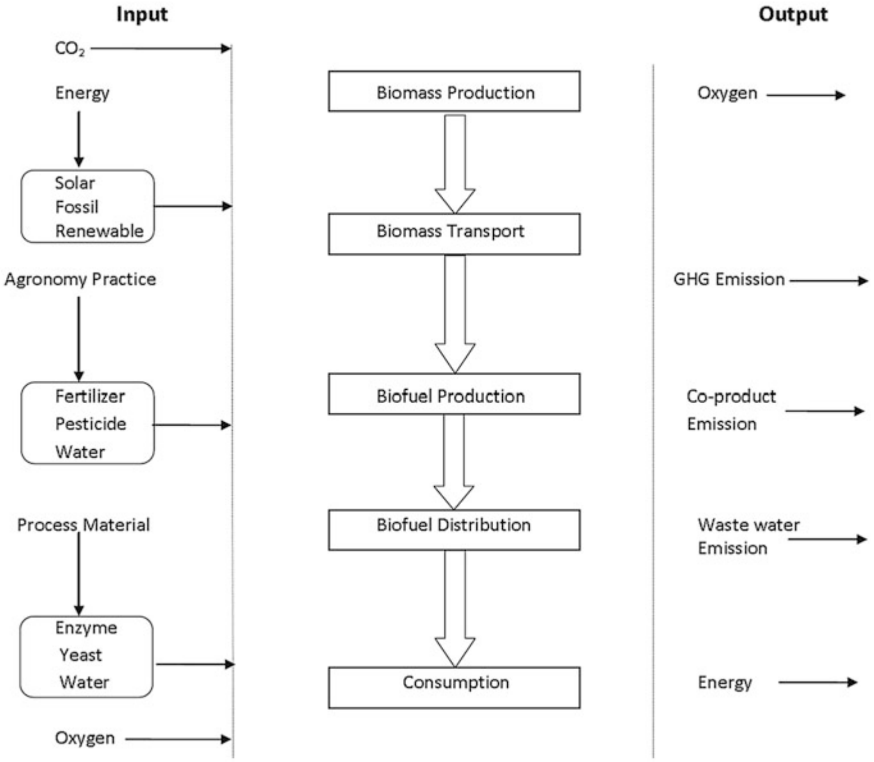

Fig. 1 A generalized scheme for LCA of biofuel production

3 Comparison of Different LCA Studies of Biofuels

Bioethanol and biodiesel are the most commonly produced biofuels, and currently these are derived mainly from food crops such as maize, soya, and sugarcane. Biofuels derived from food crops are known as first-generation biofuels. New technologies in advanced stages of development will allow alternative feedstocks to be used for bioenergy production and are known as second-generation and third-generation biofuels (IEA 2008; Maltitz et al. 2009; Nigam and Singh 2011, Singh et al. 2011). Over 200 feedstocks have been listed for the biofuel family. Use of biofuel over the fossil fuel requires a critical assessment for actual benefit from it. Various LCA studies showed variable results with different energy crop and products (Davis et al. 2009). A comparison of several LCA studies conducted by different researchers focusing on different biofuel for different purpose is presented in Table 1.

Huo et al. (2009) analyzed four different biofuels scenarios, produced from soybean oil. It was identified that allocation methods for coproducts and avoided emissions are critical to the outcome of the study. Additionally, it was also pointed

Table 1 Comparison of life cycle assessment studies of different biofuels

Feedstock	Product	System adopted	Functional unit	System boundary	Reference system	Environment Potential	Country	Reference
Rapeseed	Biodiesel	Field to wheel	1 km travelled by bus	Defined	Conventional diesel	56 % GHG savings	Italy	Finco et al. (2012)
Grass	Bio-methane	Cradle to grave	g CO_2 equivalent (CO_2e) MJ^{-1} energy replaced	Well defined	Fossil diesel	54–75 % GHG saving	Ireland	Korres et al. (2010)
Maize	Biogas	Cradle to grave	1 kg of fresh matter of maize and 1kWh of electricity	Well defined	Fossil fuel	GHG emission 0.179–0.058 kg CO_2eq./kWhe	Germany	Dressler et al. (2012)
Pongamia pinnata	Biodiesel	Field to wheel	1 MJ of energy	Well defined	Diesel	CO_2 sequestration 1.0–1.5	India	Chandrashekar et al. (2012)
Switchgrass	Ethanol	Cradle to grave	g CO_2 equivalent (CO_2e) MJ^{-1} energy replaced	Defined as scope of the study	Coal	114 % GHG saving	USA	Adler et al. (2007)
Reed canarygrass	Ethanol	Cradle to grave	g CO_2 equivalent (CO_2e) MJ^{-1} energy replaced	Defined as scope of the study	Coal	84 % GHG saving	USA	Adler et al. (2007)
Hybrid poplar	Ethanol	Cradle to grave	g CO_2 equivalent (CO_2e) MJ^{-1} energy replaced	Defined as scope of the study	Coal	117 % GHG saving	USA	Adler et al. (2007)
Corn-soybean	Ethanol	Cradle to grave	g CO_2 equivalent (CO_2e) MJ^{-1} energy replaced	Defined as scope of the study	Coal	38–41 % GHG saving	USA	Adler et al. (2007)
Jatropha	Biodiesel	Well to Tank	1 MJ of JME	Defined	Fossil Diesel	72 % GHG saving	Ivory Coast and Mali	Ndong et al. (2009)
Switchgrass, Cynara, Giant reed and Miscanthus	Biomass	Cradle to farm gate	Per unit energy/per unit land	Defined as scope of the study	Production of conventional crops	50–60 % less impact	Italy	Monti et al. (2009)
Corn stover	Bioethanol	Energy product to gate	Not defined	Well defined	Gasoline, A hypothetical case of pure ethanol	Reduction in GWP	The Netherlands	Luo et al. (2009)

(continued)

Table 1 (continued)

Feedstock	Product	System adopted	Functional unit	System boundary	Reference system	Environment Potential	Country	Reference
Switchgrass and corn stover	Ethanol	Cradle to wheel	Per km	Defined	Low-sulfur reformulated gasoline	Up to 70 % lower GHG emissions	Canada	Spatari et al. (2005)
Household and biodegradable municipal waste	Ethanol	Cradle to grave	MJ of fuel equivalent	Defined	Gasoline	Up to 92.5 % GHG emission saving	UK	Stichnothe and Azapagic (2009)
Corn stover	Ethanol	Cradle to grave	1 ha/1 km	Defined	Gasoline	Reduction of 267 g CO_2/km	USA	Sheehan et al. (2004)
Blue-green Algae	Ethanol	Cradle to grave	g CO_2e/MJ	Defined	Gasoline	67 and 87 % reductions in the carbon footprint	USA	Luo et al. 2010
Microalgae	Biodiesel	Cradle to grave	Combustion of 1 MJ biodiesel	Defined	First-generation biodiesel and oil diesel	Significantly decrease environmental impacts	France	Lardon et al. 2009
Potato steam peels	Hydrogen	Cradle to grave	g CO_2 per kilogram of hydrogen produced	Defined	Potato steam peels directly for animal fodder	Reduction in greenhouse gas emissions	USA	Djomo et al. 2008
Microalgae	Biodiesel	Cradle to grave	g CO_2e/MJ	Defined	Fossil diesel	About 80 % lower GWP	UK	Stephenson et al. 2010
Microalgae	Biodiesel	Well to pump	1,000 MJ	Defined	Fossil diesel	Up to 45 % emission	USA	Sander and Murthy 2010
Rapeseed	Biodiesel	Cradle to grave	1 person kilometer	Defined	Conventional Petrol	Shift in environmental problem	Argentina	Emmenegger et al. 2011
Corn, soybean	Bioethanol and Biodiesel	Cradle to grave	1 ha of arable land	Defined	Gasoline	Reduction in GHGs Increase in acidification and eutrophication	USA	Kim and Dale 2005
Rapeseed, oil palm, jatropha	Hydrotreated vegetable oil (biodiesel)	Cradle to grave	1 kWh energy out	Defined	Conventional diesel	About half the GWP	USA	Arvidsson et al. 2011

out that by using displacement approach, all four soybean-based fuels can achieve a modest to significant reduction in well-to-wheel GHG emissions (64–174 %) versus petroleum-based fuels. In this study, Huo and co-worker concluded that the method used to calculate coproduct credits is a crucial issue in biofuel LCA that should be carefully addressed and extensive efforts must be made to identify the most reasonable approach for dealing with the coproducts of biofuel production system. Finco et al. (2012) conducted an LCA study on rapeseed and reported a 56 % less CO_2 equivalent GHG emission from the rapeseed biodiesel than diesel. However, this study does not include negative impact caused by land use particularly from the use of N fertilizer. N_2O emissions, a by-product of N fertilization in agriculture, as one responsible factor to enhanced GHG emissions compared to consumption of fossil fuels (Crutzen et al. 2008) and can overrule the benefit of biofuel. Halleux et al. (2008) conducted a detail comparative LCA between ethanol from sugar beet and methyl ester from rapeseed and concluded an advantage of rapeseed over sugar beet biofuel in terms of total environment impact and GHG emission. Table 1 is explaining the environmental potentiality of various feedstock biofuels over reference fuel (i.e., mostly fossil diesel or fossil gasoline).

Result of Stucki et al. (2012) on LCA of biogas from different purchased substrates and energy crops viz. sugar beet, fodder beet, beet residues, maize silage, molasses, and glycerin shows that the environmental impacts of biogas from purchased substrates are in the same range than those from liquid biofuels. Chandrashekar et al. (2012) find 1.25 times negative global warming potential of *Pongamia pinnata* compared to fossil fuel and Jatropha biodiesel, and nil acidification and eutrophication potential. However, variations in the LCA result are also observed by the differences in selection of scope, system boundary, and other phases of LCA (Table 1). These issues were reviewed in detailed by Reap et al. (2008a, b) and Singh et al. (2010).

The life cycle stages can have harmful effects or benefits of different environmental, economical, and social dimensions. Therefore, an assessment of the complete fuel chains from different perspectives is of crucial importance in order to achieve sustainable biofuels (Markevicius et al. 2010). Comprehensive LCA of biofuels illustrating environmental benefits and impacts can be a tool for policy decisions and for technology development.

Current disagreements about the performance of biofuels rest on different approaches and assumptions used by the investigators (Farrell et al. 2006). The use of different input data, functional units, allocation methods, reference systems and other assumptions complicates comparisons of LCA bioenergy studies and uncertainties and use of specific local factors for indirect effects (e.g., land-use change and N-based soil emissions) may give rise to wide ranges of final results (Cherubini and Strømman 2011). The system choice for comparing different biofuels must be identical because different systems could results improper results, e.g., the choice of passenger car, the efficiency and emissions of EURO V and EURO III varied a lot, so different passenger car, bus, and other transportation vehicles could not be identical to compare different biofuels. The system boundaries of different biofuels also need to be identical, as inclusion and exclusion of coproduct use changed the whole results of the study. Liska and Cassman (2008) revealed that the prediction of emerging biofuel system's performance can pose additional challenges for LCA due to insufficient data of commercial-scale feedstock production and conversion systems. LCA of biofuel systems is currently depending on laboratory- or pilot-scale data. Extrapolation of these laboratory-/pilot-scale results to commercial-scale deployment must be made with caution because of multiple unknowns that introduce significant uncertainty in the estimation of life cycle energy efficiencies and GHG emissions (Liska and Cassman 2008). Standardized LCA methods and agreement on the most relevant metrics for assessing different biofuel systems are essential to forge a consensus in the scientific community, industrialist, and local people. That would help advance public policy initiatives to encourage development of commercial-scale biofuel industries.

There are two issues with regard to standardization. The first is choosing the appropriate metric for the goal of the assessment, and the second is the appropriate analysis framework to support the selected metric. Standardization procedure for regulatory LCA metrics for GHG and energy balances of biofuel systems is summarized by Liska and Cassman (2008) and presented in Table 2. The LCA quantifies the potential benefits and environmental impacts of biofuels but existing methods limit direct comparison of different processes within the biofuel production system and between different biofuel production systems due to inconsistencies in performance metrics, system boundaries, and available data. Therefore, the standardization of LCA methods, metrics, and tools are critically needed to evaluate biofuel production systems for estimating the net GHG mitigation of an individual biofuel production system.

Table 2 Standardization procedure for regulatory LCA metrics for GHG and energy balances of biofuel systems (adapted from Liska and Cassman 2008)

LCA element	Standardization procedure
Biofuel system boundaries	Explicit definition of system components and metrics for each component and the entire system
Input parameters	Evaluate variability, justify which are considered constant or variable, use most recent and directly measured values where possible
Crop production system	Most appropriate county, state, or regional data depending on the most appropriate scale and data availability for the biorefinery facility under evaluation
Coproduct credits	Based on representative coproduct use for the facility
Soil carbon emissions balance	Based on measured changes in soil, if not available, an estimated by appropriate ecosystem models
Nitrous oxide emissions	Based on measured emissions, if not available, use estimated by IPCC guidelines
Land-use change indirect GHG emissions	Estimated using an appropriate global econometric model depending on accepted national or international standards for allocating these effects

4 Key Issues

Life cycle assessment is carried out in phases (ISO 14044 2006; European Commission 2010a, b), and different phases of LCA are presented in Fig. 2. Various key issues in a LCA system of any process to product such as biofuel are scope and functional unit, reference system, system boundary, data source, allocation, inventory analysis, impact assessment, and sensitivity analysis (Singh et al. 2010; Askham 2012).

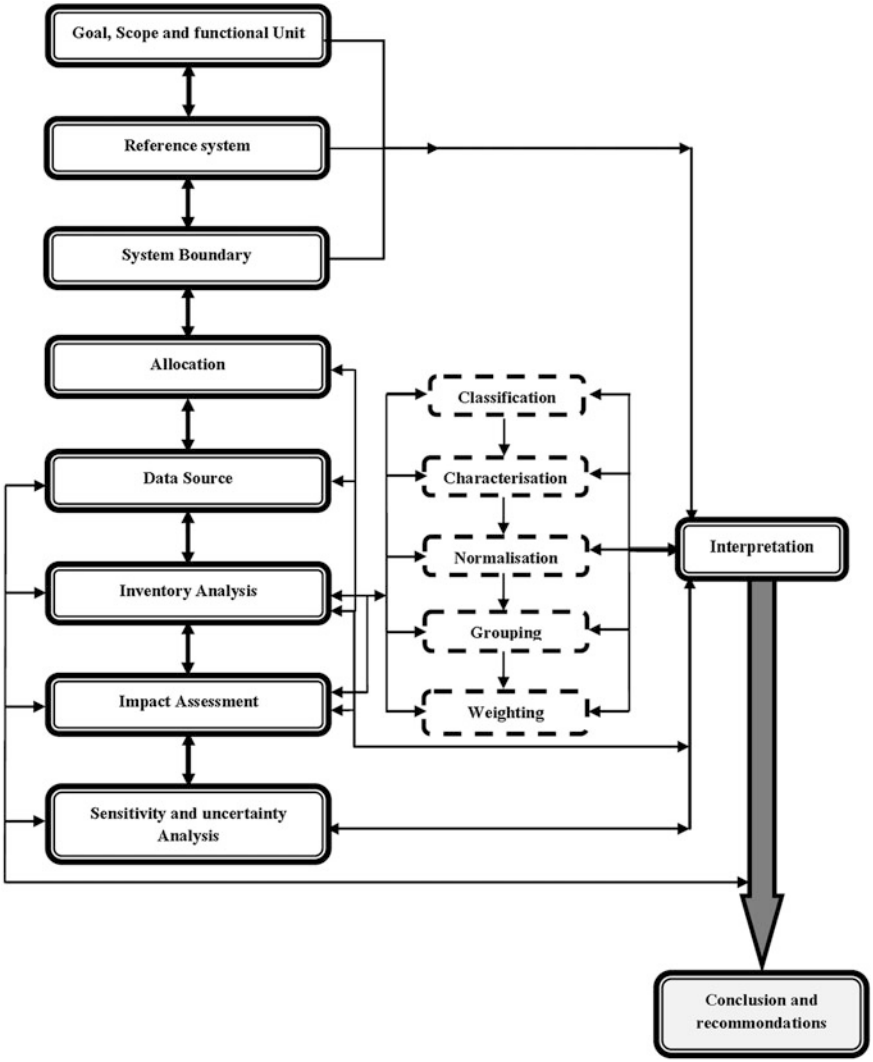

Fig. 2 Various phases of life cycle assessment

4.1 Scope and Functional Unit

First step of a LCA system requires a well-defined scope of the study, which should be compatible to the goal. Functional unit sets the scale for comparison of two or more products, provides a reference to which the input and output data are normalized, and harmonizes the establishment of the inventory (Jensen et al. 1997). The main goal for LCA of biofuels is to evaluate the environmental impacts of the system under examination and to quantify the ecological benefits from the replacement of the reference system basically conventional fossil fuels. It may also provide a tool for policy makers and consumers to determine the optimum eco-friendly fuel (Singh et al. 2010).

Functional unit is the "quantified performance of a product system for use as a reference unit" (ISO 14044 2006). The functional unit, depending on the goal of the study, must be expressed in terms of per unit output. LCA practitioners consider four types of functional units for bioenergy studies, i.e., input unit related (per tone biomass), output unit related (per MJ), unit agricultural land (per ha), and unit time (per year) (Cherubini and Strømman 2011). Output-related unit most frequently used in bioenergy studies. For energy production, functional unit can be expressed as "per kWh energy produced" and for transport, it can be "per km distance travelled" basis. For transport services, the functional unit should not be expressed in "unit energy at fuel tank"; as mechanical efficiency varies from one fuel to another and from one engine type to another (Power and Murphy 2009). Scale, if not properly chosen, could be a problem in modeling LCA studies (Addiscott 2005). Thus, adequate selection of functional unit is of prime emphasis because different functional units could lead to different results for the same product systems (Hischier and Reichart 2003; Kim and Dale 2006) and products cannot be compared accurately.

4.2 Reference System

System analysis is possible by comparing the biofuel system with a targeted (conventional) reference system. The goal of the study determines the choice of the reference system (e.g., whether biofuel is intended to replace conventional transport fuel or coal for electricity or wood pellets for heat). The choice of reference system influences the results of LCA study; therefore, it is important to choose an identical reference system to the conventional system (Singh and Olsen 2011). In most biofuel studies, reference system is limited to a fossil fuel system. It should be noticed that when production of feedstocks for bioenergy uses land previously dedicated to other purposes or when the same feedstock is used for another task, the reference system should include an alternative land-use or an alternative biomass use, respectively (Cherubini and Strømman 2011). In fact, fossil-derived electricity can be assumed to be produced from oil, natural gas, coal, or other sources, all of which having different GHG emission factors (Cherubini and Strømman 2011). The impact of different reference system can be observed in the study conducted by Pettersson and Harvey 2010), where GHG emission savings of bioelectricity production from black liquor are estimated using electricity coming from different fossil sources as reference. The Renewable Energy Directive (EC 2008) requires a 60 % savings in GHG emissions as compared to the fossil fuel it replaces to allow the biofuel to be used for national renewable energy targets after 2017. Thus, a detailed description and impact analysis of the reference system is crucial as well as mandatory for comparing the results of biofuel LCA (Singh et al. 2010).

4.3 System Boundary

On the basis of goal and scope, initial boundaries of the system are determined. Davis et al. (2009) concluded that different system boundaries among various studies of biofuel production from biomass have caused considerable variation in LCA estimates since they vary not only according to start and end points (e.g., well to tank and well to wheel) but also over space and time in a way that can dramatically affect energy and GHG balances.

Many researchers use the “well-to-tank” system boundary to compare environmental impact of biofuels with fossil fuels (Luo et al. 2009; Monti et al. 2009), while others use “well-to-wheel” or “cradle-to-grave” system (Sheehan et al. 2004; Spatari et al. 2005; Power and Murphy 2009; Stichnothe and Azapagic 2009; Korres et al. 2010).

The risk of improper boundaries selection include that LCA results may either not reflect reality well enough and lead to incorrect interpretations and comparisons (Graedel 1998; Lee et al. 1995) or provide the perception to the decision maker that it does not excogitate actual results and thus lower the confidence level of policy maker in making decisions based on the results (Reap et al. 2008a). Inconsistency of system boundaries in LCA analysis of biofuel through omission of the production of various inputs (e.g., enzymes which is used to degrade cellulosic feedstock, fertilizer, pesticides, lime), and utilization of bioethanol (Luo et al. 2009; Gnansounou et al. 2009) could cause a significant variation on the outcome of the analysis. A recent example of such problem can be observed in the debate surrounding the energy balance of ethanol where criteria for the selection of boundaries (like the inclusion of corn-based ethanol coproducts or energy from combustion of lignin in cellulosic ethanol) are strong enough to change the results significantly (Farrell et al. 2006; Hammerschlag 2006). A uniform and clear determination of system boundaries is necessary to accurately estimate the possible environmental impacts including GHG emissions in LCA comparisons between biofuels and conventional fuels (Farrell et al. 2006).

4.4 Data Source and Quality

The use of fixed databases such as ecoinvent, Edu DB, Xergi, NOVAOL srl for conducting an LCA study of bioenergy is not enough because the available databases do not have all processes required for LCA study of bioenergy. Monti et al. (2009) also realized that available databases were generic for specific agricultural problems during conducting the LCA of four potential energy crops (i.e., giant reed, miscanthus, switchgrass, and *Cynara cardunculus* or *Artichoke thistle*) in comparison with conventional wheat/maize rotation and clarify that external data from scientific literature should be obtained for life cycle inventory (LCI) enhancement and accurate representation of the system.

In a survey of approaches to improve reliability Björklund (2002) identifies the main types of uncertainty due to data quality, e.g., badly measured data/inaccurate data, data gaps, unrepresentative (proxy) data, model uncertainty, and uncertainty about LCA methodological choices. Standardized LCA databases are sought to reduce the burdens of data collection (UNEP 2003). There are few established, standardized, or consistent ways to assess and maintain data quality (Vigon and Jensen 1995). Data can become outdated, compiled at different times corresponding to different materials produced over broadly different time periods (Jensen et al. 1997), could be due to technology shift, new invention, etc. LCI data may be unrepresentative because it could be taken from similar but not identical processes (Björklund 2002). In general, the literature tends to agree that data for life cycle inventories are not widely available nor of high quality (Ayres 1995; Ehrenfeld 1997; Owens 1997), due to that during inventory analysis data with gaps are sometimes ignored, assumed, or estimated (Graedel 1998; Lent 2003), and LCA practitioners may extrapolate data based on limited data sets (Owens 1997). Such assumptions and/or extrapolation resulted inappropriate interpretation and/or huge uncertainty for decision makers.

4.5 Allocation

Allocation is the process of assigning to each of the functions of a multiple-function system only those environmental burdens associated with that function (Azapagic and Clift 1999). Allocation can be done on the basis of mass, volume, energy or carbon content or economic value of the coproducts if the inputs and outputs of the system should be partitioned between different products or functions based on physical relationships, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system (SAIC 2006). It is recommended that allocation, if possible, should be avoided (ISO 14044 2006) through subdivision of processes, if possible, or system expansion. Allocation on a mass basis relates products and coproducts using a physical property that is easy to interpret (Singh et al. 2010), although some researchers argued that it cannot be an accurate measure of energy functions (Malça and Freire 2006; Shapouri et al. 2002) and it is not a measure of environmental impacts also. When physical properties alone cannot be established or used, allocation may be based on the economic value of the products although price variation, subsidies, and market interferences could imply difficulties in its implementation (Luo et al. 2009).

In a study of soybean-derived biodiesel, Huo et al. (2009) compared five approaches to address the coproduct issues for various coproducts including protein products (such as soy meal), industrial feedstock (such as glycerin), and energy products (such as propane fuel mix and heavy oils). These five approaches includes the displacement approach, an energy-based allocation approach, a market-value based allocation approach, hybrid approach I, which employs both the displacement method (for soy meal and glycerin) and the allocation method (for other energy coproducts) and hybrid approach II, which is exactly like hybrid approach I except that it addresses soy meal with a market-value-based allocation method. The results of the displacement approach are influenced significantly by the extent of the energy and carbon intensity of the products chosen to be displaced and argued that soy meal displacement could introduce uncertainties because soy meal can displace many kinds of fodder and each fodder could have different energy and carbon intensities. Huo and coworker suggested that when the choice is between the displacement method and the allocation method, the displacement method tends to be chosen if the uncertainties and difficulties associated with it are solved, because it can reflect the energy use and emissions actually saved as a result of the coproducts replacing other equivalent products. They also pointed out that "energy-value-based allocation method is a favorable choice for a system in which the value of all the primary product and coproducts can be determined on the basis of their energy content, such as the production processes of renewable fuels. If a non-energy coproduct is involved and there are difficulties associated with using the displacement approach, the market-value-based allocation method could be an acceptable choice, although the fluctuation of prices could affect the results." Huo et al. (2009) concluded that the integration of displacement method and allocation method (hybrid approaches) could be the most reasonable choice of allocation method for every coproduct. The results of the two hybrid approaches were very close in terms of GHG emissions, indicating that the uncertainty associated with using soy meal to displace soybeans would be in an acceptable range. Reap et al. (2008b) observe that allocation failures hide or exaggerate burdens associated with a product system, effectively biasing all downstream results with an artifact of the analysis.

A number of scientific literatures are available which addresses the allocation issue in LCA and describe the alternative approaches to allocation (Frischknecht 2000; Wang et al. 2004; Curran 2007; Luo et al. 2009). Wang (2005) showed significant impact on overall energy and emission results of alternative allocation methods for corn ethanol LCA, ranging from benefits relative to petroleum of 16–52 % in the case when the ethanol is made by a wet milling process. In another study, Fergusson (2003) also found somewhat smaller (but nevertheless significant) range in GHG results for biofuels when different coproduct allocation methods are used. The expansion of system for use of coproducts within the system is recommended for biofuel production system. If allocation cannot be avoided, then allocation could be done on the basis of carbon content of all products as the target of biofuel production is to minimize the GHG emission and the mass/volume of products is not a precise measure of energy/emission and economic value is fluctuating with the market.

4.6 Inventory Analysis

A LCI is a process of quantifying energy and raw material requirements, environmental pollution for the entire life cycle of a product, process, or activity (SAIC 2006). The inventory analysis requires data on the physical inputs and outputs of the processes of the product system, regarding product flows as well as elementary flows (Singh and Olsen 2011). The main issue of inventory analysis includes data collection and estimations, validation of data and relating data to the specific processes within the system boundaries. After the initial data collection, of which the source should be clearly declared, the system boundaries can be refined as a result of decisions on exclusion of subsystems, exclusion of material flows or inclusion of new unit processes. The validation of data as a mean of data quality improvement or the need for supplementary data would improve the outcome of the analysis (Jensen et al. 1997). The inventory analysis requires very extensive data. The outcome of the study totally depends on the availability and quality of the datasets. So that, there is a great need to collection of standardized data, especially for background processes (Singh and Olsen 2011).

4.7 Impact Assessment

Impact assessment establishes a relationship between the product or process and its potential impacts on human health, environment, and sources depletion (SAIC 2006). ISO developed a standard for conducting an impact assessment entitled ISO 14042, LCIA (ISO 1998). Life cycle impact assessment (LCIA) is structured in classification, characterization, normalization, and weighting. The first three steps are mandatory steps for the determination of impact categories, which corresponds to an important environmental problem (e.g., eutrophication, depletion of non-renewable energy resources, and ozone depletion) (Singh and Olsen 2011). There is no standardized list of impact categories (IFEU 2000). Guinée et al. (2002) has tabulated most of the impact categories in the "Handbook of LCA." The main problems faced during LCIA result from the need to connect the right burdens with the right impacts at the correct time and place (Reap et al. 2008b), in this regard, impact category selection is the most important step which can influence results significantly.

Finnveden (2000) noted the slightly different impact category lists that have been proposed by different organizations. The lack of standardization of some impact categories is demonstrated in the recent debate as to whether certain impact categories such as soil salinity, desiccation, and erosion should be their own category or part of another category such as land-use impact and freshwater depletion (Jolliet et al. 2004). McKone et al. (2011) pointed out a key challenge for applying LCA to a broadly distributed system (e.g., biofuels) is to rationally select appropriate spatial and temporal scales for different impact categories without adding unnecessary complexity and data management challenges as significant geographical and temporal variability among locations over time could influence not only the health impacts of air pollutant emissions, but also soil carbon impacts and water demand consequences, among other factors. McKone and co-worker suggested that accurate assessments must not only capture spatial and variation at appropriate scales (from global to farm-level), but also provide a process to aggregate spatial variability into impact metrics that can be applied at all geographical scales. The selection of midpoint or end point (damage) impact categories is another potential result affecting criteria for both the level of confidence or relevance for decision making on the basis of LCA study results (Reap et al. 2008b). End point categories are less comprehensive and have much higher levels of uncertainty than the better defined midpoint categories (UNEP 2003), and midpoint categories, on the other hand, are harder to interpret because they do not deal directly with an end point associated with an area of protection (Udo de Haes et al. 2002) that may be more relevant for decision making (UNEP 2003).

The International Program on Chemical Safety (WHO 2006) proposed four tiers, ranging from the use of default assumptions to sophisticated probabilistic assessment to address uncertainty in risk assessment:

Tier 0: Default assumptions; single value of result
Tier 1: Qualitative but systematic identification and characterization of uncertainties
Tier 2: Quantitative evaluation of uncertainty making use of bounding values, interval analysis, and sensitivity analysis
Tier 3: Probabilistic assessments with single or multiple outcome distributions reflecting uncertainty and variability.

Cherubini and Strømman (2011) reviewed several biofuel LCA studies and found that very few studies (about 9 %) included land-use category in their impact assessment. This is an important indicator particularly for bioenergy systems based on dedicated crops or forest resources, since land use may lead to substantial impacts, especially on biodiversity and on soil quality. This is mainly due to the fact that there is no widely accepted methodology for including land-use impacts in LCA, despite some recent efforts (Dubreuil et al. 2007; Koellner and Scholz 2008; Scholz 2007). Cherubini and Strømman (2011) also stated that for the same reason, none of the reviewed studies included in the assessment the potential impact of bioenergy on biodiversity, despite an existing accurate methodology (Michelsen 2008).

Tokunaga et al. (2012) concluded that by ignoring emissions associated with land-use change, significant emissions savings could achieve via biofuel use, ranging from 10 to 80 % reductions than fossil fuel emissions. The land-use changes could significantly increase life cycle emissions, while byproduct credits could significantly reduce life cycle emissions. Emmenegger et al. (2011) reported that the use of marginal arid land for cultivation reduces land-use impacts but induces a higher demand for irrigation, which finally compensates for the environmental benefits. Emmenegger and co-worker concluded that changing from petrol to biofuels results in a shift of environmental burdens from fossil fuel resource depletion to ecosystem quality damages.

4.8 Sensitivity Analysis

The key purpose of sensitivity analysis is to identify and focus on key data and assumptions that have the most influence on a result. It can be used to simplify data collection and analysis without compromising the robustness of a result or to identify crucial data that must be thoroughly investigated. According to IFEU (2000), the sensitivity analysis can typically be carried out in three ways, i.e., data uncertainty analysis, different system boundaries, and different life cycle comparisons. The identification of lower and upper values of the process parameters could introduce subjectivity to the analysis and will reflect better on the characteristics of the parameter analyzed (Fukushima and Chen 2009).

Reap and co-workers summarize their opinions about severity and solution adequacy using a simple ordinal scale (Table 3). "Each number represents a

Table 3 Problems in LCA qualitatively rated by severity and adequacy of current solutions (1, minimal severity while 5, severe; 1, problem solved while 5, problem largely unaddressed) (adapted from Reap et al. 2008b)

Problem	Severity	Solution adequacy
Functional unit definition	4	3
Boundary selection	4	3
Alternative scenario considerations	1	5
Allocation	5	3
Negligible contribution criteria	3	3
Local technical uniqueness	2	2
Impact category selection	3	3
Spatial variation	5	3
Local environmental uniqueness	5	3
Dynamics of the environment	3	4
Time horizons	2	3
Weighting and valuation	4	2
Uncertainty in the decision process	3	3
Data availability and quality	5	3

qualitative estimate. Severity represents a combination of problem magnitude, likelihood of occurrence, and chances of detecting the error should it occur. For instance, spatial variations can lead to multiple order of magnitude differences in characterization factors for commonly used impact categories such as acidification. Solution adequacy integrates capacity to address the discussed problem and difficulty of using available solutions." (Reap et al. 2008b).

McKone et al. (2011) indicated that in developing and applying LCA to assess the environmental sustainability of transportation fuels, LCA practitioners commonly address the climate forcing, other pollutant emissions and impacts, water-resource impacts, land-use changes, nutrient needs, human and ecological health impacts, and other external costs. McKone and co-worker suggested that LCA practitioners may also consider social impacts and economic factors for more accurate sustainability assessment of transportation fuel.

5 Conclusion

The most critical issue for the development of biofuel support policies includes environmental and social sustainability of biofuel production and use. The LCA methodology is most acceptable tool for the estimation of the impact of biofuel chains, even in quantitative terms, which ultimately reflects the sustainability of biofuels. Conducting LCA of bioenergy production systems is challenging task because it attempts to combine disparate quantities in ways that require considerable explanation and interpretation as well requires large amounts of practical information. The biofuel LCA studies must have cradle-to-grave approach and function unit should be unit energy utilization as conversion efficiency varies greatly.

References

Addiscott TM (2005) Nitrate, agriculture and the environment. CABI Publishing, Oxfordshire, UK, pp 66–67

Adler PR, Grosso SJD, Parton WJ (2007) Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol Appl 17(3):675–691

Arvidsson R, Persson S, Froling M, Svanstromb M (2011) Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. J Cleaner Prod 19:129–137

Askham C (2012) REACH and LCA—methodological approaches and challenges. Int J Life Cycle Assess 17:43–57

Ayres RU (1995) Life cycle analysis: a critique. Resour Conserv Recycl 14:199–223

Azapagic A, Clift R (1999) Allocation of environmental burdens in co-product systems: product-related burdens. Int J Life Cycle Assess 4(6):357–369

Björklund AE (2002) Survey of approaches to improve reliability in LCA. Int J Life Cycle Assess 7:64–72

Chandrashekar LA, Mahesh NS, Gowda B, Hall W (2012) Life cycle assessment of biodiesel production from pongamia oil in rural Karnataka. Agric Eng Int: CIGR J 14(3):67–77

Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresour Technol 102:437–451

Chiaramonti D, Recchia L (2010) Is life cycle assessment (LCA) a suitable method for quantitative CO2 saving estimations? The impact of field input on the LCA results for a pure vegetable oil chain. Biomass Bioenerg 34:787–797

IPCC, Climate Change (2007) Mitigation of climate change. Working group III contribution to the Intergovernmental panel on climate change fourth assessment report. Cambridge University Press, Cambridge

CONCAWE: CONservation of clean air and water in Europe (Oil companies' European association for environment, health and safety in refining and distribution) (2004) Joint Research Centre of the EU Commission, and European Council for Automotive R&D. Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 1b, Jan 2004. http://ies.jrc.cec.eu.int/Download/eh

Crutzen PJ, Mosier AR, Smith KA, Winiwarter W (2008) N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys 8:389–395

Curran MA (ed) (1996) Environmental life cycle assessment. ISBN 0-07-015063-X, McGraw-Hill

Curran MA (2007) Co-product and input allocation. Approaches for creating life cycle inventory data. A literature review. Int J Life Cycle Assess 12(1):65–78

Davis SC, Anderson-Teixeira KJ, DeLucia EH (2009) Life-cycle analysis and the ecology of biofuels. Trends Plant Sci 14(3):140–146

Djomo SN, Humbert S, Blumberga D (2008) Life cycle assessment of hydrogen produced from potato steam peels. Int J Hydrogen Energy 33:3067–3072

Dressler D, Loewen A, Nelles M (2012) Life cycle assessment of the supply and use of bioenergy: impact of regional factors on biogas production. Int J Life Cycle Assess 17:1104–1115

Dubreuil A, Gaillard G, Müller-Wenk R (2007) Key elements in a framework for land use impact assessment within LCA. Int J Life Cycle Assess 12:5–15

EC (2008) Commission of the European communities. Proposal for a directive of the European parliament and of the council on the promotion of the use of renewable sources. COM 19 final, 2008/0016 (COD)

Ehrenfeld J (1997) The importance of LCAs—warts and all. J Ind Ecol 1:41–49

Emmenegger MF, Pfister S, Koehler A, Giovanetti LDe, Arena AP, Zah R (2011) Taking into account water use impacts in the LCA of biofuels: an Argentinean case study. Int J Life Cycle Assess 16:869–877

Emmenegger MF, Stucki M, Hermle S (2012) LCA of energetic biomass utilization: actual projects and new developments—23 April 2012, Berne, Switzerland. Int J Life Cycle Assess 17:1142–1147

European Commission (2010a) IUCLID dataset substance ID/CAS no.:71-43-2, Benzene. http://ecb.jrc.ec.europa.eu/iuclid-datasheet/71432.pdf. Accessed 11 July 2011

European Commission (2010b) International reference life cycle data system (ILCD) handbook—general guide for life cycle assessment—detailed guidance. EUR 24708 EN. European commission, joint research centre, institute for environment and sustainability, 1st edn. Publications Office of the European Union, Luxemburg

Farrell AE, Pelvin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. Science 311:506–508

Fergusson M (2003) Expert paper on the global impacts of road transport biofuels: a contribution to the government's analysis, national society for clean air (NSCA), cleaner transport forum, and the Institute for European Environmental Policy, p 25

Fernandes SD, Trautmann NM, Streets DG, Roden CA, Bond TC (2007) Global biofuel use, 1850–2000. Global biogeochem cycles 21, GB2019 DOI:10.1029/2006GB002836

Finco A, Bentivoglio D, Rasetti M, Padella M, Cortesi D, Polla P (2012) Sustainability of rapeseed biodiesel using life cycle assessment. Presentation at the international association of agricultural economists (IAAE) triennial conference, Foz do Iguaçu, Brazil, 18–24 Aug 2012

Finnveden G (2000) On the limitations of life cycle assessment and environmental systems analysis tools in general. Int J Life Cycle Assess 5:229–238

Frischknecht R (2000) Allocation in life cycle inventory analysis for joint production. Int J Life Cycle Assess 5(2):85–95

Fukushima Y, Chen SP (2009) A decision support tool for modifications in crop cultivation method based on life cycle assessment: a case study on greenhouse gas emission reduction in Taiwanese sugarcane cultivation. Int J Life Cycle Assess 14:639–655

Gnansounou E, Dauriat A, Villegas J, Panichelli L (2009) Life cycle assessment of biofuels: energy and greenhouse gas balances. Bioresour Technol 100(21):4919–4930

Graedel TE (1998) Streamlined life-cycle assessment. Prentice Hall, Upper Saddle River, p 310

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Kluwer Academic, Dordrecht

Halleux H, Lassaux S, Renzoni R, Germain A (2008) Comparative life cycle assessment of two biofuels. Ethanol from sugar beet and rapeseed methyl ester. Int J Life Cycle Assess 13(3):184–190

Hammerschlag R (2006) Ethanol's energy return on investment: a survey of the literature 1990–present. Environ Sci Technol 40:1744–1750

Hischier R, Reichart I (2003) Multifunctional electronic media-traditional media: the problem of an adequate functional unit. Int J Life Cycle Assess 8:201–208

Huo H, Wang M, Bloyd C, Putsche V (2009) Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. Environ Sci Technol 43:750–756

IEA (International Energy Agency) (2008) Energy technology perspectives: scenarios and strategies to 2050. OECD/IEA, Paris

IFEU (2000) Bioenergy for Europe: which ones fit best?–a comparative analysis for the community. Institute for Energy and Environmental Research, Heidelberg

ISO 14040 (2006) ISO Norm 14040:2006. Life cycle assessment: principles and framework. Environmental management. International Organisation for Standardisation, Geneva

ISO 14044 (2006) Environmental management—life cycle assessment—requirements and guidelines

ISO (1998) ISO 14041: environmental management—life cycle assessment—goal and scope definition and inventory analysis. ISO 14041:1998(E). International Standards Organization

Jensen AA, Hoffman L, Møller BT, Schmidt A, Christiansen K, Elkington J, van Dijk F (1997) Life-cycle assessment (LCA)—a guide to approaches, experiences and information sources. Environmental issues series no. 6. European Environment Agency, Copenhagen

Jolliet O, Mueller-Wenk R, Bare J, Brent A, Goedkoop M, Heijungs R, Itsubo N, Peña C, Pennington DW, Potting J, Rebitzer G, Stewart M, Udo de Haes HA, Weidema B (2004) The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. Int J Life Cycle Assess 9:394–404

Kaltschmitt M, Reingardt GA, Stelzer T (1997) Life cycle analysis of biofuels under different environmental aspects. Biomass Bioenergy 12(2):121–134

Kim S, Dale BE (2005) Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass Bioenerg 29:426–439

Kim S, Dale BE (2006) Ethanol fuels: E10 or E85—life cycle perspectives. Int J Life Cycle Assess 11:117–121

Kim S, Dale BE (2009) Regional variations in greenhouse gas emissions of biobased products in the United States—corn based ethanol and soybean oil. Int J Life Cycle Assess 14:540–546

Koellner T, Scholz R (2008) Assessment of land use impacts on the natural environment. Int J Life Cycle Assess 13:32–48

Korres NE, Singh A, Nizami AS, Murphy JD (2010) Is grass biomethane a sustainable transport biofuel? Biofuels Bioprod Bioref 4:310–325

Lardon L, Helias A, Sialve B, Steyer JP, Bernard O (2009) Life-cycle assessment of biodiesel production from microalgae. Environ Sci Technol 43(17):6475–6481

Larson ED (2006) A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy Sus Dev 10(2):109–126

Larson ED, Williams RH, Jin H (2006) Fuels and electricity from biomass with CO2 capture and storage, prepared for 8th international conference on greenhouse gas control technologies, Trondheim, Norway, June 2006

Lee JJ, O'Callaghan P, Allen D (1995) Critical review of life cycle analysis and assessment techniques and their application to commercial activities. Resour Conserv Recycl 13:37–56

Lent T (2003) Toxic data bias and the challenges of using LCA in the design community, presented at GreenBuild 2003, Pittsburg, PA

Liska AJ, Cassman KG (2008) Towards standardization of life-cycle metrics for biofuels: greenhouse gas emissions mitigation and net energy yield. J Biobased Materials Bioenerg 2:187–203

Luo L, van der Voet E, Huppes G, Udo de Haes HA (2009) Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol. Int J Life Cycle Assess 14:529–539

Luo D, Hu Z, Choi DG, Thomas VM, Realff MJ, Chance RR (2010) Life cycle energy and greenhouse gas emissions for an ethanol production process based on blue-green algae. Environ Sci Technol 44:8670–8677

Malça J, Freire F (2006) Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): assessing the implications of allocation. Energy 31:3362–3380

Maltitz G, von Haywood L, Mapako M, Brent A (2009) Analysis of opportunities for biofuel production in sub-Saharan Africa. CIFOR

Markevicius A, Katinas V, Perednis E, Tamasauskiene M (2010) Trends and sustainability criteria of the production and use of liquid biofuels. Renew Sustain Energy Rev 14:3226–3231

McKone TE, Nazaroff WW, Berck P, Auffhammer M, Lipman T, Torn MS, Masanet E, Lobscheid A, Santero N, Mishra U, Barrett A, Bomberg M, Fingerman K, Scown C, Strogen B, Horvath A (2011) Grand challenges for life-cycle assessment of biofuels. Environ Sci Technol 45:1751–1756

Michelsen O (2008) Assessment of land use impact on biodiversity. Int J Life Cycle Assess 13:22–31

Monti A, Fazio S, Venturi G (2009) Cradle-to-farm gate life cycle assessment in perennial energy crops. Eur J Agron 31:77–84

Muys B, García Quijano J (2002) A new method for land use impact assessment in LCA based on ecosystem exergy concept. Internal report. Laboratory for forest, and landscape research, Leuven, Belgium. http://www.biw.kuleuven.be/lbh/lbnl/forecoman/pdf/land%20use%20method4.pdf. Accessed 9 Jan 2012

Ndong R, Montrejaud-Vignoles M, Girons OS, Gabrielle B, Pirot R, Domergue M, Sablayrolles C (2009) Life cycle assessment of biofuels from Jatropha curcas in West Africa: a field study. Glob Change Biol Bioenergy 1(3):197–210. ISSN 1757-1707

Nigam PS, Singh A (2011) Production of liquid biofuels from renewable resources. Prog Energ Combust Sci 37:52–68

Owens JW (1997) Life-cycle assessment in relation to risk assessment: an evolving perspective. Risk Anal 17:359–365

Pettersson K, Harvey S (2010) CO_2 emission balances for different black liquor gasification biorefinery concepts for production of electricity or second-generation liquid biofuels. Energy 35:1101–1106

Power N, Murphy JD (2009) Which is the preferable transport fuel on a greenhouse gas basis: biomethane or ethanol? Biomass Bioenergy 33:1403–1412

Reap J, Roman F, Duncan S, Bras B (2008a) A survey of unresolved problems in life cycle assessment. Part 1: goal and scope and inventory analysis. Int J Life Cycle Assess 13:290–300

Reap J, Roman F, Duncan S, Bras B (2008b) A survey of unresolved problems in life cycle assessment. Part 2: impact assessment and interpretation. Int J Life Cycle Assess 13:374–388

SAIC (2006) Life cycle assessment: principles and practice. Scientific applications international corporation (SAIC), report no. EPA/600/R-06/060. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Ohio

Sander K, Murthy GS (2010) Life cycle analysis of algae biodiesel. Int J Life Cycle Assess 15:704–714

Scholz R (2007) Assessment of land use impacts on the natural environment. Part 1: an analytical framework for pure land occupation and land use change. Int J Life Cycle Assess 12:16–23

Shapouri H, Duffield J, Wang M (2002) The energy balance of corn ethanol: an update. Agricultural economic report no. 813. US Department of Agriculture

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, Nelson R (2004) Energy and environmental aspects of using corn stover for fuel ethanol. J Ind Ecol 7:117–146

Singh A, Olsen SI (2011) Critical analysis of biochemical conversion, sustainability and life cycle assessment of algal biofuels. Appl Energy 88:3548–3555

Singh A, Pant D, Korres NE, Nizami AS, Prasad S, Murphy JD (2010) Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. Bioreso Tech 1001:5003–5012

Singh A, Olsen SI, Nigam PS (2011) A viable technology to generate third generation biofuel. J Chem Tech Biotech 86(11):1349–1353

Spatari S, Zhang Y, MacLean HL (2005) Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. Environ Sci Technol 39(24):9750–9758

Stephenson AL, Kazamia E, Dennis JS, Howe CJ, Scott SA, Smith AG (2010) Life-cycle assessment of potential algal biodiesel pro-duction in the United Kingdom: a comparison of raceways and air-lift tubular bioreactors. Energy Fuels 24:4062–4077

Stichnothe H, Azapagic A (2009) Bioethanol from waste: life cycle estimation of the greenhouse gas saving potential. Resour Conserv Recycl 53(11):624–630

Stucki M, Jungbluth N, Leuenberger M (2012) Life cycle assessment of biogas production from different substrates—Schlussbericht. Auftragnehmer: ESU-Services Ltd., Publikation 290514. Bundesamt für Energie BFE, Berne, Switzerland, Accessed from Int J Life Cycle Assess 17:1142–1147

Tokunaga K, Bernstein P, Coleman C, Konan D, Makini E, NASSERI I (2012) Life cycle analysis of biofuels implementation in Hawai‘i. The economic research organization. University of Hawaii at Manoa, Hawaii

Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klopffer W, Krewitt W, Lindeijer E, Mueller-Wenk R, Olsen SI, Pennington DW, Potting J, Steen B (eds) (2002) Life-cycle impact assessment: striving towards best practice. Society of Environmental Toxicology and Chemistry (SETAC), Pensacola

UNEP (2003) Evaluation of environmental impacts in life cycle assessment, United Nations environment programme, division of technology, industry and economics (DTIE), production and consumption unit, Paris

UNEP/GRID-Arendal (2011) http://www.unep.org/climatechange/mitigation/Portals/93/documents/Bioenergy/VBG_Ebook.pdf. ecsase on 30 Dec 2012

Vigon BW, Jensen AA (1995) Life cycle assessment: data quality and databases practitioner survey. J Clean Prod 3:135–141

Wang M (2005) Energy and greenhouse emission impacts of fuel ethanol, presentation at the DOE/EC biorefinery workshop, Washington, DC, 21 July

Wang M, Lee H, Molburg J (2004) Allocation of energy use in petroleum refineries to petroleum products. Int J Life Cycle Assess 9(1):34–44

Watson RT, Zinyowera MC, Moss RH, Dokken DJ (eds) (1996) Climate change 1995: impacts, adaptations and mitigation of climate change. Cambridge University Press, Cambridge

WHO (World Health Organization), International Program on Chemical Safety (IPCS) (2006) Guidance document on characterizing and communicating uncertainty of exposure assessment. World Health Organization, Geneva, Switzerland, Nov 2006