Development of life cycle assessment for residue-based bioenergy
Wiloso, E.I.

Author: Wiloso, Edi Iswanto
Title: Development of life cycle assessment for residue-based bioenergy
Issue Date: 2015-10-29

Chapter 1

General introduction

1.1 Sustainability of bioenergy

Bioenergy is expected to play an increasingly significant role in the development of sustainable energy supplies. This, consequently, incites concerns regarding the sustainability of biomass supply for bioenergy feedstock, choices of conversion technologies, and policies on the future energy mix. In that context, the impacts of bioenergy systems must be meticulously assessed before a decision can be made to develop them on a more extensive scale. In order to make a determination, a reliable sustainability assessment framework is required to evaluate the environmental, social, and economic performances of a bioenergy system. Potential unfavorable impacts of a bioenergy system include land use changes, biodiversity loss, water availability, and threats to food security. These risks must be weighed against the potential benefits such as a reduction in global warming, increased energy security, income generation, and rural development. This thesis focuses on specific elements of the sustainability criteria for a bioenergy system, i.e., environmental sustainability.

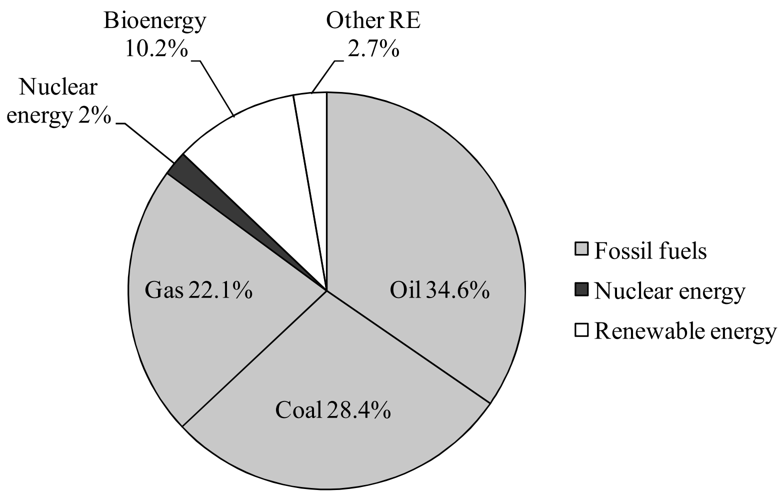

Figure 1.1. Global energy mix (based on IPCC, 2011; RE = renewable energy; the largest contribution is from fossil fuels, 85%).

As indicated in Figure 1.1., the recent global energy mix continuous to be dominated by fossil fuels consisting of oil, coal, and gas. Bioenergy places second, followed by other renewable energy, and nuclear energy. It is clear that bioenergy plays a role as the greatest contributor to renewable energy. In the future, production and exploitation of bioenergy is also predicted to sharply increase. For example, in 2008, the total primary energy supply from biomass in the forms of electricity, heat, combined-heat and power, and transport fuels amounted to 11.3 EJ; meanwhile, future deployment of bioenergy of any forms could reach 100 EJ to 300 EJ by 2050 (IPCC, 2011), noting that there is large uncertainty associated with these estimated potential figures. The numerous increases in the future estimate for bioenergy production express substantial current concerns for the continuing depletion of fossil oil.

There have been ongoing debates concerning the environmental status of bioenergy systems. On the one hand, bioenergy is believed to possess significant greenhouse gas (GHG) mitigation potential. For example, IPCC (2011) stated that bioenergy has the ability to reduce emissions by 80% to 90% compared to the fossil energy baseline, provided that the biomass is sustainably prepared and efficient bioenergy systems are employed. On the other hand, bioenergy has also been suspected of increasing GHG emissions due to the substantial loss of carbon stocks as a consequence of land use changes (Searchinger et al., 2008). Furthermore, intensive agriculture practices within bioenergy systems could potentially affect soil fertility which subsequently influences future biomass productivity. This cause-and-effect interaction is still insufficiently understood and is likely to exhibit strong regional differences. With such contradicting statements, it is difficult for policy makers to make beneficial decisions on the future development of bioenergy.

Scientific analysis aided by analytical tools such as life cycle assessment (LCA) can be employed to assist in solving the problem. LCA is a tool to evaluate the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006). The tool has been applied quite extensively to bioenergy systems but, again, with ambiguous or even contradicting answers (van der Voet et al., 2010; Cherubini and Strømman, 2011). The issue is that LCA has not been mature enough to be able to answer questions in an emerging field such as bioenergy and even more so for those bioenergy based on biomass residues. A significant amount of efforts is essential in order to harmonize these diverging results (van der Voet et al., 2010; Cherubini and Strømman, 2011). This thesis discusses the development of LCA as an assessment tool for residue-based bioenergy.

1.2 Residue-based bioenergy

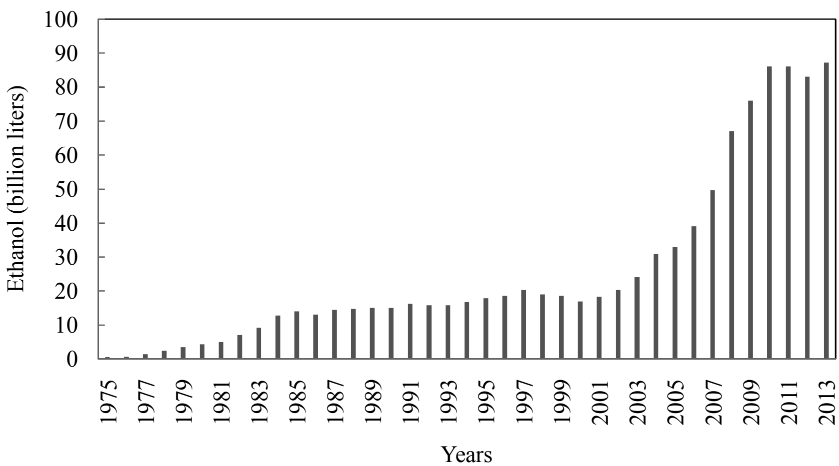

Figure 1.2. World production of bioethanol (based on Sorda et al., 2010; Gupta and Verma, 2015).

The term biomass in general is often used in a broad meaning to include plant materials, animal product and manure, food processing and forestry by-products, and urban wastes (Lal, 2005). In this thesis, bioenergy feedstocks are categorized into biomass products (food products, energy crops) and biomass residues. More specifically, biomass residues are referred to as non-edible portions of plants that are generated in fields or post-harvest processing plants. They are called residues because not intentionally produced for certain purposes, instead, as co-products of other product systems (for example, food, feed, or fibers). From an environmental perspective, biomass residues could be exploited as an alternative feedstock with less risk than biomass products. The International Energy Agency categorized biomass residues as one of the potential candidates for sustainable bioenergy feedstocks (IEA, 2009). Such preference for a more sustainable bioenergy could become a major driver for an increase in demand for biomass residues in the future.

This thesis generally refers to bioenergy as being in the forms of solid (wood chips or pellets), liquid (ethanol or biodiesel), and gas (biogas). In addition to discussing bioenergy in general, special emphasis is given to second-generation bioethanol, a major potential driver for the future increase in demand for biomass residues as bioenergy feedstock. It refers to bioethanol derived from non-edible lignocellulosic biomass (Bright and Strømman, 2009; Garcia et al., 2009; Slade et al., 2009).

As indicated in Figure 1.2., over the last decade, there has been a dramatic increase in global bioethanol production with a total amount of 87 billion liters in 2013. This contribution is dominated by the USA and Brazil producing bioethanol based on corn grain and sugarcane syrup, respectively. The bioethanol is primarily employed as an alternative transportation biofuel to substitute for gasoline. This development, however, has been hindered by the burgeoning concerns regarding the competition for raw materials with food sectors and the consequences related to land-use change (de Oliveira et al., 2005). The competition with food sectors, for example, has been partially blamed for the increase of food prices in the USA between 2003 and 2008 (Sorda et al., 2010).

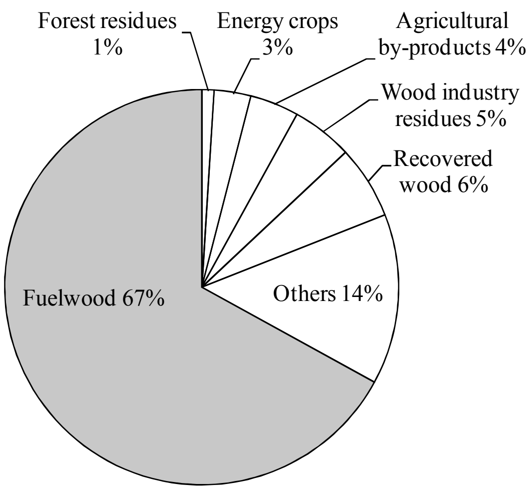

Figure 1.3. Shares of global non-edible biomass for bioenergy (based on IPCC, 2011; Others = charcoal, animal by-products, municipal solid wastes and landfill gas, black liquor; shaded = the largest utilization is for traditional cooking).

The competition with food sectors has encouraged the exploitation of non-food resources for use as bioenergy feedstocks. This non-edible biomass is often exceedingly available in many regions of the world which shares for global bioenergy are depicted in Figure 1.3. It illustrates the different types of biomass used for bioenergy. The figure also indicates that wood biomass has been primarily used for traditional cooking. This fact shows that there continuous to be significant opportunities for improved utilization for bioenergy that is more efficient and environmentally friendly.

Although there is extensive potential for the feedstocks of second-generation bioethanol, the production levels in many countries has been, thus far, discouraging. Expensive production costs prohibit employing bioethanol as a transportation biofuel (Schnoor, 2011). In addition, extensive removal of biomass residues from agricultural fields is not without dilemmas.

Biomass residues fulfill an important role for agricultural lands. Their stock of nutrients provides a basic recycling mechanism that maintains soil fertility, and they can improve the structure of soil for enhanced aeration and water management. This is the primary issue related to the removal of biomass residues from plantation fields. Excessive removal of biomass residues may degrade soil quality and further potentially influence future crop yields (Wilhelm et al., 2004; Lal, 2005; Cherubini et al., 2009). This can be a serious detriment to the long-term sustainability of residue-based bioenergy and should, therefore, be considered as a component of the sustainability assessment. One of the challenges is to compensate the substantial nutrient export with additional fertilizers. However, this will eventually bring further environmental and financial cost that needs careful evaluation.

Another feature associated with biomass residues is concerning the treatment of biogenic carbon in life cycle inventory (LCI). In this thesis, biogenic carbon is defined as carbon contained in the biomass that is accumulated during plant growth involving photosynthetic processes. Currently, Divergence in ways to develop biogenic carbon inventories is extensively found in the scientific literature of bioenergy LCA (Johnson, 2009; Haberl et al., 2012; Levasseur et al., 2013; Downie et al., 2014). In addition, it is speculated that different system boundaries, forms of carbon emissions, and valuation of biogenic carbon will pose certain consequences on the LCI of bioenergy systems (Heijungs and Wiloso, 2014). This thesis elaborates the inventory aspect of the above parameters.

1.3 LCA of residue-based bioenergy

In addition to the general problems in conducting an LCA of product-based bioenergy, those generated from biomass residues add another layer of complexity requiring specific approaches. Generic bioenergy systems consist of typically three main stages, i.e., agricultural processes to produce biomass, conversion into bioenergy, and use of bioenergy. The agricultural processes will in general coproduce biomass products (which are harvested) and biomass residues (which are typically left in fields) which respectively have different economic values. If these two biomasses are to be utilized as bioenergy feedtocks, they would in general undergo the same evaluation schemes, i.e., an LCA procedure involving stages in the generic bioenergy system mentioned above. Feedstocks from biomass residues however require additional considerations. For example, in addition to the bioenergy option, they could also decompose in fields, emitting GHG into the atmosphere and adding organic carbon into soil. These latter options are unique to biomass residues which bring specific consequences. Such consequences will be elaborated further in this thesis.

The majority of LCA studies on bioenergy have initially focused on systems based on food products or energy crops (Cherubini and Ulgiati, 2010; Cherubini and Strømman, 2011). Recent development indicates that more LCA studies have also been expanded toward the utilization of biomass residues conventionally left on fields (Cherubini and Ulgiati, 2010; Cherubini and Strømman, 2011). These studies are often assumed to employ only the surplus biomass or to utilize a greater fraction of residues, but with fertilizer compensation to maintain soil fertility. In certain forest and crop management practices, biomass residues are burned following harvest. In this later case, it can be assumed that the burned biomass residues will not significantly alter carbon flow entering the soil carbon pool (Cowie et al., 2006).

The effect of removing biomass residues from soil has been increasingly recognized as an important component in LCA studies (Mckechnie et al., 2011; Repo et al., 2011 and 2012; Liska et al., 2014). However, at the same time, they are often disregarded because methods to quantify their effects are inadequate, or, if methods are available, they are not easy to implement (Cherubini and Strømman, 2011). These various practices in handling biomass residues in LCA may lead to different results, thus, they must be harmonized for improved characterization of residue-based bioenergy.

As previously indicated, biomass residues are differentiated from biomass products as the former is not intentionally produced for certain purposes. The common criteria in the valuation of biomass residues are that coproducts provide relatively similar proceeds as the primary product, by-products have less value than coproducts, while waste has a negative value (Singh et al., 2010). However, in the LCA community, by-products are not typically differentiated from coproducts. Rather, all economic outputs other than the main product are considered coproducts, but with different values. This valuation scheme can be employed as a criterion to distinguish the impacts of bioenergy based on product- and residue-based bioenergy. This criterion in LCA is referred to as partitioning or allocation methods, which application in bioenergy systems has been discussed thoroughly by Guinée et al. (2009).

Potential supplies of biomass as indicated in Figure 1.3 may not all be entirely available for only bioenergy purposes. There are other potential, competing uses. The feasibilities of the preferred options depend on many factors including new development in emerging technologies such as second-generation bioethanol. In a palm oil system, empty fruit bunches which were initially desired only as mulch are now increasingly explored as a potential feedstock for compost, bioenergy, biochar, biooil, and syngas (Hansen et al., 2012). Considering enormous variations in possible technological options and in the valuation of biomass residues, significant divergence in LCA results are often encountered in practice. In this regard, the development of a specific method to accurately compare and interpret the LCA results is warranted.

1.4 Objective and structure of the thesis

This thesis aims at identifying the key issues in conducting an LCA of residue-based bioenergy. More specifically, the thesis focuses on four primary characteristics associated with the raw materials (biomass residues), i.e., excessive removal from plantation fields which can affect soil fertility; valuation (relative to biomass products); competing uses (bioenergy, feed, fiber, fertilizers); and treatment of biogenic carbon (assumptions of carbon neutrality vs. complete inventory). These unique features require specific LCA approaches which vary from those of conventional product-based bioenergy.

This thesis also proposes improvement in LCA procedures, specifically in the areas of LCI, life cycle impact assessment (LCIA), and methodological choices in the comparative LCA. In that regard, the specific goals of the thesis are to propose the following approaches: [1] solutions to the existing dissimilar practices in the LCI of biogenic carbon; [2] an LCIA method of removing biomass residues from soil on biomass productivity; and [3] methodological choices in comparative LCA of biomass residues utilization. To accomplish the above objectives, the following research questions are addressed:

1. What are the key issues in conducting an LCA of bioenergy systems?
2. What is the environmental sustainability status of second generation bioethanol?
3. How much would the final results of biogenic carbon neutrality assumptions deviate from the true values based on a complete inventory?

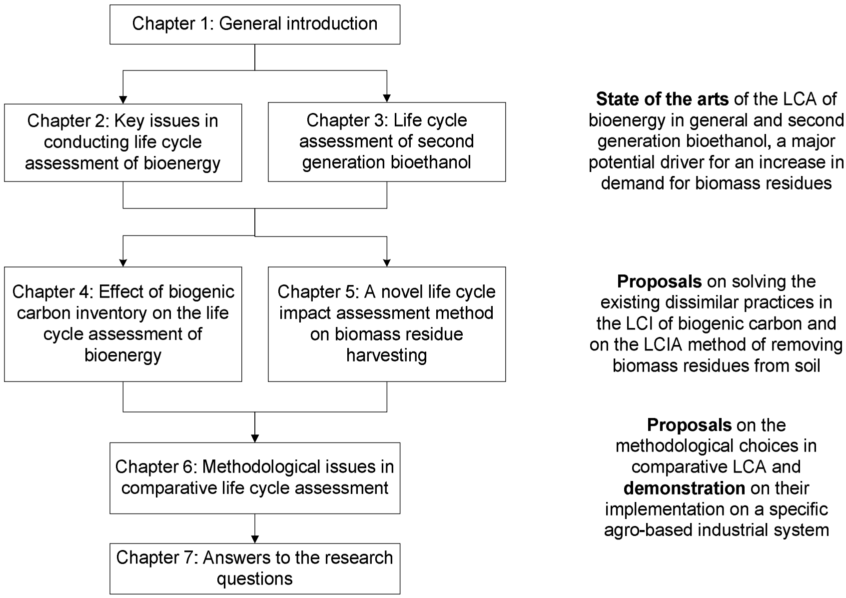

Figure 1.4. Structure of the thesis.

4. How to assess the impact of removing biomass residues from soil on biomass productivity?
5. How to compare the impact of various treatment options on biomass residues in a palm oil system?

These research questions are discussed in seven chapters whereby the structure is exhibited in Figure 1.4. The thesis initially incorporates background information in terms of statistics on the global energy mix, bioenergy in general, and residue-based bioenergy in order to justify the importance of the subject (Chapter 1). Further, it identifies the state-of-the-art of the LCA of bioenergy in general (Chapter 2). Subsequently, it is followed by a review on the environmental sustainability status of second generation bioethanol, a major potential driver for an increase in demand for biomass residues (Chapter 3).

1.5 Outline of the thesis

Chapter 1 describes the background information on the statistics of bioenergy, the LCA of residue-based bioenergy, the research questions, and the structure of the thesis. The primary issues are emphasized and methods to address the associated problems are discussed.

Chapter 2 identifies key issues in conducting an LCA of bioenergy systems. There is an ISO-standardized method for conducting an LCA, but its application to bioenergy is not free from ambiguity. Tremendous numbers of LCA studies on bioenergy have been conducted, however, it continuous to create difficulty when drawing general conclusions on its environmental sustainability due to large variations in the outcomes. Sources of these variations include differences in product systems, data uncertainties, and methodological choices. In particular, bioenergy poses more methodological challenges than other renewable energy because the feedstocks are derived from agricultural chains. In this sub-system, the methodology has not been unambiguous in terms of system boundary, direct and indirect land-use change, treatment for biogenic carbon, and regional variability. Therefore, it is important to define the key issues in conducting an LCA of bioenergy systems, and employ this information as a framework for future studies. Such a framework is beneficial, for example, when analyzing a specific technology like second-generation bioethanol in terms of net-energy output, greenhouse gas emissions, and hotspots along the supply chains.

Chapter 3 identifies the sustainability status of second generation bioethanol, a major stimulator for an increased demand for biomass residues. It reviews the LCA literature on second generation bioethanol and identifies the issues to be resolved to improve LCA practices. The reviews focus on discrepancies in methodological and practical approaches. Emphasis has been placed on system definitions in relation to feedstock specifications (energy crops, biomass residues, and biomass wastes), levels of bioethanol conversion technology (current and future scenarios), bioethanol use as transportation fuel, functional units, allocation methods, and impact categories. The outcome aims at providing decision makers with an increased understanding of the status of second generation bioethanol based on the most studied sustainability aspects, net-energy output and global warming. It may also aid researchers in developing a framework for the bioethanol LCA with correct parameters considering typical problems encountered in the agricultural and bioethanol production chains.

Chapter 4 proposes a solution to the existing dissimilar practices of the LCI of biogenic carbon in bioenergy systems. Biogenic carbon is defined as carbon contained in biomass that is accumulated during plant growth. In spite of considerable progress towards the inventory of biogenic carbon in the life cycle assessment (LCA) of bioenergy in policy guidelines, many scientific articles tend to give no consideration to biogenic carbon, due to the neutrality assumption, rather than employing a complete inventory according to the LCA principles. Meanwhile, the assumption of biogenic carbon neutrality has been previously challenged on the basis of changes in soil carbon stock due to land use change and carbon storage capacities of long-rotation trees or wood products. Supporting this argument, we investigate three other inventory aspects, namely, differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (carbon dioxide vs. methane), and valuation of biogenic carbon (biomass products vs. biomass residues). Referring to a generic bioenergy system, our analysis is focused on eight scenarios of various carbon flows encompassing biomass decomposition in fields and its alternative utilization as bioenergy feedstocks. These scenarios are applicable to both biomass products and biomass residues, which impacts proportionally depend on the chosen allocation criteria between the two.

Chapter 5 proposes a novel life cycle assessment method for biomass residue harvesting in bioenergy systems. Bioenergy plays a role as the largest global contributor to renewable energy as alternative sources for heat, electricity, and biofuel. In addition to reducing dependence on fossil fuels, it is believed that bioenergy can reduce GHG emissions as targeted by many countries around the world. Concerns regarding global competition with food sectors have encouraged the exploitation of non-food resources as feedstocks, for example, for developing second generation bioethanol. One promising source of feedstocks, from an environmental perspective, is biomass residues which are defined as the non-edible parts of plants that are left on the fields following a harvest. However, excessive removal of these residues may negatively affect soil quality and hamper future harvests. In order to estimate this specific impact, it is essential to develop a new characterization model within the LCA framework based on the assumption that the residues also serves as nutrient stock to improve soil quality. The proposed model must also consider organic carbon flows into the soil matrix which will affect future biomass productivity.

Chapter 6 proposes methodological choices in comparative LCA and demonstrates their implementation on a specific agro-based industrial system. Palm oil systems generate substantial amounts of biomass residues which are from an agronomy perspective preferably returned to plantation in order to maintain soil fertility. However, there are often variations in this practice. Diverse treatment options and differences in economic status determine the preferences of performing an LCA, leading to a divergence in results. Consequently, difficulties encountered when comparing LCA results based on literature are not unusual due to dissimilar approaches. The objectives of this chapter are to provide guidelines for methodological choices. The guidelines enable a systematic comparison of diverse scenarios for the treatment and valuation of empty fruit bunches and to explore the effects of, for example, different scenarios on the environmental performances of a palm oil system.

Chapter 7 summarizes the answers to the research questions that are discussed in Chapters 2 through 6. This chapter further discusses the potential application of the developed approaches as well as areas of future research and is finally ended with concluding remarks.

1.6 References

Bright RM, Strømman AH. 2009. Life-cycle assessment of second generation bioethanols produced from Scandinavian boreal forest resources: a regional analysis for middle Norway. J Indust Ecol 13: 514–31.

Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess- Gallasch S. 2009. Energy and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resources, Conservation and Recycling 53: 434-447.

Cherubini F, Strømman AH. 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresource Technology 102: 437-451.

Cherubini F, Ulgiati S. 2010. Crop residues as raw materials for biorefinery systems - a LCA case study. Applied Energy 87: 47-57.

Cowie AL, Smith P, Johnson D. 2006. Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? Mitigation and Adaptation Strategies for Global Change 11: 979-1002.

de Oliveira MED, Vaughan BE, Rykiel Jr. EJ. 2005. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. BioScience 55: 593-602.

Downie A, Lau D, Cowie A, Munroe P. 2014. Approaches to greenhouse gas accounting methods for biomass carbon. Biomass Bioenerg 60: 18-31.

Garcia SG, Gasol CM, Gabarrell X, Rieradevall J, Moreira MT, Feijoo G. 2009. Environmental aspects of ethanol-based fuels from *Brassica carinata*: a case study of second generation ethanol. Renew Sust Energ Rev 13: 2613–20.

Guinée JB, Heijungs R, van der Voet E. 2009. A greenhouse gas indicator for bio-energy: some theoretical issues with practical implications. Int J Life Cycle Assess 14(4): 328-339.

Gupta A, Verma JP. 2015. Sustainable bio-ethanol production from agro-residues: A review. Renewable and Sustainable Energy Reviews 41: 550-567.

Haberl H, Sprinz D, Bonazountas M, Cocco P, Desaubies Y, Henze M, Hertel O, Johnson RK, Kastrup U, Laconte P, Lange E, Novak P, Paavola J, Reenberg A, van den Hove S, Vermeire T, Wadhams P, Searchinger T. 2012. Correcting a fundamental error in greenhouse gas accounting related to bioenergy. Energy Policy 45: 18-23.

Hansen SB, Olsen SI, Ujang Z. 2012. Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel. Bioresource Technology 104: 358-366.

Heijungs R, Wiloso EI. 2014. Life cycle assessment of bioenergy systems. In: Sustainable bioenergy production [L. Wang (editor)], CRC-Press, Boca Raton, Florida, Chapter 4, pp: 99–114.
IEA. 2009. Bioenergy - a Sustainable and Reliable Energy Source. International Energy Agency - Bioenergy, Paris.
IPCC. 2011. Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (editors)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
ISO. 2006. ISO Norm 14040: life cycle assessment: principles and framework, environmental management. Geneva: International Organization for Standardization.
Johnson E. 2009. Goodbye to carbon neutral: getting biomass footprints right. Environ Impact Assess Rev 29(3): 165-168.
Lal R. 2005. World crop residues production and implications of its use as a biofuel. Environmental International 31: 575-84.
Levasseur A, Lesage P, Margni M, Samson R. 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J Ind Ecol 17(1): 117-128.
Liska AJ, Yang H, Milner M, Goddard S, Blanco-Canqui H, Pelton MP, Fang XX, Zhu H, Suyker AE. 2014. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. Nat Clim Change 4: 398–401.
Mckechnie J, Colombo S, Chen J, MabeeW, Maclean, HL. 2011. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with woodbased fuels. Environ Sci Technol 45: 789–795.
Repo A, Kankanen R, Tuovinen JP, Antikainen R, Tuomi M, Vanhala P, Liski J. 2012. Forest bioenergy climate impact can be improved by allocating forest residue removal. GCB Bioenergy 4: 202–212.
Repo A, Tuomi M, Liski J. 2011. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy 3: 107–115.
Schnoor JL. 2011. Cellulosic biofuels disappoint. Environmental Science and Technology 45: 7099.
Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319(5867): 1238-1240.
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. Bioresource Technology 101: 5003-5012.
Slade R, Bauen A, Shah N. 2009. The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe. Biotechnol for Biofuels 2: 1–19.
Sorda G, Banse M, Kemfert C. 2010. An overview of biofuel policies across the world. Energy Policy 38: 6977-88.
van der Voet E, Lifset RJ, Luo L. 2010. Life-cycle assessment of biofuels, convergence and divergence. Biofuels 1: 435-449.
Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR. 2004. Crop and soil productivity response to corn residue removal: a literature review. Agronomy Journal 96: 1-17.