PAPER II

How to ensure greenhouse gas emission reductions by increasing the use of biofuels?

Suitability of the European Union sustainability criteria

In: Biomass & Bioenergy 35, 3504–3513.

BIOMASS AND BIOENERGY 35 (2011) 3504–3513

Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

How to ensure greenhouse gas emission reductions by increasing the use of biofuels? – Suitability of the European Union sustainability criteria

Sampo Soimakallio, Kati Koponen*

VTT Technical Research Centre of Finland, Department of Energy Systems, Tekniikantie 2, P.O. BOX 1000, 02044 VTT, Finland

ARTICLE INFO

Article history:
Received 11 March 2010
Received in revised form
14 April 2011
Accepted 22 April 2011
Available online 23 June 2011

Keywords:
Biofuel
Greenhouse gas emission
Sustainability
Criteria
Life-cycle assessment

ABSTRACT

Biofuels are promoted in many parts of the world. However, concern of environmental and social problems have grown due to increased production of biofuels. Therefore, many initiatives for sustainability criteria have been announced. As a part of the European Union (EU) renewable energy promotion directive (RED), the EU has introduced greenhouse gas (GHG) emission-saving requirements for biofuels along with the first-ever mandate methodology to calculate the GHG emission reduction. As explored in this paper, the RED methodology, based on life-cycle assessment (LCA) approach, excludes many critical issues. These include indirect impacts due to competition for land, biomass and other auxiliary inputs. Also, timing issues, allocation problems, and uncertainty of individual parameters are not yet considered adequately. Moreover, the default values provided in the RED for the GHG balances of biofuels may significantly underestimate their actual impacts. We conclude that the RED methodology cannot ensure the intended GHG emission reductions of biofuels. Instead, a more comprehensive approach is required along with additional data and indicators. Even if it may be very difficult to verify the GHG emission reductions of biofuels in practice, it is necessary to consider the uncertainties more closely, in order to mitigate climate change effectively.

1. Introduction

Transportation accounts for approximately 15% of the global greenhouse gas (GHG) emissions; more than 70% of these come from road transport [1]. The use of gasoline and diesel for road transport will double in the next 25 years and GHG emissions will increase commensurably unless preventative actions are taken [2]. In the past few years several countries, including the United States, China, and the European Union, have announced ambitious policies for promoting the production and use of transportation biofuels (later biofuels) [2]. This is commonly justified by the reduction of GHG emissions through replacing fossil fuels by biofuels. Improvements in energy security, energy independency, and regional employment are other reasons for the particular policies. The supply of biofuels has increased rapidly, though it accounted for only 3% of the total road transport fuel consumption in 2009 [2]. The forecasted share equals 8% in 2035 [2].

A number of recent studies have concluded that the increased production of biofuels may cause significant environmental and social problems [3–12]. Firstly, GHG emission reductions achieved by substituting fossil fuels with biofuels are unclear due to the auxiliary material and energy inputs

* *Corresponding author*. Tel.: +358 207226767; fax: +358 207227604.
E-mail address: sampo.soimakallio@vtt.fi (S. Soimakallio).
0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2011.04.041

required, the direct land-use impact and, in particular, due to indirect impacts such as deforestation. Secondly, other environmental impacts such as nutrient losses due to biomass cultivation and harvesting, and loss of biodiversity may also be significant. Thirdly, the production of biofuels, from raw materials also suitable for food production, has been found to increase food prices and thus cause social problems. Currently, the area of land that is used for biofuel crop production is estimated to be around 1% of the total land used for crop cultivation [13]. However, fulfilling the aggressive targets of increasing the use of biofuels set by various countries will significantly increase the contribution of biofuels in global agricultural land use. The forecasted long-term potential for all bioenergy varies significantly between studies, from some 40 EJ/a to over 1000 EJ/a in the most pessimistic and optimistic scenarios, respectively [14]. The sustainable potential for all bioenergy in 2050 may be only 40–80 EJ/a, which corresponds to 10–20% of fossil energy use today [14].

In order to ensure the sustainable production of biomass and biofuels, several initiatives and certification systems on the sustainability criteria of biofuels and biomass production have been proposed by various organisations and institutions [15]. These initiatives differ from one other. For example they depend on the scope of application; their validity and extent; the variety of environmental, social, and economic aspects considered, and on the conditions set for fulfilling the criteria.

In June 2009, the European Union Directive on the promotion of the use of energy from renewable sources (RED) was published [16]. It establishes a mandatory target to increase the use of renewable energy sources in transportation to 10% in 2020 in the EU. In 2008, the share of renewable energy (probably biofuels) in the overall transportation fuel consumption in the EU is 3.5% [17]. For biofuels and other bioliquids to be accounted in the targets and subsidised, the RED introduces environmental sustainability criteria which need to be met. According to these criteria, the GHG emission reductions compared to fossil comparator shall be at least 35% for biofuels and other bioliquids produced before the end of 2016. From the beginning of 2017, the GHG emission reductions should be at least 50% and from the beginning of 2018, the GHG emission saving should be at least 60% for biofuel production installations where production begins after 1 January 2017. As a part of the sustainability criteria, the RED also introduces a first-ever mandate methodology (later the RED methodology) to calculate the GHG emission balance of biofuels and other bioliquids as well as the GHG emission reduction compared to fossil fuels.

According to the knowledge of the authors the RED methodology has not been critically analysed before. In this paper, we analyse and discuss the suitability of the RED methodology to ensure the GHG benefits of transportation biofuels and other bioliquids (later referred to as biofuels) when fulfilling the biofuel promotion target set by the RED. The paper explores the most critical issues, problems and challenges that are encountered when assessing GHG balances of biofuels in general and compares them with the RED methodology. Based on the most crucial observations we provide suggestions on the way forward.

2. Theoretical framework

2.1. *Life cycle assessment*

Life Cycle Assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts related to the life cycle of a product system (product or service) [18,19]. Setting the appropriate system boundary and selecting the approach for LCA depends on the goal and scope of the particular study. Two main categories of LCA have been defined: attributional (also defined as descriptive, retrospective) and consequential (also defined as change-oriented, prospective) [20–22]. The Attributional LCA (ALCA) has been defined as a method “to describe the environmentally relevant physical flows of a past, current, or potential future product system”. It can be used to describe GHG emissions of each product manufactured or service produced in the economy at a given point of time. In contrast, the Consequential LCA (CLCA) can be defined as a method that aims to describe how environmentally relevant physical flows would have been or would be changed in response to possible decisions that would have been or would be made. The ALCA reflects the system as it is whereas the CLCA attempts to respond to the question: “What if?”.

2.2. *The RED methodology*

The RED provides default values for GHG emission reductions (%) compared to fossil reference fuels for a range of biofuels. These default values can be used if GHG emissions from land-use changes can be proved to be equal to or less than zero. In addition, the RED also provides disaggregated default values, separately and as aggregate, for cultivation, fuel processing, and transport and distribution for a range of biofuels expressed as g CO_2-eq./$MJ_{fuel.}$. Disaggregated default values for cultivation can only be used if the raw materials are cultivated outside the European Community, are cultivated in the Community areas included in the specific list referred to in the RED, or are waste or residues from other than agriculture, aquaculture, and fisheries. If the above mentioned conditions are not filled, if the default value for the GHG emission saving from a specific production pathway falls below the required minimum level, or if the default value does not exist, biofuel producers are required to use the RED methodology to show that the actual GHG emission reductions resulting from their production process fulfil the set criteria. In addition, the biofuel producer may always use the actual value instead of the default value [16].

The part C of Annex V of the RED defines the relative reduction in greenhouse gas emissions achievable by replacing fossil fuel comparator by certain biofuel as:

$$EMISSION\ SAVING = (E_F - E_B)/E_F \tag{1}$$

where,

EB = total emissions from the biofuel or other bioliquid; and

EF = total emissions from the fossil fuel comparator.

The formula with details for calculating the actual values for the total emissions from the use of biofuel or other bioliquid (EB) is given in the part C of Annex V of the RED [6]. It takes into account the greenhouse gas emissions from the different phases of the biofuel production from cultivation or collection of raw-material to the use of biofuel. Greenhouse gas emissions are expressed in terms of g CO_2-eq./MJ in Eq. (1). Relating to the implementation of the RED into national legislation of the EU Member States, the European Commission issued two Communications, which include practical guidelines on the implementation of the sustainability system and the associated calculation rules [23], and on voluntary certification systems and default values [24]. In addition, a Decision on the calculation of land carbon stocks in the case of land-use changes was issued [25].

According to the RED methodology, the spatial system boundary includes the biofuel product system from raw material cultivation (crops), harvesting (residues), and collection (waste) to the distribution of biofuel [16]. However, GHG emissions from production of machinery, infrastructure, buildings and plants are excluded. The climate impacts are assessed with the Global Warming Potential (GWP) values for 100 years given by the IPCC [26].

3. Analysis and discussion

3.1. *Conservativeness of the GHG emission default values of the RED*

We compared the GHG emission default values of some biofuels provided in the RED with the figures found from the recent literature. Based on 25 recent studies (see Supporting information for details), the GHG balance figures for various biofuel supply chains vary significantly around the default values provided in the RED (Fig. 1). Some very high GHG emission estimates were found from the literature for biodiesel derived from palm oil and soya oil. However, also lower GHG emission estimates compared to the default values of the RED were found. Based on the literature review it was not possible to conclude in general whether the default values of the RED are conservative or optimistic concerning specific biofuel chains. The variation in the results for specific raw materials may be due to differences in spatial system boundary setting, handling of timing issues, allocation procedure, parameter assumptions, or case-specific features. These issues are discussed in more details in the analysis of the RED methodology in the following chapters.

3.2. *Spatial system boundary*

The RED methodology provides a framework to set the spatial system boundary to calculate actual GHG emissions of biofuels (Fig. 2). The RED methodology seems to follow the principles of ALCA as physical flows relevant for GHG emissions of biofuel product systems are under consideration. Within the defined system boundary, the GHG balances of biofuels depend on the GHG intensity of raw materials and other auxiliary inputs required. Indirect impacts through market effects are not taken into account. Next we discuss the major mechanisms that may result in significant indirect impacts that are excluded from the RED methodology and provide some suggestions to improve the methodology.

3.2.1. *Land and raw material requirement*

As regards crop-based biofuels, the RED encourages the use of land which provides raw materials whose GHG emission

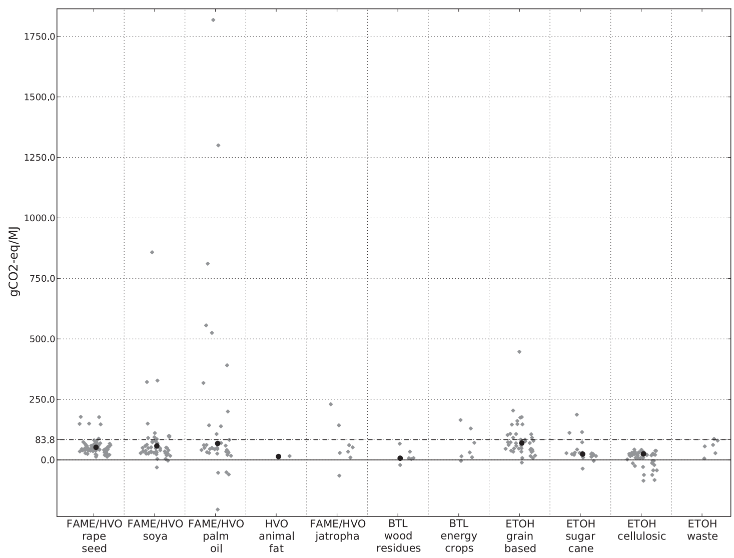

Fig. 1 – GHG balances of different biofuels produced from various raw materials in different regions and using different process technologies (sources presented in the Supporting information). The dotted line illustrates the GHG balance of the fossil reference fuel (gasoline and diesel) including CO_2 emission from fossil fuel combustion in accordance with the RED. The default values of the RED for certain raw materials and technologies are illustrated by black circles. In case the RED provides more than one default value for certain technology route, the maximum value was selected.

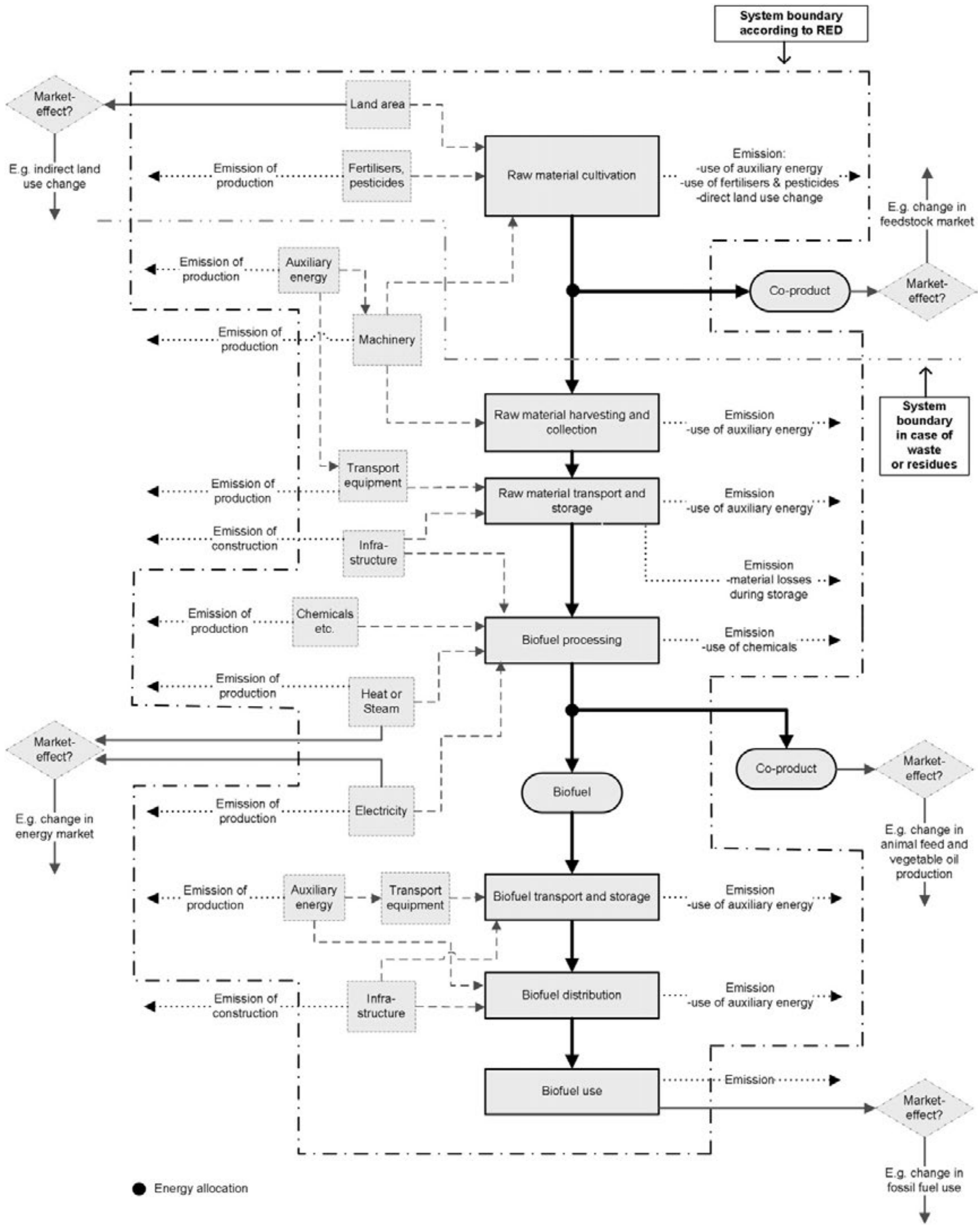

Fig. 2 – Generic illustration of the spatial system boundary according to the RED methodology with possible impacts outside the system boundary.

intensity is low enough to reach the set GHG emission saving requirements. This incentive is reasonable as long as raw materials and land are available for such purposes. Campbell et al. [27] estimated that the global potential for bioenergy on abandoned agriculture lands is less than 8% of the current primary energy demand, which corresponds to some 40% of the current primary energy consumption in personal and commercial transportation. The forecasted population increase together with the expected changes in eating habits will have a significant impact on the requirement of land for food and feed production, and will thus also significantly affect the availability of land for bioenergy production in the future. For example, Hakala et al. [28] estimated that the overall global field bioenergy potential would be roughly 10–30% of the current primary energy use in 2050 depending mainly on the development of the diets. Many recent studies have concluded that the increased production of biofuels from crops or raw materials requiring land that is currently used for agricultural purposes probably increases deforestation and thus results in significant carbon dioxide emissions (e.g [3,10,29]). In practice, these indirect land use changes (iLUC) may be difficult to identify, quantify, and attribute to various economic actions [30]. The European Commission is currently examining how iLUC should be considered [31]. However, at this time it is not clear whether iLUC is included in the RED methodology or handled somehow separately. The EU Member States are deeply divided over the issue of including an iLUC factor in calculation of actual GHG emissions of biofuels. Currently, there is no decision on modifying the RED methodology [31].

In order to reduce the incentives to use raw materials that compete directly with food, the RED encourages, in particular, the production of biofuels from wastes, residues, non-food cellulosic material, and ligno-cellulosic material. The energy contents of the specific biofuels are considered as double when fulfilling the 10% target set for the use of renewable energy in transportation in 2020. The RED methodology encourages the use of residues, such as forest residues, agricultural side streams, and waste streams such as municipal, industrial, or commercial waste as raw materials by considering them free of GHG emissions before collection. However, neither the RED nor the practical guidelines [23] provide a clear definition of 'waste or residues'. There is a possibility that raw materials already utilised might be classified as 'waste or residues' in the context of the RED and thus be promoted for use as biofuels. This may have significant indirect impacts. The definition of 'waste or residue' should be clarified in the context of the RED, and then further analyses of the impacts are possible and certainly required.

Promoting the use of waste or residues in general is reasonable as long as these are generated by other economic activities, when they are not effectively utilised, and when they can be gathered and utilised in a sustainable way. However, avoiding the generation of waste streams is likely to reduce GHG emissions more than generating and utilising waste streams. It is crucial for the incentives provided for the use of waste streams that they do not reduce incentives to avoid generating wastes [32]. Stricter climate policies and ambitious targets to reduce GHG emissions in various economic sectors are likely to increase the competition for waste and residue biomass resources for various end-use purposes; such as power and heat production, material recycling and production, and chemical production. There is scientific evidence that cascading the use of biomass (first as materials and then as energy), when possible, is likely to yield more reductions in GHG emissions than direct energy use [33,34]. Ohlrogge et al. [35], de Santi et al. [10] and Soimakallio et al. [12] concluded that more GHG benefits are gained by using raw materials for power or heat production to substitute coal than by producing more energy intensive liquid biofuels to substitute oil. Increased use for biofuels may thus decrease the availability of raw materials for other purposes and increase the use of more GHG emission-intensive raw materials.

3.2.2. *Other auxiliary inputs*

In addition to land and raw material resources, the production of biofuels requires other auxiliary inputs, such as energy. Koponen et al. [36] studied the GHG balances of lignocellulosic-based ethanol derived from commercial and industrial waste streams in Finland in accordance with the RED methodology. Soimakallio et al. [12] studied the GHG balances of biodiesel derived from logging residues and reed canary grass. The production was based on gasification and Fischer-Tropsch (FT) synthesis integrated into pulp and paper mills. Both studies concluded that GHG emission reductions are highly dependent on the GHG emission intensity of the auxiliary energy. Consequently, a way must be found to keep the GHG intensity of the auxiliary energy required in biofuel production low enough to fulfil the target set by the RED. This can be done, for instance, by increasing the use of renewable energy sources with low GHG emission intensity as auxiliary energy inputs to the biofuel production chain. However, as in the competition for land and raw material resources, the requirement of other auxiliary inputs for biofuel production decreases the overall availability of the particular resources. For example, purchasing hydro power for biofuel production decreases its availability for other purposes; as a result, it needs to be replaced by some other form of electricity [37].

3.2.3. *Co-product outputs*

Biofuel production may generate various types and amounts of co-products such as animal feed, power, and heat. Putting the co-products to the market likely influences the use of competitive products. This tends to have a decreasing impact on the overall GHG emissions from biofuel production. In some cases GHG emission reductions due to product substitution may be very significant.

3.2.4. *Possible methods to include indirect impacts*

Introduction of mandatory targets to increase the use of biofuels together with narrow LCA-based approach to ensure that GHG emissions of biofuels do not exceed certain level, increase significantly the risk that various indirect impacts through market mechanisms take place. The higher is the requirement for the GHG emission reduction of biofuels the more raw materials and other auxiliary inputs with low GHG emission intensity as well as the more productive land is probably transferred to serve biofuel production. This way the emissions may be outsourced to other product systems. The use of certain types of average national, regional, or global figures instead of case-specific figures in determining GHG emissions of resource consumption would probably decrease the emission outsourcing effect. In order to encourage biofuel producers to improve GHG balances of their process in a reasonable way, exceptions could be made if the actors can prove that the resources required would not have been used otherwise. However, this may be very difficult in practice.

The consequences of increasing the use of biofuels may be very far-reaching in space and time. Therefore, they are very difficult to be captured exactly, as there is not enough data and sufficient understanding of the phenomenon available. Scenario analyses can be carried out by using various types of modelling such as economic equilibrium models (e.g [38–40],), partial equilibrium energy system models [41,42] and land use models [43]. However, scenarios are always subjective and uncertain due to the significant number of assumptions required. Applying both the simple and more understandable but narrow LCA, and the more complex and comprehensive but more assumption-sensitive scenario analysis might provide more perspectives in selecting biofuels to be promoted.

3.3. *Timing issues of emissions, sinks, and avoided emissions*

The mitigation of climate change requires rapid and effective actions. According to the IPCC, global GHG emissions should be reduced by at least 50–85% by 2050 from their levels in 2000 in order to limit the global mean temperature increase under 2 °C compared to the pre-industrial level [44]. In the RED methodology and many LCA studies (e.g [45].), the GHG emission impacts are considered by a static method. This means that all GHG emissions and sinks are assumed to take place at the same time and they are then equalised over the lifecycle studied. However, exclusion of dynamics of GHG emissions, sinks and avoided GHG emissions is problematic, particularly when they differ significantly over time, which may be the case for many bioenergy options [46]. For annual crops, the carbon that is released during the combustion is accumulated back into the growing biomass and is not an issue. However, if significant pulse GHG emissions for example from deforestation, the destruction of peat swamps, or from other carbon stock losses take place directly or indirectly due to biofuel production, the consideration of the dynamics of GHG emissions and sinks becomes more crucial in terms of reflecting the actual climate impacts. The sequestration of carbon into forests and soils, and the conservation of large carbon pools (such as peat swamps and pristine forests) are comparable options in climate change mitigation with the use of biomass to substitute fossil fuels.

The RED methodology defines a 20-year horizon for considering the impact of GHG emissions from direct land-use changes (dLUC) to be equalised over the period [16]. The direct deforestation of pristine forests and the use of wetlands for the cultivation of biofuel raw materials are not permitted in the RED, which is likely to prevent the use of land with the most significant soil-based carbon dioxide emissions. However, significant dLUC may take place for example due to the clearing of managed forests. In addition, deforestation and the destruction of peat swamps may take place indirectly, causing significant carbon dioxide emissions. If the iLUC issue is intended to be included in the RED in the future, one problem to be resolved is how to handle the time difference between emissions and avoided emissions. Kendall et al. [46] concluded that when aiming to stabilise the atmospheric GHG concentrations at the ambitious level, the actual climate effects of pulse emissions (for example from land-use changes) are significantly underestimated (70–80%) if annualized for many years (10–50a). Consequently, the suitability of the static LCA method, as introduced in the RED, to assess the climate impacts of bioenergy chains with significant time differences between emissions and sinks or avoided emissions can be questioned. Dynamic indicators (e.g [47].) or derivates from dynamic approaches (e.g [48].) would be much more appropriate, at least when there is a considerable time difference between GHG emissions and sinks or avoided emissions.

Changes in forest carbon stocks, including terrestrial and soil carbon stocks, due to forest biomass harvesting are probably the most important issue to be considered concerning GHG emissions from biofuels derived from forest biomass [49]. It is not clear how changes in biogenic carbon stocks related to land management but not land-use change are intended to be considered in the RED methodology. The timing issues and indicators discussed in this chapter are relevant also for these kinds of carbon stock changes.

3.4. *Allocation procedure*

One of the main challenges in the ALCA involves the allocation of the environmental impacts to the different products, since there is not a single objective or superior method to carry out the allocation procedure [20,50]. Various methods have different pros and cons and the choice of the method may have a significant impact on the LCA results [50]. The allocation in the RED methodology is mainly defined to be based on the energy content of the products determined by lower heating value in the case of co-products other than electricity. However, it should be noted that not all the products are used, primarily or in general, for energy production purposes (for example various materials, animal feed). This makes the general suitability of the particular allocation procedure more or less uncertain depending on the end-use purposes of the co-products. In addition, if heat or steam is generated as a co-product of biofuel processing, as is for example the case of FT diesel processing [11], the RED methodology does not define how the allocation should be carried out as heat does not have lower heating value. If no emissions are allowed to be allocated to heat produced and utilised, the methodology does not encourage integration of biofuel production into a system which can utilise the heat (e.g. pulp and paper mill).

When allocation cannot be avoided, and if only one particular allocation method is to be applied, allocation based on economic value of the products could be the most suitable option [51]. Although the method is not necessarily stable due to fluctuations in the price of co-products, it reflects changes in market conditions and thus prevents allocating emissions to co-products that have no economic value or use.

3.5. *Parameter uncertainty*

Besides systematic uncertainty resulting from normative choices (discussed in Sections 3.2–3.4), the GHG balances of biofuels are subject to uncertainties due to a lack of reliable data. Here we refer to this as 'parameter uncertainty'. In any LCA there are always parameters that vary in terms of their certainty and significance on the results. A large range of uncertainty does not necessarily mean major significance in the overall result if the contribution of the parameter on the result is relatively low. However, as regards the GHG balances of biofuels, many of the most uncertain parameters have been assessed to be the most significant as well [12,52].

Nitrous oxide (N_2O) emissions in agriculture constitute a remarkable uncertainty source in the lifecycle GHG balances of many biofuel pathways [10,12,52]. The use of nitrogen fertilizers and the related nitrogen balance and N_2O emissions strongly depend on site-specific aspects such as crop, soil, and climatic conditions. Consequently, it is difficult to identify representative average emission factors.

According to IPCC [53], soil carbon losses may be significant for agricultural biomass cultivation based on ploughing. In addition, soil organic carbon is an important determinant of soil fertility and to a certain degree, crop productivity has a positive effect on the soil organic matter content [54]. Similarly, the harvesting of logging residues and stumps may change the forest carbon and nutrient cycles due to the removal of organic matter and nutrients along with the raw material [55]. Changes in soil carbon balances may vary significantly depending on the soil and biomass type, biomass cultivation and harvesting measures, and on the climatic conditions [56]. In addition to soil carbon losses, erosion and nutrient losses may have a significant impact on land productivity. According to Jason [57], particularly high rates of erosion accompany soy production, especially in areas where long cycles of crop rotation are not implemented. Pengue [58] reported that intensive soybean cultivation has led to massive soil nutrient depletion in Argentina. All these factors cause uncertainty in upcoming yield rates of land and fertilisation requirement that influences the GHG balances of biofuels.

Uncertainty is involved in every parameter required in the calculations of actual GHG emissions of biofuels or relative GHG emission saving compared to fossil fuels. The level of accuracy required in the determination of the parameters and the cut-off criteria to track the upstream emissions of various auxiliary energy and material inputs are open issues. It is unclear how parameter uncertainties are to be considered in the RED methodology. The more careful consideration of the parameter uncertainties in quantifying CO_2 emission reduction in the RED, especially in large-scale projects, is suggested by Chiaramonti & Recchia [59].

3.6. Emission saving indicator

In many recent studies, and in the RED methodology, GHG emission reductions resulting from the use of biofuels instead of fossil reference fuels are measured as the difference of the GHG emission balance between the fossil reference fuel and the biofuel compared to the fossil reference fuel (Eq. (1)). Some of the studies take the end use into account [45] while others exclude it. The exclusion of the end use is appropriate if no changes in the emissions compared to the functional unit (for example kilometer driven) can be expected between the fuels compared. This is also the definition of the RED methodology. More importantly, the fundamental problem of this kind of 'relative emission reduction' indicator is the inability to measure the effectiveness of biomass utilisation as a measure to reduce greenhouse gas emissions. Consequently, the GHG emission savings results may look particularly favourable for biofuel processes in which significant amounts of low GHG emission intensive raw materials are used in relation to the amount of biofuel produced. At the same time, another process for converting biomass to biofuel in more energy-efficient way while using more fossil resources may appear unfavourable in terms of the particular indicator. The effectiveness of use of limited resources - biomass and land - is excluded when using this kind of 'relative emission reduction' indicator. Consequently, this particular indicator cannot be used to compare GHG emission reductions between different end use options for biomass, for example transportation biofuel and electricity production. In order to promote the most efficient options of biomass and land use in climate change mitigation, it would be reasonable to measure the GHG emission balances or savings of biofuels in terms of the limiting factors, for example biomass, land area, or money spent [12,60] instead of the 'relative emission reduction' as defined in the RED.

GHG emission for fossil fuel comparator is defined to be the latest available actual average emission for the fossil part of petrol and diesel consumed in the European Community. If no such data is available, the value used shall be 83.8 g CO_2-eq./MJ_{fuel} for transportation biofuels [16]. GHG emission saving from substitution of fossil fuels is also subject to various uncertainties. First, the direct GHG emissions from fossil fuel provision are not naturally exact and may vary due to differences in extraction and transportation of crude oil, fuel processing (mainly flaring), storing, distribution, and dosage of products. However, the variation is typically significantly lower compared to the variation presented for biofuels. For example, Edwards et al. [61] reported approximately $\pm 15\%$ variation for fossil gasoline and even lower for fossil diesel provision. Second, fossil fuel energy systems may also result in indirect impacts, such as deforestation due to production of access roads, drilling platforms and pipelines, oil shale and oil sand production, and military security, which may also be significant [30]. However, it is very uncertain how much these indirect impacts can be reduced by replacing a certain relatively minor amount of fossil fuel use by biofuels. Thirdly, it is unclear how much one unit of biofuel actually replaces fossil fuel as such substitution effects are subject to various market mechanisms, and carbon leakage possibilities due to lack of comprehensive, ambitious, and binding GHG emission reduction targets worldwide. This indirect fuel use change issue is explored by Rajagopal et al. [62]. Due to the above mentioned reasons the GHG emission reduction from fossil fuel replacement may vary significantly from the default value given in the RED.

4. Conclusions

The GHG emissions of biofuels calculated in accordance with the RED methodology depend on the case specific features, but more importantly, on the interpretation of the concepts and definitions given in the RED. For example, classification of 'waste or residues' and accuracy in determination of every single parameter required in the calculations are open issues at the moment. Thus, it is not possible to conclude how exactly the GHG emissions will be calculated. However, as discussed in this paper there are serious risks that the RED methodology underestimates the GHG emissions related to biofuel production due to subjective setting of system boundary and other methodological choices.

LCA is a limited approach with various potential sources of uncertainty and variability in input data, scenarios, and models and with no “right” answer. According to Finnveden et al. [20], the uncertainty can be dealt with in the “scientific” way to reduce the uncertainty, the “social” way to discuss the uncertainty in order to find a consensus, and the “statistical” way to incorporate the uncertainty. Lloyd and Ries [63] concluded that qualitative uncertainty analysis in LCA will improve decision making by identifying the likelihood that an alternative will have a lower environmental impact than others or the likelihood of exceeding inventory or impact thresholds. They also concluded that by determining the important contributors to uncertainty in LCA, areas in which an improved understanding is needed will be highlighted. The methods and the data used in LCA should always be subjected to the critical discussion. Therefore, it is reasonable to ask whether the LCA is ready to move from an analysis tool to a decision tool. We conclude that applying the RED methodology to select the biofuels to be promoted in the EU cannot ensure that GHG emissions are reduced.

There is a risk that the RED methodology promotes biofuels with low reduction or even increase in the overall GHG emissions, and prevents biofuels with higher benefits at the same time. It is reasonable to ask whether a biofuel supply chain that exceeds the GHG emission reduction target set in the RED but which is likely to cause significant negative indirect effects through resource competition is a better option to gain incentives than a biofuel supply chain significantly less likely to cause indirect effects but which does not exceed the GHG emission reduction target set in the RED. Consequently, we suggest that the overall calculation methodology for determining GHG emission savings of biofuels should be reconsidered and modified. In addition, the suitability of the principles to select the biofuels to be promoted should be critically assessed.

In order to mitigate climate change, only biofuels resulting in actual GHG emission reductions should be promoted. Certain fundamental principle requirements can be defined for that purpose. Firstly, in order to avoid the significant negative indirect effects, unused raw materials and land area for biomass cultivation should be available. Secondly, the lifecycle GHG impacts of the biofuel product system should be lower than those of fossil reference fuels. Thirdly, biofuel production should not lead to a more ineffective use of fossil fuels. However, ensuring case by case that all the conditions mentioned above are met may be challenging. Thus, the overall use of biomass and land for food, feed, fibre, fuels, and ecosystem services should possibly be based on a comprehensive, integrated, and sustainable action plan. Integrated programs for land use and territorial planning, sectoral policies as well as targeted policy instruments, such as protected area networks were claimed by European Environment Agency (EEA) to tackle trade-offs between many interests for land use in Europe [64]. Also the understanding of the critical issues needs to be improved in order to reduce the most significant uncertainties involved. We finally suggest that in climate change mitigation, more attention should be paid to uncertainties related to various emission reduction measures, in order to promote primarily the most certain ones.

Acknowledgements

The authors wish to acknowledge BIOVAIKU and SUBICHOE projects of the BioRefine programme of the Finnish Funding Agency for Technology and Innovation (Tekes), FOBIT project of the Academy of Finland (124421), the EU Bioenergy Network of Excellence project, and the VTT Technical Research Centre of Finland for financing.

Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biombioe.2011.04.041.

REFERENCES

[1] Baumert KA, Herzog T, Pershing J. Navigating the numbers: greenhouse gas data and international climate policy. World Resources Institute.; 2005.
[2] International Energy Agency. World energy outlook 2010; 2010.
[3] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. Croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 2008;319:1238–40.
[4] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319:1235–8.
[5] Runge CF, Senauer B. How biofuels could starve the poor. Foreign Aff 2007;86(3):41–53.
[6] Mitchell DO. A note on rising food prices. Policy Research Working paper 4682, Development Prospects Group. Washington, DC: World Bank; 2008.
[7] Reijnders L, Huijbregts MAJ. Palm oil and the emission of carbon-based greenhouse gases. J Clean Prod 2008;16:477–82.
[8] Righelato R, Spraclen DV. Carbon mitigation by biofuels or by saving and restoring forests. Science 2007;317:902.
[9] Doornbosch R, Steenblik R. Biofuels: is the cure worse than the disease. Round table on sustainable development. Paris: OECD; 2007.
[10] de Santi G, Edwards R, Szekeres S, Neuwahl F, Mahieu V, editors. Biofuels in the European context: facts and uncertainties. European Commission Joint Research Centre, JRC; 2008.
[11] VTT Research notes 2482. Espoo. In: Soimakallio S, Antikainen R, Thun R, editors. Assessing the sustainability of liquid biofuels from evolving technologies – A Finnish approach; 2009.
[12] Soimakallio S, Mäkinen T, Ekholm T, Pahkala K, Mikkola H, Paappanen T. Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland—dealing with the uncertainties. Energy Pol 2009;37:80–90.
[13] De Fraiture C, Giordano M, Liao Y. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Pol 2008;10(1):67–81.

[14] Bringezu S, Schütz H, O'Brien M, Kauppi L, Howarth RW, McNeely J. Towards sustainable production and use of resources: assessing biofuels. United Nations Environment Programme (UNEP) & International Panel for Sustainable Resource Management; 2009.
[15] International Biofuels Project Rapid Assessment 22–25 September 2008 Gummersbach, Germany. In: Howarth RW, Bringezu S, editors. Biofuels: environmental consequences and Interactions with changing land use Proceedings of the scientific Committee on problems of the Environment (SCOPE); 2009.
[16] Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. 2009/28/EC. The Official Journal of the European Union, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF 5.6.2009.
[17] Eurostat. Share of biofuels in fuel consumption of transport –[tsdcc340], http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdcc340; 9 December 2009.
[18] ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization (ISO); 2006. 20 p.
[19] ISO 14044. Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization (ISO); 2006. 46 p.2006.
[20] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. J Environ Manage; 2009:1–21.
[21] Ekvall T, Tillman AM, Molander S. Normative ethics and methodology for life cycle assessment. J Clean Prod 2005;13: 1225–34.
[22] Curran MA, Mann M, Norris G. The international workshop on electricity data for life cycle inventories. J Clean Prod 2005; 13(8):853–62.
[23] Communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels. Official Journal of the European Union. 2010/C 160/02.
[24] Communication from the Commission on voluntary schemes and default values in the EU biofuels and bioliquids sustainability scheme. Official Journal of the European Union. 2010/C 160/01.
[25] Commission decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC. Official Journal of the European Union. 2010/335/EU.
[26] IPCC. Climate change. In: Houghton J, Ding Y, Griggs D, Noguer M, Van der Linden P, Xiaosu D, editors. The scientific Basis. Contribution of Working Group I to the Third assessment Report of the Intergovernmental Panel on climate change. Cambridge: Cambridge University Press, http://www.grida.no/publications/other/ipcc_tar/?src=/CLIMATE/IPCC_TAR/WG1/index.htm; 2001.
[27] Campbell JE, Lobell DB, Genova RC, Field CB. The global potential of bioenergy on abandoned agriculture lands. Environ Sci Technol 2008;42:5791–4.
[28] Hakala K, Kontturi M, Pahkala K. Field biomass as global energy source. Agri Food Sci 2009;18(3–4):347–65.
[29] JRC. Indirect land use change from increased biofuels demand. Comparison of models and results for marginal biofuels production from different feedstocks. http://www.jrc.ec.europa.eu/.
[30] Liska AJ, Perrin RK. Indirect land use emissions in the life cycle of biofuels: regulations vs. science. Biofuels Biorpod Bioref 2009;3(3):318–28.
[31] Report from the Commission on indirect land-use change related to biofuels and bioliquids. 811 final. Brussels, 22.12.2010. COM, http://ec.europa.eu/energy/renewables/biofuels/doc/land-use-change/com_2010_811_report_en.pdf; 2010.
[32] Directive of the European Parliament and of the Council on waste. 2006/12/EC. The Official Journal of the European Union, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:114:0009:0021:EN:PDF 27.4.2006.
[33] Pingoud K, Pohjola J, Valsta L. Assessing the integrated climatic impacts of forestry and wood products. Silva Fenn 2010;44(1):155–75.
[34] Valsta L, Lippke B, Perez-Garcia J, Pingoud K, Pohjola J, Solberg B. Use of forests and wood products to mitigate climate change. In: Bravo F, LeMay V, Jandl R, von Gadow K, editors. Managing forest ecosystems: the challenge of climate change, Vol. 17; 2008. p. 137–49.
[35] Ohlrogge J, Allen D, Berguson B, DellaPenna D, Shachar-Hill Y, Stymne S. Driving on biomass. Science 2009;324(5930): 1019–20.
[36] Koponen K, Soimakallio S, Sipilä E. Testing the European Union sustainability criteria for biofuels - case study of waste-derived ethanol. 18th European Biomass Conference and Exhibition, 3–7 May 2010, Lyon, France, 2019–24.
[37] Pereira, MVF. Optimal Scheduling of Hydrothermal Systems – An Overview. Planning and Operation of Electric Energy Systems Proceedings of the IFAC Symposium, Rio de Janeiro, Brazil, 1985, Pergamos Press, Oxford, England; 1986.
[38] Manne A, Mendelsohn R, Richels R MERGE. A model for evaluating regional and global effects of GHG reduction policies. Energy Pol 1995;23(1):17–34.
[39] Nordhaus WD. Roll the DICE Again: the economics of global warming. Yale University; January 28, 1999. Version rice98 pap 121898.wpd.
[40] Nijkamp P, Wang S, Kremers H. Modeling the impacts of international climate change policies in a CGE context: the use of the GTAP-E model. Econ Model 2005;22:955–74.
[41] Klaassen G, Riahi K. Internalizing externalities of electricity generation: an analysis with MESSAGE-MACRO. Energy Pol 2006;35:815–27.
[42] Ekholm T, Soimakallio S, Syri S, Savolainen I, Höhne N, Moltmann S. Effort sharing in ambitious global mitigation scenarios. Energy Pol 2010;38(4):1797–810.
[43] Adams DM, Alig RJ, Callaway JM, McCarl BA, Winnett SM. The forest and agricultural sector optimization model (FASOM): model structure and policy applications. Res. Pap. PNW-RP-495. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 1996. 60 pp.
[44] IPCC. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L, editors. Climate Change 2007: Mitigation. contribution of working group III to the Fourth assessment report of the intergovernmental panel of climate change. Summary for policymakers and technical summary; 2007. p. 108. Cambridge.
[45] Edwards R, Larivé J, Mahieu V, Rouveirolles P. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. CONCAWE – EUCAR – JRC -report. Version 2c; March 2007.
[46] Kendall A, Chang B, Sharpe B. Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. Environ Sci Technol 2009;43: 7142–7.
[47] Kirkinen J, Palosuo T, Holmgren K, Savolainen I. Greenhouse impact due to the use of Combustible fuels: life cycle Viewpoint and relative Radiative Forcing Commitment. Environ Manage 2008;42:458–69.
[48] Cherubini F, Peters G, Bernsten T, Strømman A, Hertwich E. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy; 2011.

[49] Repo A, Tuomi M, Liski J. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy 2011;3(2):107–15.
[50] Ekvall T, Finnveden G. Allocation in ISO 14041 – a critical review. J Clean Prod 2001;9:197–208.
[51] Guinée JB, Heijungs R, Huppes G. Economic allocation: examples and derived decision Tree. Int J LCA 2004;9(1):23–33.
[52] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys 2008;8:389–95.
[53] IPCC. 2006 IPCC guidelines for national greenhouse gas inventories, http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; 2006.
[54] Reijnders L. Ethanol production from crop residues and soil organic carbon. Resour Conserv Recycling 2008;52:653–8.
[55] Palosuo T, Peltoniemi M, Mikhailov A, Komarov A, Faubert P, Thürig E, et al. Projecting effects of intensified biomass extraction with alternative modelling approaches. Forest Ecol Manage 2008;255(5–6):1423–33.
[56] Schils R, Kuikman P, Liski J, van Oijen M, Smith P, Webb J, et al. Review of existing information on the interrelations between soil and climate change. ClimSoil, Final Report 16; December 2008.
[57] Jason WC. World Agriculture and the Environment: a commodity-by-commodity guide to impacts and practices. Island Press; 2004. 570 pp.
[58] Pengue W. Transgenic crops in Argentina: the ecological and social debt. Bull Sci Technol Soc 2005;25:314–22.
[59] Chiaramonti D, Recchia L. Is life cycle assessment (LCA) a suitable method for quantitative CO_2 saving estimations? the impact of field input on the LCA results for a pure vegetable oil chain. Biomass Bioenergy 2010; 34(5):787–97.
[60] B. Schlamadinger, R. Edwards, K.A. Byrne, A. Cowie, A. Faaij, C. Green et al. Optimizing the greenhouse gas benefits of bioenergy systems. 14th European Biomass Conference, 17–21 October 2005, Paris, France, 4p.
[61] Edwards R, Larivé J, Mahieu V, Rouveirolles P. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. CONCAWE – EUCAR – JRC -report. Version 3.0, http://ies.jrc.ec.europa.eu/uploads/media/WTT%2520App%202%20v30%20181108.pdf; November 2008.
[62] Rajagopal D, Hochman G, Zilberman D. Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. Energy Pol 2011;39(1):228–33.
[63] Lloyd SM, Ries R. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment. A Survey of quantitative approaches. J Ind Ecol 2007;11(1): 161–79.
[64] European Environment Agency (EEA). The European Environment. State and outlook 2010. Land use. http://www.eea.europa.eu.