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LCA OF BIOREFINERIES

IDENTIFICATION OF KEY ISSUES AND METHODOLOGICAL RECOMMENDATIONS

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
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PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil-free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se).

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SUMMARY

The current trend in biomass conversion technologies and production systems is towards more efficient utilisation of the biomass feedstock in biorefineries, where products such as food, feed, bioenergy (power, heat and biofuels for transport) and bio-based products (chemicals, materials) can be produced together. Such synergetic production can pave the way for high efficiency in terms of economics, energy, resource use etc.

Over the years, many life cycle analysis (LCA) studies of bioenergy systems have been performed, but LCA of bioenergy still faces some methodological issues regarding e.g. land use changes. Another issue currently being discussed is how to treat the timing of sequestration and emission of biogenic carbon. For biorefinery systems this applies both for the raw material, e.g. the carbon in living biomass and soil, and for the products, e.g. production of bioplastics that will not be combusted for a number of years. However, LCA of biorefineries also faces issues regarding the basic methodological choices in LCA, e.g. choice of functional unit, allocation, data and system boundaries. One reason for this is that the biorefinery system produces multiple high-value outputs with different functions, so it is not always possible to determine a single main product.

The main objective of this report is to identify and discuss key methodological issues for LCA of biorefinery systems in relation to existing literature, standards and guidelines. The intention is to improve current insights into the complexities when performing LCA of biorefinery systems, which can be useful for LCA practitioners within e.g. research, industry and policymaking. A further objective is, where possible, to provide methodological recommendations on how to handle critical key issues. The recommendations are intended to help enhance consistency and comparability among future case studies and increase the credibility of results. The report focuses on methodological choices connected to the impact categories energy and climate, although much of the discussion is relevant for other impact categories too.

Some of the issues treated in this report are not specific to LCA of biorefineries, but can be applied to all types of bio-based production systems. Some are even applicable for LCA in general. However, while the discussions and recommendations may not be biorefinery-specific, we do believe they are all relevant when performing LCAs of biorefinery systems.

Based on a literature review of biorefinery LCA case studies and existing standards and guidelines, seven different key issues were identified and discussed:

1. Goal definition
2. Functional unit
3. Allocation issues of the biorefinery outputs
4. Allocation issues at the production of biomass feedstock
5. Choice of data
6. Land use
7. Biogenic carbon and timing of emissions

In the literature review, we found major inconsistencies in methodological choices, e.g. the functional unit is often not in line with the aim of the study. The problem is magnified by a lack of

proper documentation of assumptions, or transparency, in many studies. Furthermore, the large differences in methodological choices make comparisons between studies difficult.

We also concluded that many of the standards and guidelines only provide general methodological recommendations. Some standards and guidelines provide more specific methodological recommendations, but these often differ between standards.

Some of the general key issues (choice of functional unit, methods to handle multifunctionality and choice of data) are illustrated using the example of a hypothetical biorefinery, in order to show how large the differences in results can be depending on a few methodological choices.

Based on the review of existing standards and guidelines, the literature review, the hypothetical biorefinery example and the discussions of the key issues, we reached a number of conclusions and recommendations on what we believe is the best way to treat these key issues in LCAs of biorefinery systems:

Key issue 1: Goal definition

- Specify the intended audience and intended application
- Specify the time horizon of the study. Note that there are several different kinds of time horizons in the same LCA: how long the results are valid for, how far into the future the analysis of the socio-technical system extends, how long a time horizon is used to calculate emissions from landfills and the climate impact of greenhouse gases, etc. Ideally, all of these time horizons should be specified in the study's goal and scope definition
- Specify the research question and type of modelling approach (e.g. attributional LCA (ALCA) or consequential LCA (CLCA)). The research question and the modelling approach are linked, although this link is not always straight-forward in practice. It can be noted that what appear to be limited changes in the formulation of a question can change an ALCA into a CLCA, and vice versa.

Key issue 2: Functional unit

- The functional unit should be well chosen in relation to the research question
- In comparative studies, it is important that the products compared have comparable functions
- Several functional units can be applied in a study, but be aware that different functional units will give answers to different type of questions.

Key issues 3 and 4: Multiple outputs from biorefinery and Feedstock production

- We recommend the following order of priority for handling multifunctionality of output products from biorefinery systems:
  1. Avoid allocation by increasing the level of detail with a sub-process approach (applicable mainly for ALCA).
  2. Avoid allocation by system expansion (applicable for both ALCA using average data and CLCA using marginal data).
  3. Avoid allocation by choice of functional unit/system enlargement, if this is compatible with the aim of the study and the results can answers the research question under study

(applicable for both ALCA and CLCA). *NOTE: There is no order of priority between system expansion and system enlargement!*

4. If the ratio of the output products is flexible, use physical causation or a reasonable approximation of it (applicable for ALCA).
5. If the ratio between output products cannot be changed, use economic allocation. If this is not possible due to lack of information, make an arbitrary choice of a physical parameter (applicable for ALCA).

- Use the same method for handling multifunctionality when possible for both the inputs and the outputs of the biorefinery system. If a mix of methods is used, this should be clearly stated, together with a justification of this choice.
- When calculating environmental load for biorefinery output products that are small in quantity, or of less importance for the overall existence of the biorefinery, i.e. products which are not determining for the process, the biorefinery process should not be included in a CLCA. Instead, the alternative use (or possibly waste management) of the co-product should be included. Some products that are small in terms of quantity of output from the biorefinery can represent a large share of the economic output. In these cases, economic allocation could be a viable option if performing an ALCA.
- We advise LCA practitioners to acknowledge the importance of choice of method for handling multifunctionality and, for each study, to think through whether the method is in line with the intended audience, the intended application and the research question. We also advise LCA practitioners to be consistent and transparent about their choices.
- It is advisable to test different methods of handling multifunctionality, as well as underlying assumptions, in a sensitivity analysis.

Key issue 5: Choice of data

- Data relevant to describe the aim of the study should be chosen. In general, this means that average data should be used for ALCA. For CLCA, the choice depends on the scale of change; for small changes marginal data are suitable, while for larger changes (e.g. fundamental changes of production systems affecting a large number of technologies), average data could in some cases better reflect the change.
- We do not recommend mixing average and marginal data in a study, unless there is an obvious reason (e.g. lack of data), which in that case should be clearly stated.
- If the choice is to use average data, for the most important input data the number of years for which the average is calculated and the geographical region assumed should be specified. If the choice is to use marginal data, how the marginal production was chosen and the time frame assumed (e.g. short-term or long-term) should be specified.
- Input data that are uncertain and have a major impact on the results should be highlighted in a sensitivity analysis.

Key issue 6: Land use change (LUC)

- If there is a direct land use change, it should be included in both ALCA and CLCA studies.

- In principle, indirect land use change should be included in a CLCA. However, due to the uncertainties in economic modelling, a strict recommendation to include indirect land use change in every case cannot be made at present. However, use of indirect land use change in a sensitivity analysis is encouraged.
- In principle, indirect land use change should not be included in an ALCA, since indirect land use change models quantify marginal effects.

Key issue 7: Biogenic carbon

- The global warming potential (GWP) metric has certain limitations as regards its ability to reflect timing of emissions. However, as GWP is a widely accepted metric and there is no other standardised alternative available, we advise use of GWP in the meantime.
- For delayed emissions due to storage of biogenic carbon in products, residues, wastes, carbon capture and storage etc., there are several different methods to choose from which can be incorporated into existing LCA methodology and the GWP metric. If there is a significant difference in the emissions of carbon dioxide compared with the uptake over time in the system under study, this should not be ignored. At the very least, this should be discussed in the study and efforts to quantify the impact should be made.

SAMMANFATTNING

En teknisk trend när det gäller omvandling av biomassa är samproduktion av å ena sidan livsmedel, foder och bioenergi (el, värme och biodrivmedel) och å andra sidan kemikalier och material i s.k. bioraffinaderier. Dessa är produktionssystem där omvandlingen av råvaror och samproduktionen av ett flertal produkter kan bana väg för en hög ekonomisk, energi- och resursmässig effektivitet.

Under årens lopp har många livscykelanalyser (LCA) av bioenergisystem utförts. Ändå kvarstår flera metodologiska frågor rörande t.ex. ändrad markanvändning eller hur man behandlar olika tidpunkter för upptag och utsläpp av biogent kol. För bioraffinaderisystem gäller detta både för råvaran, t.ex. upptag av kol i levande biomassa och mark, och för kolinbindning i produkterna, t.ex. biobaserad plast. Men LCA-studier av bioraffinaderier utmanar även grundläggande metodfrågor, bl.a. val av funktionell enhet, allokering, data och systemgränser. En orsak är att bioraffinaderier ofta producerar flera värdefulla produkter med vitt skilda funktioner och där det inte alltid är möjligt att fastställa en enda huvudprodukt.

Syftet med denna rapport är att i förhållande till existerande litteratur, standarder och riktlinjer identifiera och diskutera viktiga metodfrågor inom LCA-studier av bioraffinaderisystem. Rapporten vill bidra till ökad insikt om komplexiteten vid genomförande av LCA-studier av bioraffinaderisystem vilket kan vara användbart för LCA-utövare inom forskning, industri och beslutsfattande. Vidare är syftet att ge metodologiska rekommendationer i hantering av nyckelfrågor. Rekommendationerna är avsedda att bidra till förbättrad konsekvens och jämförbarhet mellan framtida fallstudier, samt att öka trovärdigheten i resultaten. Rapporten fokuserar på metodologiska val som berör påverkanskategorierna energi och klimat, även om mycket av diskussionen är relevant också för andra påverkanskategorier.

Några av de metodfrågor som behandlas i denna rapport är inte specifika för bioraffinaderisystem, utan kan appliceras på alla typer av biobaserade produktionssystem. Vissa frågor är till och med mer generella för LCA i allmänhet. Även om inte alla diskussioner och rekommendationer är bioraffinaderispecifika, tror vi dock att samtliga är relevanta för de som utför LCA-studier av bioraffinaderisystem.

Baserat på en litteraturgenomgång av LCA-fallstudier på bioraffinaderier samt på befintliga standarder och riktlinjer har sju olika nyckelfrågor identifierats och diskuterats:

- Definition av mål
- Funktionell enhet
- Allokeringssituationer för output-produkter
- Allokeringssituationer för biomassa-input
- Val av data
- Markanvändning
- Biogen koldioxid och tidpunkt för utsläpp

I litteraturen fann vi stora brister i val av metod, t.ex. var den funktionella enheten i många fall inte i enighet med syftet med studien. Problemet förstoras ytterligare genom bristande dokumentation av antaganden i många studier. Vidare gjorde de stora skillnaderna i metod att jämförbarheten

mellan studier blev problematisk. Vi konstaterar också att många existerande standarder och riktlinjer ger generella metodologiska rekommendationer medan vissa ger mer specifika rekommendationer som ofta skiljer sig åt.

En del av de mer LCA-generella nyckelfrågorna (val av funktionell enhet, metoder för att hantera multifunktionalitet och val av data) illustreras i ett hypotetiskt bioraffinaderiexempel för att åskådliggöra hur stora skillnaderna i resultat kan bli beroende på val av metod.

Baserat på genomgången av befintliga standarder, riktlinjer och litteratur, nådde vi ett antal slutsatser och rekommendationer för de identifierade nyckelfrågorna:

Nyckelfråga 1: Definition av mål

- Ange målgrupp och avsedd tillämpning.
- Specificera tidshorisonten för studien. Observera att det finns flera olika typer av tidshorisonter i samma LCA: hur länge resultaten är giltiga, hur långt i framtiden analysen av det socio-tekniska system sträcker sig, hur lång tidshorisont som används för att beräkna utsläpp från deponier och klimatpåverkan av växthusgaser, etc. Helst bör alla dessa tidshorisonter anges i målet.
- Specificera forskningsfrågan och typ av modellering (t.ex. ALCA eller CLCA). Frågan och typ av modellering är kopplade till varandra, men praktiken inte alltid på ett uppenbart sätt. Notera att en liten förändring i formuleringen av en fråga kan ändra en ALCA till en CLCA och vice versa.

Nyckelfråga 2: Funktionell enhet (FE)

- Den funktionella enheten ska vara väl vald i relation till forskningsfrågan.
- I jämförande studier är det viktigt att de jämförda produkterna har jämförbara funktioner.
- Flera FE kan tillämpas i en studie, men tänk på att olika FE kommer att ge svar på olika typer av frågor.

Nyckelfråga 3 och 4: Allokeringssituationer för råvaror och produkter

- Vi rekommenderar följande prioriteringsordning vid hantering av multifunktionalitet för utgående produkter från ett bioraffinaderisystem:
    1. Undvik allokering genom att öka detaljnivån (gäller främst för ALCA).
    2. Undvik allokering genom systemexpansion (gäller för både ALCA med hjälp av medeldata och för CLCA med marginaldata).
    3. Undvik allokering genom val av funktionell enhet/systemutvidgning om det är förenligt med syftet med din studie och resultaten kan ge svar på dina frågeställningar (gäller för både ALCA och CLCA). *OBS: det finns ingen prioritetsordning mellan systemexpansion och systemutvidgning!*
    4. Om förhållandet mellan de utgående produkterna är flexibelt, använd fysiska orsakssamband eller en rimlig approximation av det (gäller för ALCA).

5. Om du inte kan ändra förhållandet mellan utgångsprodukter, använd ekonomisk allokering. Om detta inte är möjligt p.g.a. brist på information, gör ett godtyckligt val av en fysisk parameter (gäller för ALCA).

- Använd i största möjliga mån samma metod för hantering av multifunktionalitet för både råvara och produkter. Om en blandning av metoder används, bör detta anges och motiveras tydligt.
- Vid beräkning av miljöpåverkan för produkter som är små i kvantitet eller av mindre betydelse för bioraffinaderiers totala existens (d.v.s. produkter som inte är avgörande för processen), bör bioraffinaderiet inte ingå i beräkningarna om du gör en CLCA. I stället bör den alternativa användningen (eller möjligen avfallshanteringen) beräknas. Vissa produkter från bioraffinaderiet som är små i kvantitet kan dock utgöra en stor del av inkomsten. I dessa fall kan ekonomisk allokering vara ett alternativ, om du utför en ALCA.
- Valet av metod för hantering av multifunktionalitet är viktigt och bör vara i linje med avsedd målgrupp, användning och forskningsfrågan i fokus. Vi rekommenderar även LCA-utövare att vara konsekventa och öppet redovisa sina val.
- Det är lämpligt att i en känslighetsanalys testa olika metoder för hantering av multifunktionalitet och underliggande antaganden.

Nyckelfråga 5: Val av data

- Data bör väljas i samklang med studiens syfte. I allmänhet innebär detta att medeldata används för ALCA. För CLCA beror valet av data på omfattningen av förändringen som modelleras; för små förändringar är marginaldata ofta att föredra, för större förändringar (t.ex. grundläggande förändringar av produktionssystem som påverkar ett stort antal tekniker) kan medeldata i vissa fall bättre spegla förändringen.
- Vi rekommenderar att inte blanda medel- och marginaldata i en studie om det inte finns en uppenbar anledning (t.ex. brist på data), vilket i så fall bör anges tydligt.
- Om valet är medeldata bör man för de viktigaste indata specificera hur många år genomsnittet beräknas över och vilken geografisk region som antagits. Om valet är marginaldata, bör det anges hur den marginella produktionen valdes och vilken tidsram som antas (kort- eller långvarig).
- Indata som är osäkra och har stor inverkan på resultaten bör belysas i en känslighetsanalys.

Nyckelfråga 6: Ändrad markanvändning

- Direkt ändrad markanvändning bör tas med i beräkningarna, både i ALCA och CLCA.
- I princip bör indirekt ändrad markanvändning (ILUC) ingå i en CLCA. P.g.a.av osäkerheten i de ekonomiska modeller som används kan dock en strikt rekommendation att alltid ta med ILUC för närvarande inte ges. Att inkludera ILUC i känslighetsanalysen uppmuntras dock.
- I princip bör ILUC inte ingå i ALCA studier, eftersom ILUC- modeller kvantifierar marginaleffekter.

Nyckelfråga 7: Biogen koldioxid och tidpunkten av utsläpp

- Enheten GWP, Global Warming Potential, har vissa begränsningar i förmågan att reflektera tidpunkten för utsläpp. Men eftersom GWP är ett allmänt accepterat mått och det saknas motsvarande standardiserade enheter rekommenderar vi att använda GWP tills vidare.

- För fördröjda utsläpp till följd av lagring av biogent kol i produkter, avfall, CCS, etc., kan flera olika metoder väljas som kan inkluderas i befintlig LCA-metodik och GWP-enheten. Om skillnaderna i utsläpp av CO_2 jämfört med upptag över tiden i det studerade systemet är betydande, bör detta inte ignoreras. Fördröjda utsläpp bör som minimum alltid lyftas till diskussion i studien. Försök att kvantifiera effekterna rekommenderas.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

The current trend in biomass conversion technologies and production systems is towards more efficient utilisation of the biomass feedstock in biorefineries, where products such as food, feed, bioenergy (power, heat and biofuels for transport) and bio-based products (chemicals, materials) can be produced together. Such synergetic production can pave the way for high efficiency in terms of economics, energy, resource use etc.

Much attention has been paid to the sustainability performance of different bioenergy carriers compared with fossil fuels and the relative ranking of different fuels. For the quantification of environmental impacts, life cycle assessment (LCA) methodology is often used. Over the years, many LCA studies of bioenergy systems have been performed, but LCA of bioenergy still faces some methodological issues. For example, during recent years there has been intensive debate on how to include land use changes in the calculations (Sanchez et al., 2012). However, LCA of biorefinery systems also faces issues regarding the basic methodological choices, for a number of reasons.

First of all, biorefineries produce several high-value outputs rather than one main product and co-products. This means that the choice of functional unit can be very important. The functional unit is the basis of all calculations in an LCA and the unit on which the environmental impact is expressed. For bioenergy products, it could be 1 MJ or kWh, while for bio-materials it could be 1 kg active ingredient of a specific biochemical product. For a biorefinery producing several functions, choice of functional unit is less obvious. It could even be the case that additional functional units are needed for the same study.

Furthermore, the environmental impact somehow has to be divided over the high-value products. This can be done either by allocation or by systems expansion (e.g. Finnveden et al., 2009). Allocation means dividing the impact based on physical or economic properties of the products. Systems expansion means that the study is expanded to include the effects the products will have on other production systems. As Cherubini et al. (2011b) point out, this choice is critical for the outcome. ISO standard 14044 on LCA states that system expansion is preferable to allocation. However, performing a system expansion means that the product (or products) under study must be identified and that alternative products for the other products can be identified and quantified, which is not always straight-forward. In particular, if there are many output products, as in a biorefinery system, system expansion requires many assumptions and much data collection, which is a time-consuming task. The many assumptions can also increase the uncertainty of the results.

An LCA involving a biorefinery will also involve other methodological choices which can influence the comparability and reproducibility of studies, e.g. example related to system boundaries. A very important issue is whether to use average or marginal input data. For both cases, models of future energy systems may be required where uncertainties can have a large influence on the results (e.g. Soimakallio and Koponen, 2011). Another important issue is the time perspective used. This applies both for the raw material, e.g. carbon in living biomass and in soil, but also for the products, e.g. production of bioplastics that will only be released to the atmosphere after a number of years.

The complexities involved when performing LCA of biorefinery systems can lead to inconsistency, making comparisons between studies difficult. Large variations in the results from case studies can also raise questions of credibility, regarding the specific results or in general regarding LCA as a method.

1.2 AIM

The main aim of this report is to identify and discuss key methodological issues for LCA of biorefinery systems. The identification of key issues is based on a literature review of existing LCAs of biorefinery systems, existing standards and guidelines and discussions in a project group. This identification and discussion of the key issues is intended to improve current insights into the difficulties when performing LCA of biorefinery systems. Some of the key issues are illustrated in calculations for a hypothetical biorefinery example, in order to show how large the differences in results can be depending on methodological choices. A further aim is to provide methodological recommendations on how to handle these key issues, when possible. These recommendations are intended to help improve the consistency and comparability of future case studies and increase the credibility of the results.

1.3 DELIMITATIONS

The focus in this report is on key methodological issues that need to be resolved when performing LCA of products from biorefinery systems. The overall reliability of LCA is affected by different sources and types of uncertainty. Those of major importance are often called ‘key issues’. Uncertainty in LCA can be broadly categorised as either stemming from the collection and selection of numerical data in inventory and characterisation models, or from methodological choices (Björklund, 2002). Although it is difficult to draw an exact boundary between different types of key issues, this report focuses on key issues related to methodological choices in biorefinery LCAs and does not deal with key issues related to the collection and selection of numerical data in the inventory.

Furthermore, the report focuses on methodological choices connected to the impact categories energy and climate. We do not deal with this characterisation as such, but the delimitation to energy and climate restricts the number of key issues. If e.g. biodiversity or social impacts were to be included, this would bring a number of other methodological questions. Since the discussion on characterisation is not specific for biorefineries, but general for LCA studies, we believe this to be outside the scope of this study.

Concerning the delimitation between general and biorefinery-specific issues, it is difficult to draw an exact line. It is not always possible to give biorefinery-specific recommendations without going into general LCA issues, such as goal and scope, choice of functional unit etc. Furthermore, in some cases in this report there is no clear distinction in discussions and recommendations between those specific for biorefinery systems and those applying more generally for biobased production systems. However, even though not all discussions and recommendations are biorefinery-specific, we do believe they are all relevant when performing an LCA of biorefinery systems.

Whenever possible, the recommendations of this report are in line with existing standards and guidelines for LCA and related areas of relevance to LCA of products from biorefineries. In the discussions and formulation of recommendations for dealing with the key issues, the standards and guidelines were consulted. It is also important to note that it is not always possible to give specific recommendations, as certain choices are highly dependent on the context of each study.

1.4 STRUCTURE OF THE REPORT

Before getting into the details of LCA of biorefineries, it is important to give some definitions, e.g. of the biorefinery concept, which is done in Chapter 2. It is also important to have an overview of existing standards and guidelines, as provided in Chapter 3. A number of LCA studies on biorefineries already exist and these are summarised and analysed in Chapter 4. In that analysis, we sought to identify how the studies were defined in terms of general LCA key issues (functional unit, attributional/consequential, handling co-products etc.).

Based on the existing standards and guidelines described in Chapter 3, the literature on LCA and biorefineries in Chapter 4 and discussions in the project group, a number of key issues for LCA of biorefinery systems were identified. In Chapter 5 these key issues are described and analysed in more detail and, when possible, we provide recommendations on how we believe these key issues can best be handled. In Chapter 6 we illustrate the consequences of the methodological choices in a biorefinery LCA by use of a hypothetical and very simplified generic biorefinery example. In Chapter 7, we draw conclusions and summarise our recommendations.

1.5 INTENDED AUDIENCE AND APPLICATION

We believe this report will be useful for LCA practitioners in both research and industry. Increased knowledge of the key issues in LCA of biorefinery systems will help LCA practitioners make relevant choices. The recommendations provided can increase the accuracy and relevance and enhance the comparability of studies. Furthermore, greenhouse gas emissions (GHG) in different sectors are increasingly being regulated by use of LCA and this report can provide policymakers with some insights into the complexities of LCA methodology.

2 DEFINITIONS

2.1 BIOREFINERIES

A biorefinery can be described as a facility in which biomass is processed and converted to useful products such as biofuels, chemicals and energy carriers. Several attempts have been made to create a definition of biorefineries that distinguishes them from other biomass processing industries, such as conventional biofuel plants, food industries or chemical industries.

One pioneering article in the field of biorefineries is that by Kamm and Kamm (2004), which provides examples of how biomass can be transformed into a variety of products using different technological approaches. A more recent and often cited definition of biorefineries is that presented by Cherubini et al. (2009), which is also the definition adopted by IEA Task 42. The latter states that (Jungmeier et al., 2013):

"Biorefining is the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat)"

This definition refers to the function of a biorefinery, but it does not specify how the production process should be designed. For example, a biorefinery can be a single plant in which several difFerrent products are produced, it can be two plants that are integrated, or it can be several biomass processing plants that cooperate and utilise each other's side-streams and co-products. A typical feature of a biorefinery is the broader spectrum of products and processing technologies, as well as a high degree of integration between processes (Ekman, 2012).

In Sweden, due to declining profitability in pulp and paper production, the forest industry is pursuing several activities around biorefining. The Swedish forest industry has also been formulating its own definitions of the concept. According to Joelsson and Tuuttila (2012), a biorefinery should include a high level of integration between products, utilisation of new raw materials from forests and chemical decomposition of the biomass. Biorefinery activities are thus clearly distinguished from conventional forest industry operations, as well as from production of heat and power and simple mechanical processing.

In this report we use the terms "biorefinery" and "biorefinery system" synonymously to indicate that all types of biorefineries, as well as the other systems associated with the processing plant (or plants) itself, e.g. the biomass raw material supply system and the market for output products, are included.

For further reading on the subject, an extensive overview of different definitions of the biorefinery concept can be found in Berntsson et al. (2013).

2.2 PRODUCT, CO-PRODUCT, RESIDUE AND WASTE

In some cases, the classification into product, co-product, by-product, waste and residue can be very important. In policy, classification of a product as a main product or a waste or residue can be decisive. For example, in the Renewable Energy Directive (RED) (EC, 2009a), which regulates GHG emissions from biofuels, a by-product should be allocated emissions, while a waste product should not. There have been several efforts to classify materials into categories, some of which are listed in Table 2.1. The classification criteria differ, but can be based on economic relationships including revenue (CDM, 2007), optimisation of production processes (EC, 2009a) and the guidance in SEA (2011).

From Table 2.1, it is clear that a co-product has a market value. However, a by-product, although it may have a use, does not necessarily have a market value. The definition of residue is even more problematic. We found that the definition of a by-product, e.g. as having “lower revenue than the main product” (CDM, 2007) and “further use of the substance or object is certain” (EC, 2008), partly overlaps with the definition of a co-product and partly with the definition of a residue.

The definition of a residue is not straight-forward either. For example, residue is a commonly used term for biomass feedstock (EC, 2009a; SEA, 2011; Wiloso et al., 2012), where it is clear that residues can have economic value (SEA, 2011; Wiloso et al., 2012), although the process (in this case cultivation) is not deliberately altered to produce more of the residue (SEA, 2011).

The aim of this report is not to define these categories, as they are specific for each application. However, in the subsequent discussions on key issues, it is it important to have a clear definition of what is meant by different terms. For the purposes of the report, it is not necessary to separate the definitions of residues and by-products. We therefore apply the following definitions:

Main product
A product is the main product of a process if the optimisation of the process is only or mainly decided by the demand for this product.

Co-product
A product is a co-product if the optimisation of the production process depends partly on the demand for a main product, but also on the demand for other co-products. Note that a production process does not necessarily need to have a main product, and instead there can be a number of co-products.

Residue
A product is a residue if the use of the production process is not affected by the demand for this specific product. The product is not deliberately produced in the production process.

Waste
Waste is any substance or object which the holder discards, intends to or is required to discard.

Note that these definitions may not completely coincide with the other definitions in the literature. When applying a specific standard, the specific definitions in that standard must be considered. In the remainder of this report, the term co-product is consistently used where possible for products generated in biorefinery systems. However, in e.g. the literature review, the original terms applied in the studies cited are used.

Table 2.1. Classification of product categories in four different contexts.

	CDM (2007) Clean Development Mechanism	**EC (2008) Directive on Waste**	**Swedish law 2010:598 on sustainability criteria for biofuels. Implementation of EU Directive 2009/28/EC**[1]	**ISO (2006a) ISO 14040**
Product				Any goods or service
Main Product	"..where the main product is produced and/or consumed/used in a CDM project activity.."[2]	"Product – all material that is deliberately created in a production process. In many cases it is possible to identify one (or more) "primary" products, which is the principal material produced"	The material for which the process is normally optimised is the main product	
Co-product	Co-products are defined as products with similar revenues to the main product		If the production process is optimised for more than one product, the products are defined as co-products	Any of two or more products coming from the same unit process or product system
By-product	"by-products are defined as products that have a lower revenue than that of the main product"	A production residue that is not a waste. "A substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste …but as being a by-product only if the following conditions are met: (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful…"		
Residue		Production residue – a material that is not deliberately produced in a production process but may or may not be a waste.[3]	A material that remains after a process the primary purpose which is not production of the item. The process should not have been deliberately altered to produce the item.[4]	
Waste	Wastes are materials that "provide little or no revenue"	"waste means any substance or object which the holder discards or intends or is required to discard"	Same as in the EU Directive on Waste	Substances or objects which the holder intends or is required to dispose of

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[1] SEA (2011).

[2] We interpret this as meaning that the "main product" could be a by-product in the production process, but a main product in the study.

[3] The product residue may or may not be regarded as waste. This is decided based on the criteria laid down in the EU Directive on Waste (see 'By-product').

[4] If a material flow from a process contributes significantly in quantity or economically to the outcome of the process and the material has other usages than for energy production purposes, then the product or material flow should be classified as a co-product even though the production process is not optimised to that product.

2.3 ATTRIBUTIONAL AND CONSEQUENTIAL LCA

In the literature, LCA is typically categorised into two types, attributional (ALCA) and consequential (CLCA). Many efforts have been made to define the two types of LCA; Zamagni et al. (2012) gives a good overview of different definitions and how they have evolved over time. In short, ALCA is said to account for immediate physical flows in a life cycle, while CLCA aims to study the environmental consequences of a change in a life cycle, often with a market-orientated approach. ALCA typically utilises average data for each unit process, while CLCA describes the changes in physical flows. Differences in how co-products are handled have also been mentioned as something that characterises the two types of LCA (Earles and Halog, 2011). In ALCA allocation is typically carried out, while in CLCA allocation is avoided by system expansion.

All of these definitions can of course be discussed. For example, Finnveden et al. (2009) argue that system expansion may well be done in ALCA using average data. Furthermore, as Zamagni et al. (2012) point out, CLCA as a concept was introduced as late as in the 1990s, and the number of studies using CLCA has boomed during the past decade. The methodology is therefore relatively new, and is not yet properly systematised. Zamagni et al. (2012) suggest that CLCA is not yet fully understood either at a conceptual or a modelling level, and therefore that it is often used in an inconsistent way.

This tendency in the LCA discourse to associate ALCA with descriptions of the state and CLCA with assessments of changes and decisions can also be discussed. We would like to stress that ALCA and CLCA can both be used to describe a state, although they would describe the state of different systems: the life cycle and the sphere of influence, respectively. They can also both be used to assess a change in the functional output of a system and as the basis for choices between goods and other decisions.

3 EXISTING STANDARDS AND GUIDELINES

There are many LCA standards and guidelines that are relevant to LCA of biorefineries, either with a focus on LCA in general or on specific applications. This section gives an overview of such standards and guidelines, along with brief descriptions of the way in which they may be relevant in the context of biorefineries.

Recommendations from these standards and guidelines are considered when formulating recommendations for dealing with key methodological issues in Chapter 5.

3.1 GENERAL LCA STANDARDS AND GUIDELINES

3.1.1 ISO 14040 Series

The International Organization for Standardization (ISO) issued a standard outlining the principles and framework of LCA in ISO 14040 (ISO, 2006a), along with more detailed guidance on the life cycle inventory analysis, impact assessment and interpretation phases of LCA in ISO 14044 (ISO, 2006b). These two standards are complemented by a Technical Report with examples of practices in carrying out a life cycle inventory analysis (ISO, 2012b), a Technical Report providing examples of current practice in life cycle impact assessment (ISO, 2012a), and a Technical Standard providing requirements and a structure for a data documentation format (ISO, 2002).

The ISO LCA standards constitute a common reference point for most guides and standards within the area of life cycle assessment and life cycle thinking. In order for methodological recommendations for LCA of biorefineries to be credible and generally accepted, they need to be based on, and in accordance with, the ISO standards for LCA.

3.1.2 International Reference Life Cycle Data System (ILCD)

The International Reference Life Cycle Data System (ILCD), or ILCD Handbook, was developed by the European Commission Joint Research Centre (JRC) in co-operation with the Environment Directorate General (DG). It consists of a set of documents that aim to provide methodological guidance, in line with, but expanding on, the ISO 14040 and 14044 standards on LCA (JRC, 2010).

Due to its increased level of detail in methodological guidance compared with the ISO standards, the ILCD Handbook may be used as a complement to the ISO standards when dealing with methodological key issues encountered in LCA of biorefineries.

3.1.3 EU Product Environmental Footprint and Organisation Environmental Footprint (under development)

Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methodologies have been developed by the EU Environment DG together with the JRC, with the aim of harmonising the methodology for environmental footprinting of products, services and organisations. These methodologies are now available in a final draft format (EC, 2013a, 2013b). They build on existing standards, among them the ISO14040 series and the ILCD Handbook, and the methods are largely in line with the standards considered. However, for many methodological decisions both the PEF and the OEF method go further than the existing standards. The main purpose behind this has been to provide guidance that will contribute to more consistent, robust and reproducible PEF and OEF studies (EC, 2013a, 2013b).

As PEF and OEF are proposed by the European Commission to be used as EU-wide methods to measure the environmental performance of products and organisations, these methods may turn out to have a significant impact on the way LCA is practised in the future. The methodological clarifications provided by the PEF and the OEF are therefore important in developing recommendations for LCA of biorefineries.

3.2 ENVIRONMENTAL DECLARATIONS

3.2.1 ISO Type III Environmental Declarations of product and services

Type III Environmental Declarations are LCA-based environmental declarations of products and services primarily intended for business-to-business communication. ISO 14025 (ISO, 2006d) specifies principles and procedures for the development of Type III Environmental Declaration programmes and Type III Environmental Declarations, in line with LCA methodology as described in the ISO 14040 series, and in line with the guiding principles for the development and use of environmental labels and declarations as defined by ISO 14020 (ISO, 2006c).

Internationally, there are different initiatives for developing Type III Environmental Declarations. The Global Environmental Declarations Network (GEDnet, http://www.gednet.org/) is an international non-profit association of Type III Environmental Declaration organisations and practitioners. The International EPD® System is operated by the Swedish Environmental Management Council (http://environdec.com/). The Norwegian EPD Foundation (http://edp-norge.no/) is a joint effort by the Confederation of Norwegian Enterprise (NHO) and the Federation of Norwegian Building Industries (BNL).

Type III Environmental Declarations can be developed for products from biorefineries. At the core of developing Type III Environmental Declarations is development of Product Category Rules (PCR), which is a set of specific rules, requirements and guidelines for one or more product categories. A few Type III Environmental Declarations have been developed for chemicals from biorefineries. Examples are vanillin, lignosulphonate powder and ethanol. These were all based on a PCR for chemical products, which has since been replaced by new PCRs for basic organic chemicals and basic inorganic chemicals.

3.2.2 EU Renewable Energy and Fuel Quality Directives

The Renewable Energy Directive or RED was established to promote energy from renewable sources (EC, 2009a). It sets mandatory national targets for the overall share of energy from renewable sources and for the share of energy from renewable sources in transport. It also establishes sustainability criteria for biofuels and bioliquids.

The sustainability criteria state that for GHG, biofuels and bioliquids are required to provide a minimum reduction of 35% compared with emissions from fossil fuels (rising to 50% in 2017 and 60% in 2018 for new installations). The RED defines how GHG reductions should be calculated using life cycle methodology (specified in Article 19 and Annex V of the Directive). The same criteria are included in the Fuel Quality Directive (EC, 2009b) (specified in Article 7d and Annex IV). In this regard, these directives are highly relevant to LCA of biorefineries.

In order to harmonise GHG accounting for biofuels according to the RED across Europe, the BioGrace project has developed calculation tools and published standard values for accounting for GHG from biofuels. Calculation tools and standard values are publicly available on the BioGrace website (http://biograce.net/). Values are transparently documented and based on calculation rules that are in line with those laid down in the RED.

3.2.3 CEN Sustainability Criteria for Biomass

The European Committee for Standardization (CEN) is in the process of developing a standard (EN 16214) covering sustainability principles, criteria and indicators for biomass for energy applications, including GHG emissions and fossil fuel balances (http://www.cen.eu/). The RED sets the framework for this standard. To this date, three out of four parts have been finalised. Of immediate relevance to LCA of biorefineries is Part 4, which is already published, on calculation methods for the GHG emission balance using LCA (EN, 2013).

3.3 CARBON FOOTPRINTING

3.3.1 ISO 14067 – Carbon Footprint of Products (under development)

ISO is developing a standard on carbon footprinting (ISO 14067), which is expected to be finalised for publication in March 2014. It is being developed to conform to ISO 14025 (Type III Environmental Declarations), ISO 14044 (Life Cycle Assessment) and BSI PAS 2050 (life cycle GHG emissions of goods and services). Hence, it should not be expected to change the LCA methodology outlined in these standards. However, since its aim is to increase transparency in quantifying and reporting of GHG emissions over the entire life cycle of products and services, it will include issues specifically important to this, such as land use change, carbon uptake, biogenic carbon emissions and soil carbon change. Guidelines for LCA of biorefineries could therefore benefit from taking this new standard into account.

3.3.2 BSI PAS 2050:2011 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services

Publicly Available Specifications (PAS) are standards issued by the British Standards Institution (BSI). PAS 2050 (British Standards, 2011) builds on existing life cycle assessment methods according to the ISO 14040 series. Its specific aim is to clarify the implementation of these standards with regard to principles for the assessment of GHG emissions of goods and services.

3.3.3 Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard

The Greenhouse Gas Protocol (GHG Protocol, 2013) is a partnership between the World Resource Institute and the World Business Council for Sustainable Development. Like ISO 14067, this standard is largely in compliance with ISO 14040/44, but specifically focuses on GHG accounting. The standard includes many practical examples. The GHG Protocol product standard was launched in October 2011 and has been adopted as the basis for various industry-driven initiatives, including the Sustainability Consortium.

3.4 SUMMARY: STANDARDS TO BE CONSIDERED IN OVERVIEW OF KEY ISSUES

In Table 3.1, the aim and scope of those standards and guidelines which are considered when formulating recommendations for dealing with key methodological issues in Chapter 5 are summarised, along with an explanation of why they are relevant for LCA studies of biorefinery systems.

Table 3.1. Summary of standards and guidelines.

Standard/Guideline	**Aim and scope**	**Relevance to LCA of BR**
ISO 14040:2006, Environmental management – Life cycle assessment – Principles and framework	LCA principles and framework	Common reference point for most guides and standards within the area of life cycle assessment and life cycle thinking.
ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines	More detailed guidance on the life cycle inventory analysis, impact assessment and interpretation phases of LCA.	Common reference point for most guides and standards within the area of life cycle assessment and life cycle thinking.
International Reference Life Cycle Data System (ILCD)	Methodological guidance, in line with, but expanding on, the ISO 14040 and 14044 standards on LCA.	Complement to the ISO standards when dealing with methodological key issues encountered in LCA of biorefineries.
EU Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF)	Harmonise the methodology for environmental footprinting of products, services and organisations. Build on existing standards, but for many methodological decisions they go further than existing standards	Proposed by the EC to be used as an EU-wide method. Methodological clarifications provided by the PEF and the OEF are therefore important in developing recommendations for LCA of biorefineries.
ISO 14025:2006, Environmental labels and declarations – Type III Environmental Declarations - Principles and procedures	LCA-based environmental declarations of products and services, primarily intended for business-to-business communication.	Type III Environmental Declarations can be developed for products from biorefineries.
PCR 2011:17: Basic organic chemicals	PCR for the assessment of the environmental performance of basic organic chemicals and the declaration of this performance by an environmental product declaration	Organic chemicals could be one of the output or input products from a biorefinery.
Renewable Energy Directive (2009/28/EC, Article 19 and Annex V) and Fuel Quality Directive (2009/30/EC, Article 7d and Annex IV)	Among other things, establish sustainability criteria for biofuels and bioliquids.	Definition of how GHG reductions should be calculated for biofuels and bioliquids, which are product categories from biorefineries.
EN 16214-4: Sustainably produced biomass for energy applications – Principles, criteria, indicators and verifiers for biofuels and bioliquids – Part 4: Calculation methods of the greenhouse gas emission balance using a life cycle analysis	Calculation methods of the greenhouse gas emission balance using a life cycle analysis within Renewable Energy Directive framework	Definition of how GHG reductions should be calculated for biofuels and bioliquids, which are product categories from biorefineries.
ISO 14067: Carbon footprint of products – Requirements and guidelines for quantification and communication. (Expected to be published in 2014)	Increase transparency in quantifying and reporting of greenhouse gas emissions over the entire life cycle of products and services. Conform with ISO 14044, ISO 14025, BSI PAS 2050	Carbon footprint can be developed for products from biorefineries.
PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.	Clarify the implementation of ISO 14040 standards with regard to principles for the assessment of GHG emissions of goods and services	Complement to the ISO standards when dealing with methodological key issues encountered in LCA of biorefineries.

4 LCA OF BIOREFINERIES – STATE OF THE ART

4.1 LITERATURE REVIEW

In the study of the literature, 12 scientific papers published between 2009 and 2013 were reviewed. The articles were found by a screening in which both the publically available Google Scholar and Lund University Library database were used. Screenings for papers were performed in August 2012 and February 2013. The papers had to be published after 2008 when the debate on LUC and iLUC intensified. The studies were chosen to provide examples of case studies of biorefinery systems and they do not represent the entire collection of papers in the field. Another selection criterion for the papers included in the literature review was that they should present an LCA-based environmental assessment of a system in which more than one valuable product is produced from biomass. Thus, LCA of e.g. dedicated biofuel production was not included in this literature review. The term biorefinery is not specified in all of the studies included, which may have its explanation in the lack of a clear and universal definition of biorefineries. Thus in the papers reviewed, biorefineries are defined as entities ranging from a simple ethanol factory to a complex, integrated system in which a number of actors cooperate and a variety of products are produced. The literature was reviewed with the focus on the key issues for LCA of biorefineries as defined in previous sections of this report. The stated aim, the definition of a functional unit, system boundaries, whether the LCA is accounting or consequential, the type of data used, and how the issue of allocation is handled, are summarised in Table 4.1 and analysed in section 4.2.

Table 4.1. Specific properties of a number of selected LCA case studies of biorefinery systems.

Study	Aim	FU	System boundaries	Type of LCA[5]	Type of data	Feedstock type and allocation method	Allocation method for output products
(Cherubini and Jungmeier, 2010)	Compare the environmental performance of a biorefinery that produces bioethanol, bioenergy and phenols from switchgrass with a conventional fossil-based production system	477 ktonnes of switchgrass/year	Cradle-to-gate (cultivation of switchgrass, biorefinery processes and transport), Austria	Not specified	Average	Switchgrass/land use reference	No allocation
(Cherubini and Ulgiati, 2010)	Assess the environmental performance of a biorefinery system that converts agricultural residues into bioethanol, bioenergy and phenols	477 ktonnes of biomass/year	Cradle-to-gate (residue removal/ collection, biorefinery operations and transport), Austria	Not specified	Average	Straw and maize stover/land use reference	No allocation
(Earles et al., 2011)	Characterise the environmental impacts during the life cycle for the OSB biorefinery and thereafter present a process in which the environmental impact is minimised. Compare with a conventional production system	1000 kg ethanol, 368 kg acetic acid and 55.3 MSF OSB Panels	"Gate-to-gate", It cannot be determined whether forestry operations are included or whether the LCA only refers to the biorefinery, USA	Not specified	Average	Timber/no allocation	No allocation
(Ekman and Börjesson, 2011)	Investigate the environmental performance of propionic acid produced in a biorefinery system with a fossil reference.	1 kg propionic acid at factory gate	Cradle-to-gate (production of raw materials, biorefinery operations and transport), Sweden	ALCA	Site-specific, average	Agricultural residues/ economic allocation	Economic allocation
(Gonzalez-Garcia et al., 2011)	Assess, identify and quantify the environmental burdens associated with dissolving pulp manufacture in Sweden – Propose improvements and identify key steps for environmental impact along the process chain.	1 tonne of dissolving cellulose[6]	Cradle-to-gate (silvicultural operations and industrial activities in the biorefinery), Sweden	Not specified	Site-specific, Swedish average data and data from Ecoinvent-database	Soft wood/no allocation.	Economic allocation
(Kimming et al., 2011)	Analyse two systems for energy self-sufficiency on an organic farm to quantify their energy efficiency, resource use and greenhouse gas emissions.	MWh energy supplied in one year	Cultivation when expanded production, otherwise collection of agricultural residues, production and transport), Västra Götaland, Sweden	CLCA	Long-term marginal data	Straw and ley/and use reference	Substitution
(Lim and Lee, 2011)	Provide information about how the current palm oil biodiesel system can be improved by introducing bioethanol production into the system	1 ha of land for palm oil plantation in 100 years.	Seed-to-wheel (palm oil plantation and processing in the biorefinery) South East Asia (Malaysia)	CLCA	Site-specific, Average	Palm tree/system expansion	No allocation

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[5] Not specified means that the text does not state whether the LCA is accounting or consequential.

[6] 1 tonne of air-dried (10% moisture content), high quality dissolving cellulose from a blend of pine (20%) and spruce (80%).

(Piemonte, 2012)	Provide a LCA for a lignocellulosic biorefinery that produces energy and bioethanol from wood residues. To demonstrate the environmental benefits in other terms than GHG emission savings since wood residues are less influenced by LUC impacts than grains.	1 kg fuel (bio-ethanol or light fuel oil) and 1 kWh of electricity	Cradle-to-gate. However, the process starts with pre-treatment of biomass. Geographical boundaries not specified	Not specified	Average data (Data from the Ecoinvent-database)	Wood residues/no allocation (free up to collection)	Economic allocation
(Pourbafrani et al., 2013)	Quantify the life cycle GHG emissions associated with CW biorefinery configurations and compare the results with those of relevant reference systems	1 MJ of E85, 1 kWh of generated electricity utilising bio-methane, 1 kg of limonene and 1 kg of digestate	(Feedstock delivery, biorefinery processes, transport and use) Florida	Not specified	Average data Data from the GREET database	Citrus waste, no allocation (sensitivity analysis mass allocation)	System expansion and economic allocation (in sensitivity analysis energy allocation)
(Souza et al., 2012)	Compare a traditional system for production of sugarcane ethanol with a system in which sugarcane ethanol and palm oil biodiesel are produced.	7.55 m^3 ethanol (1 ha sugarcane for trad. prod, 1.12 ha sugarcane + 0.14 ha palm trees)[73]	Well-to-gate (agricultural activities and biorefinery processes) Brazil	Not specified	Site-specific, average Brazilian data	Sugarcane and palm tree/allocation method not specified	System expansion
(Tonini and Astrup, 2012)	Evaluate the environmental sustainability using life-cycle assessment of a specific waste refinery concept with specific focus on energy production and material recycling	Treatment of one ton (1000 kg) of Danish residual municipal (wet) waste	Collection of raw material, refinery operations and transports. Denmark	CLCA	Marginal data (long-term and short-term marginal data)	Residual municipal waste/system expansion	System expansion and exergy
(Uihlein and Schebek, 2009)	Assess whether a future LCF biorefinery system will have better environmental performance than a fossil-based system and identify hot-spots in the production, what kind of environmental impact and which production steps are responsible.	1000 kg straw	Cradle-to-gate (agricultural production of straw, processing and transport)	Not specified	Average data	Straw/economic allocation	System expansion

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[7] Corresponds to a reference flow of 1 ha sugarcane for the traditional system and 1.12 ha of sugarcane plus 0.14 ha of palm trees for the integrated system because ethanol is used in transesterification.

4.2 LITERATURE ANALYSIS

The *aims* of the studies included in the literature review are shown in Table 4.1. As can be seen from the table, the majority of the studies, regardless of type of LCA, aim to assess, identify, quantify, characterise, investigate or evaluate the environmental impact of a biorefinery system and compare it with that of a reference system. This refers to either a fossil-based production system (Uihlein and Schebek, 2009; Cherubini and Jungmeier, 2010; Cherubini and Ulgiati, 2010; Kimming et al., 2011; Ekman and Börjesson, 2011; Tonini and Astrup, 2012; Pourbafrani et al., 2013) or conventional biofuels (Lim and Lee, 2011). A few studies also aim to identify hotspots and suggest improvements to lower the environmental impacts of the biorefineries (Uihlein and Schebek, 2009; González-García et al., 2011; Lim and Lee, 2011; Tonini and Astrup, 2012). None of the studies specifies an intended audience. This may be due to the fact that they are scientific publications mainly addressing other researchers.

As can be seen in Table 4.1, the *functional units* in the studies are mainly of three types. The first type is one selected product, e.g. 1 tonne dissolving cellulose (González-García et al., 2011), 1 kg propionic acid (Ekman & Börjesson, 2011) or 1 kg fuel (Piemonte, 2012). The second category includes functional units that contain a combination of products produced such as 1000 kg ethanol, 368 kg acetic acid and 55.30 MSF OSB panels (Mason Earles et al., 2011) or MWh of different energy carriers supplied to a system/year (Kimming et al., 2011; Pourbafrani et al., 2013). The third category of functional unit refers to the input of feedstock expressed either as 1 tonne of biomass or waste (Uihlein & Schebek, 2009; Tonini & Astrup, 2012), 477 ktonnes of biomass (the total annual input) (Cherubini & Jungmeier, 2010) or 1 ha of sugarcane (Souza et al., 2012) or 1 ha palm oil plantation in 100 years (Lim & Lee, 2011). Functional units in this third category proved to be most common alternative and in some cases were justified as being the only reasonable alternative since one single main product could not be identified. In one case, a sensitivity analysis was performed in which the functional unit was altered (Pourbafrani et al., 2013).

The studies reviewed had different *system boundaries*, cradle-to-gate being one of the most commonly stated. The geographical specifications were also different and proved to have some impact, especially regarding the choice of input data such as type of energy used as input or to be replaced/compared with. This applies for all studies, since they all refer to different geographical regions.

Average *data* were used as input in most of the studies. The studies by Kimming et al. (2011) and Tonini & Astrup (2012) are the only ones that take this aspect into consideration when they define the systems to be replaced by the biorefieries as long or short-term marginal data. In particular, the study by Tonini & Astrup (2012) makes a detailed sensitivity analysis related to the time perspective assumed. It is also these studies together with the study by Lim and Lee (2011) that define themselves as *consequential LCAs*. The study by Ekman & Börjesson (2011) is the only one that is defined as an *accounting LCA*. The other studies do not define whether the analysis is accounting or consequential, but this may be deduced from the aim of the study as well as the type of data chosen or the allocation method applied. It is noteworthy that the majority of LCAs in this review do not specify the type of LCA performed. Furthermore, they do not state whether the LCA used followed the ISO standards 14040-14044. However, studies performed according to the ISO standards was not one of the criteria used in the search for literature.

The most common method used to partition the environmental impact between products is by *system expansion*. Three studies (González-García et al., 2011; Ekman and Börjesson, 2011; Piemonte, 2012) use economic allocation in the base case, with the justification that this is suitable to apply also for products with diverse characteristics. Some studies (Ekman & Börjesson, 2011; Pourbafrani et al., 2013) test the application of other allocation methods, energy- or mass-based, in a sensitivity analysis. The studies that apply economic allocation based on market prices are those describing systems that are either in operation (González-García et al., 2011) or produce products identical to existing alternatives on the market today (Ekman & Börjesson, 2011). The studies that use input-based functional units do not apply allocation but compare with a fossil-based reference system for products (Cherubini and Jungmeier, 2010; Cherubini and Ulgiati, 2010). Lim and Lee (2011) also apply an input-based functional unit, but state that they avoid allocation of by-products by applying system expansion. However, this is in practice the same approach used by Cherubini and Jungmeier (2010) and Cherubini and Ulgiati (2010).

Some common *hotspots* of GHG emissions that were identified in the LCAs were: the raw material (system boundaries, factors related to cultivation of crops or removal of residues), the reference system, process efficiency, inputs to the process (chemicals and energy). If other environmental impact categories were considered, such as those related to toxicity or resource consumption, other hotspots were identified.

The main focus of this report is on energy and GHG emissions, but most of the studies that were reviewed also take into account other factors such as those related to toxicity, resource consumption and nutrient leaching. However, few of the studies go into detail concerning methodology.

5 KEY METHODOLOGICAL ISSUES FOR LCA OF BIOREFINERY SYSTEMS

Based on the existing standards and guidelines described in Chapter 3, the literature on LCA and biorefineries in Chapter 4 and discussions in the project group, seven key issues for LCA of biorefinery systems were identified.

In the following chapter, these key issues are described and analysed. The aim is to categorise each key issue in a systematic manner in order to allow methodological recommendations to be made. Each key issue is handled in the following way: First, we introduce the topic and provide a justification for why we believe it to be an important key issue. Second, we give a short summary of what we found in the literature review. Third, we relate those findings to what we found in our review of existing standards and guidelines to identify definitions, requirements and whether there are any specific methodological recommendations for each key issue. The standards were also especially screened to find connections between the first key issue (goal definition) and the other key issues. Fourth, based on the above, we discuss each key issue and, when possible, give our recommendations for how we believe these key issues should be handled in LCA studies of biorefinery systems.

It should be noted that even when based on logical arguments, giving recommendations always involves a certain measure of subjectivity. Thus the recommendations given here should not be seen as some universal truth, but rather as a reflection of the authors' considered opinions.

5.1 KEY ISSUE 1: GOAL DEFINITION

5.1.1 Introduction

In every LCA study, the goal should be clearly stated, the purpose or aim of the study explained, an intended application and audience identified and the research question specified. This is a key issue since it determines several methodological choices that need to be made throughout an LCA. A clear, initial goal definition is also essential for subsequent correct interpretation of the results (JRC, 2010).

As previously mentioned, LCA studies are typically divided into two different types, attributional LCA (ALCA) and consequential LCA (CLCA). Generally, these two LCA types address different questions. An ALCA can be defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems, while a CLCA can be defined by its aim to describe changes of a life cycle, often with a market-orientated approach (Finnveden et al., 2009). In connection with goal definition and the issues of ALCA/CLCA, we formulated two relevant questions:

- What kind of research questions can CLCA/ALCA answer?
- What modelling approach is suitable for the type of research question to be answered?

Both of these questions are relevant for LCA of biorefineries. In the perspective of LCA method development and discussions, the first question might be the most relevant, while the second question might be more appropriate when performing case studies. In the following, we use both perspectives in our discussions.

5.1.2 Handling of the issue in the literature on biorefinery LCA

In the literature review, a number of different aims were found, the most common being to compare biorefinery systems or the products that they produce with conventional systems or products or conventional biobased products. None of the studies specified an intended audience.

The majority of the LCAs reviewed did not specify whether consequential or attributional modelling was performed, and it was not possible to define this based on the information given in the papers. In a literature review by Zamagni et al. (2012), similar results were found; i.e. based on the stated purpose of the study, it was not possible to decide whether CLCA or ALCA is the most appropriate method to use.

5.1.3 Summary of requirements/recommendations on key issue in standards and guidelines

According to the ISO 14040 and 14044 standards, the goal should state the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions to be disclosed to the public. Furthermore, the ISO standards stress that the methodological choices made in the LCA should be consistent with the goal and intended application, but give little or no guidance on how this should be done. However, the ISO standards specify a number of possible applications of LCA, including environmental management systems and environmental performance evaluation, environmental labels and declarations, environmental communication etc.

The ILCD Handbook (JRC, 2010) links possible aims/applications or decision situations to methodological decisions. The Handbook identifies three “goal situations”, which are then linked to mode of analysis (attributional or consequential):

- Situation A: Micro-level decisions (products)
- Situation B: Meso-macro level decisions (policy)
- Situation C: Accounting (products and policy)
    - C1: Include interactions with other systems
    - C2: Exclude interactions with other systems

The first two represent different levels of decisions. Meso-/macro-level decisions (Situation B) are major changes assumed to have structural consequences outside the decision context, i.e. they are assumed to change available production capacity (defined based on percentage change in relation to average percentage of the annually replaced production capacity in the production system). In contrast, micro-level decisions (Situation A) are small changes assumed to have limited and no structural consequences outside the decision context. Situation C is merely for accounting purposes, i.e. it does not take into account changes and can include either large or small systems. The ILCD Handbook gives detailed guidance on how to classify these goal situations for different purposes.

For micro-level decisions such as in Situation A, attributional LCA is recommended by the ILCD Handbook. Consequential modelling is suggested when large-scale consequences are involved (Situation B). The typical decision context for Situation B is that of policy development/information, in which the decision and the related changes affect the rest of the economy by having large-scale structural effects.

Situation C has a descriptive/accounting purpose. In C1, existing interactions with other systems are included, meaning e.g. that benefits of recycling or avoided production of co-products are accounted for. Situation C2 analyses the system under study in isolation and no effects on surrounding systems are included. In the ILCD Handbook, it is argued that Situation C is only descriptive and cannot be used for decision support.

The Product Environmental Footprint (PEF) (EC, 2013a) and the Organisation Environmental Footprint (OEF) (EC, 2013b) are guides for environmental footprinting of products, services and organisations. The aim of the PEF Guide is to harmonise the methodology and increase the comparability of future results within the same product category. The PEF Guide stresses the importance of a clearly defined goal so that “the analytical aims, methods, results and intended applications are optimally aligned” (PEF Guide, p. 16) although it does not give explicit instructions on exactly how this alignment should be done. However, just as in the ISO standards, a number of applications of LCA are given:

- In-house applications, including e.g. support to environmental management and identification of environmental hotspots.
- External applications (e.g. Business-to-Business (B2B), Business-to-Consumers (B2C) covering e.g. marketing, environmental labelling, responding to the requirements of environmental policies at European or Member State level etc.
- Benchmarking, which includes defining a product with average performance and grading the performance of other products in relation to the benchmark.

5.1.4 Discussion and recommendations

In several of the standards and guidelines, the importance of goal definition when performing an LCA is stressed, i.e. clearly specifying (1) the intended audience, (2) the intended application and (3) the research questions. However, most standards do not discuss any further the link between goal and methodological choices. One exception is the ILCD Handbook, where there is a link between the different goal situations and type of modelling, e.g. it recommends using ALCA in Situations A and C, and CLCA in Situation B.

There are numerous conceivable audiences for LCAs of biorefinery systems: policymakers, authority executors, investors, consumers, plant owner/managers, researchers, students, etc. There are numerous ways in which they intend to use the results and the questions they will be interested in. Furthermore, some LCA studies can be explorative, without aiming to be useful for e.g. decision support or product declaration. As Zamagni et al. (2012) point out; many LCA studies are also performed to test and learn about the methodology itself. Therefore we were unable to link the intended audience or application to different types of research questions (as done in the ILCD Handbook).

However, we are able to list a number of research questions that can be answered when performing an LCA of a biorefinery system, and questions that are general but relevant for biorefinery systems.

It is not possible to list all possible research questions, but this gives an indication of the type of questions that can be answered.

We also make an attempt to categorise the different questions as ALCA or CLCA, as this is important for many methodological choices, including choice of data and system boundaries. The choice of ALCA and CLCA is linked to the research questions, although this link is not always straight-forward in practice. It can be noted that what appear to be limited changes in the formulation of the questions can change an ALCA into a CLCA and vice versa.

Specific questions in LCA of biorefineries include:

- What is the environmental impact of a biorefinery product/products? (ALCA or possibly CLCA)
- How is the environment affected by the use of a biorefinery product?
- What is the environmental impact of a biorefinery? (ALCA or possibly CLCA)
- What is the environmental impact of process integration (i.e. biorefinery vs. stand-alone bioenergy production systems)? (ALCA or possibly CLCA)
- What is the environmental impact of different feedstocks for the biorefinery? (ALCA or possibly CLCA)
- How are the environmental profiles of the biorefinery products affected by the use of different feedstocks? (ALCA, or possibly CLCA)
- How is the environment affected by the use of different feedstocks? (CLCA)
- What is the environmental impact of increased demand for a biorefinery product/products? (CLCA or possibly ALCA)
- What is the environmental impact of building and running a new biorefinery compared with business as usual? (CLCA or possibly ALCA)
- What is the environmental impact of choosing process integration (i.e. biorefinery) or a stand-alone bioenergy production system? (CLCA or possibly ALCA)
- What is the environmental impact of choosing a different feedstock for the biorefinery? (CLCA or possibly ALCA)
- What is the environmental impact of choosing a different technology in the biorefinery? (CLCA or possibly ALCA)
- What are the hotspots in the biorefinery production system? (ALCA or possibly CLCA)

General questions that are also relevant to biorefineries include:

- What biofuels are eligible for financial support connected with e.g. GHG emission limits? (ALCA)
- What are the consequences for the environment of using biomass or land in different ways? (CLCA)
- What are the consequences for the environmental profile of a product of using biomass or land in different ways? (ALCA or possibly CLCA)
- What are the consequences for the environment of using biomass waste in different ways? (CLCA)
- What are the consequences for the environmental profile of a product of using biomass waste in different ways? (ALCA or possibly CLCA)

- What is currently the environmentally best use of biomass or land? (ALCA/CLCA)
- What is currently the environmentally best use of biomass waste? (ALCA/CLCA)
- What are the environmental profiles of the different feedstocks? (ALCA, or possibly CLCA)

Again, we would like to point out that this is a tentative list. Due to the difficulties in classifying research questions into ALCA or CLCA, we recommend that practitioners describe the research question, but also whether they intend to use an ALCA or CLCA. This is necessary since the type of LCA often does not follow unambiguously from the question. The choice of LCA approach should in turn be carefully considered for each specific study, particularly as regards whether the methodological choices made will be able to give a meaningful answer to the research questions.

In formulation of the goal, it is also important to be specific about the time horizon of the study. Note that there are several different kinds of time horizons in the same LCA: how long the results can be used as a basis for decisions (typically 1-10 years), how far in the future analysis of the socio-technical system extends (typically 10 to 100 years for different parts of the system), how long is the time horizon used to calculate emissions from landfills (often 100 years after waste is placed there), the climate impact of greenhouse gases (often 100 years after they are emitted), etc. Ideally, all of these time horizons should be specified in the study’s goal and scope definition.

All the above-listed questions are of a traditional LCA type, i.e. are static, linear, usually based on historic data and limited to environmental aspects. Attempts have been made to develop LCA in other directions, e.g. to be dynamic, non-linear, reflect future performance, and to include social and economic aspects (Ekvall et al., 2007). In that case, other types of questions can become relevant to study, e.g.:

- At what point in time should a biorefinery be built?
- What production capacity should a biorefinery have?
- How sustainable are biorefineries or a specific biorefinery product?

5.2 KEY ISSUE 2: FUNCTIONAL UNIT

5.2.1 Introduction

The choice and formulation of functional unit has been identified as a key aspect in several standards and guidelines (e.g. in the ILCD Handbook) and in the literature (e.g. Weidema et al. (2004). The functional unit should describe the main function of the product system. According to Wiloso et al. (2012), there are two main general concerns regarding the choice of FU: which function to choose and which unit is representative of this function. The choice of functional unit is important both with regard to comparability of results and interpretation of results (Cherubini and Strømman, 2011).

Guinée et al. (2002) suggest that the function be defined as close to the end use as possible. Weidema et al. (2004), on the other hand, suggest that the objective of the study is determining for the choice of functional unit. However, both Weidema et al. (2004) and Guinée et al. (2002) agree that in comparative studies it is important that similar functions, both qualitatively and quantitatively, are compared.

Choice of functional unit has also been discussed in LCA studies of bioenergy/biofuel systems. In studies on biofuels, several authors (Gnansounou et al., 2009; Singh et al., 2010; Cherubini and Strømman, 2011) have stressed that the functional unit for transportation services should be expressed on a per vehicle-km basis. The reason for this is that different engines have different efficiency and for comparison with other fuels the primary function of the fuel, i.e. the transportation service, should be the basis of the calculations.

For biorefineries the choice of functional unit is very important. By definition, biorefineries produce more than one product and it may be difficult to identify one main function, which requires some extra thought when choosing a functional unit.

5.2.2 Handling of the issue in the literature on biorefinery LCA

In the literature review, we found that three types of functional units were used; amount of input (feedstock), a single output product, and a combination of output products. The input-based functional unit, representing e.g. amount of biomass, was the most common functional unit. In some cases the functional unit was not in accordance with the described aim, e.g. the aim of a study was said to be an evaluation of biorefinery products, but the functional unit was input-based.

5.2.3 Summary of requirements/recommendations on key issue in standards and guidelines

The ISO 14040 and 14044 standards give general requirements on the functional unit, but with no specific methodological guidance on how it should be defined. Other than stating that the functional unit should be consistent with the goal of the study, the standards make no methodological connections to the goal definition.

The ILCD Handbook specifies a number of requirements and optional procedures for the formulation of the functional unit, such as to identify all the functions of the production system studied. Many of the recommendations are in line with the ISO standards, although several additional recommendations are proposed. However, the ILCD Handbook does not link the choice of functional unit to the goal of the study, apart from the specific requirements for studies with a comparative application, when the systems compared should have the same functional unit or only differ slightly.

Similarly, PEF and OEF give guidance on how the functional unit should be formulated (e.g. it should be defined according to the following aspects: “what”, “how much”, how well”, “how long”), but do not link it to the goal or any other methodological choices.

Some environmental declaration standards state the functional unit, e.g. in the RED the functional unit is always 1 MJ of fuel, in the PCR for basic organic chemicals the functional unit is 1000 kg of packaged product ready for delivery.

5.2.4 Discussion and recommendations

In both the literature and standards, there is much written on how to choose and formulate functional unit, but very few mention the link between functional unit and goal definition. In the literature review, we found that there is often a mismatch between the goal and the choice of functional unit. For example, many studies had the aim of comparing the biorefinery system with a fossil fuel reference, but chose an input-based functional unit (e.g. 1 tonne biomass). An input based functional unit can be advantageous when determining the best use for a specific feedstock or land area (Cherubini & Strømman, 2011), but not for product comparison. In some cases, the treatment of feedstock in biorefineries can be regarded as waste treatment. A waste treatment is also a function and amount of treated waste in the biorefinery can be a relevant functional unit, but must be compared with other waste treatment options.

An output (product)-related functional unit (such as 1 m^3 ethanol, 1 MJ electricity or 1 vehicle km) can enhance comparison with other studies with the same functional unit (product or service) and similar system boundaries. However, choosing a single product output as the functional unit means that the other co-products from the biorefinery have to be dealt with, e.g. by system expansion or allocation. Methods to deal with multifunctionality are discussed further under the next key issue.

However, biorefineries are defined as producing several useful products, meaning that the selection of one main product may be difficult. Using several functions (e.g. a combination of output products, or 1 biorefinery) as the functional unit may be very useful in e.g. process development, although it may be a disadvantage in some situations, such as for communicating of the results. For example, it can be difficult to interpret the results if they are expressed as kg global warming potential per “1 MJ ethanol, 1 kg bio-plastic and 1 MJ electricity”. This type of functional unit can be useful when comparing supply of the same functions based on fossil fuels, or when comparing stand-alone plants with integrated systems (i.e. biorefineries). Again, this has to be linked to the aim of the study. A multifunctional functional unit can only answer certain types of questions.

We believe that the functional unit is closely related to the aim of the study. Thus depending on the research question, different types of functional units will be suitable. This is illustrated with some examples in Table 5.1. It is impossible to cover all types of plausible research questions and related functional units, but based on the literature review and discussions in the project group, we identified four different categories of functional units and some examples of functional unit and research questions for these categories.

Table 5.1. Categories, and examples of the functional unit (FU) and research questions in LCA studies of biorefineries.

Category and example of FU		**Examples of type of research questions**
Use of feedstock		
	1 hectare	• What is the best use of biomass or land? • What are the consequences for the environment of using biomass or land in different ways?
	1 ton biomass	• What technological pathway is best for conversion of this biomass? • What are the environmental profiles of the different feedstock?
	Waste treatment of 1 tonne biomass (e.g. municipal household waste)	• What is the best waste treatment for this waste? • What is the best use of biomass waste?
Single product		
	1 kg product	• What is the environmental impact of a biorefinery product? • How is the environment affected by the use of a biorefinery product? • What is the environmental impact of increased demand for a biorefinery product?
	1 MJ product	
Function of single product		
	1 MJ electricity	
	1 person-km	
Multifunctional		
	1 biorefinery	• What are the hotspots in the biorefinery production system? • What is the environmental impact of the biorefinery? • How is the environment affected by the use of different feedstocks for the biorefinery?
	Combination of output products	• What is the environmental impact from these biorefinery products? • What is the optimal combination of output products for reducing environmental impact? • What is the environmental impact of process integration (i.e. biorefinery vs. stand-alone bioenergy production?

In several studies, we found that one base case functional unit was chosen and then other functional units tested in a sensitivity analysis. Using several functional units within one study is recommended by Cherubini & Strømman (2011), who argue that this can deepen the understanding and provide different perspectives on the same production system.

Based on the above discussions, we can give some general recommendations:

- The functional unit should be well chosen in relation to the research question.
- In comparative studies, it is important that the products compared have comparable functions
- Several functional units can be applied in a study, but be aware that different functional units will give answers to different types of questions.

5.3 KEY ISSUE 3: ALLOCATION ISSUES WITH THE BIOREFINERY OUTPUTS

5.3.1 Introduction

A so-called multifunctionality problem (also commonly called allocation problem) arises when two (or more) products share or partly share a production system. The choice of method to deal with multifunctionality has a strong influence on the results, as shown e.g. by Luo et al. (2009) and Gnansounou et al. (2009).

Biorefineries are defined as producing more than one output and in many cases it is difficult to identify one main product. Furthermore, the output products from a biorefinery can have different functions and physical attributes e.g. the function of products can be heating, nutritional, pharmaceutical, packaging etc., which complicates the task. Therefore the issue of how to handle multiple outputs in LCA of biorefinery systems is a core question, and is treated in the following section.

From the literature, we identified a number of ways to deal with multifunctionality in LCA:

- Avoiding allocation by increasing the level of detail
- Avoiding allocation by choice of functional unit
- Avoiding allocation by system expansion
- Avoiding allocation by system enlargement
- Allocation between the different products according to causal relationships or in proportion to a common parameter
- Mixing different methods

In the following, we explain and discuss these different alternatives for handling multifunctionality in LCA of biorefineries.

Avoiding allocation by increasing the level of detail

By increased the level of detail in modelling within the inventory analysis, emissions within a unit process can be ascribed to the different products. This is not always possible due to lack of detailed data. Many unit processes also produce more than one output without the possibility to separate the flows. Furthermore, detailed modelling does not solve upstream allocation problems regarding e.g. emissions from production of biomass input.

Increasing the detail in the modelling can be an option for some biorefinery studies, depending on the available information and the design of the biorefinery. Some sub-processes in biorefineries require inputs such as yeast and enzymes in ethanol production. A larger part of the environmental impact from producing yeast and enzymes could be attributed to the ethanol produced, since these inputs are required only in the ethanol production process step. However, this kind of assessment could be difficult since the residues after ethanol production could later be used in e.g. biogas production. Parts of the inputs used for ethanol production would then affect the biogas output. In addition, this kind of detailed process information might not be available and assessments of individual process energy and input demand might be very difficult to obtain.

Strangely enough, more detailed modelling may lead to more points in the system where allocation needs to be applied. For instance, when a feedstock is pre-treated and the part for biogas production and the part for ethanol production are separated, the upstream impacts from the pre-treatment need to be allocated. Later in the process, the ethanol and fermentation by-product are separated, leading to another allocation point. However, these allocations are less arbitrary and should normally be based on process data (mass balances).

De Meester et al. (2012) compared the sub-process approach and a black box approach and applied both allocation and system expansion. They found that the variation in the results was higher when system expansion was used compared with allocation and recommended the sub-process approach over the black box approach, since the former gives a better picture of reality. However, as previously mentioned, one can seldom solve the multifunctionality problem completely by a sub-process approach and some allocation issue usually remains (e.g. one process reactor could yield more than one product), which needs to be addressed with another methodology.

Avoiding allocation by choice of functional unit

When dealing with multi-output systems, some studies in the literature review choose a functional unit in which allocation is avoided. This can be an input-related functional unit (e.g. 1000 kg of straw), as in Cherubini & Jungmeier (2010), Cherubini & Ulgiati (2010) and Wiloso et al. (2012). Allocation of environmental burden between products can also be avoided by setting the functional unit to 1 biorefinery, or to a combination of all outputs. Note that this is actually not a good way of handling multifunctionality; choice of functional unit should rather be a consequence of the research question under study and not a way to “escape” difficult multifunctionality problems. However, given that LCA is an iterative process, reformulating the research question in response to issues in the inventory analysis (e.g. a significant multifunctionality) can be commendable. As previously mentioned, LCA results based on an aggregated functional unit can in some cases be difficult to communicate and compare with those of other studies, e.g. results stating that the potential global warming impact is 100 kg CO_2-eq for 10 kg of product A, 2 kg of product B and 0.1 kg of product C are not always so useful. However, in other situations they can be very useful. One example can be to show the potential benefits of a biorefinery system (producing products A, B and C) compared with traditional systems producing the equivalent products. Aggregated functional units can also be useful when comparing stand-alone plants with integrated systems (i.e. biorefineries).

Avoiding allocation by system expansion (substitution)

When choosing a main product as the functional unit, the environmental burden can be calculated as the emissions from the main production system minus the avoided emissions from the use of the co-products. This application of system expansion is sometimes also called substitution (Guinée et al., 2002). The idea is that increased production of a specific product or service will replace other products or services with the same function.

One of the main challenges when performing system expansion is that there might be high uncertainty concerning which product system should be included, i.e. which other product systems are affected by changes in the system under study, as this depends on complex market interactions (Gnansounou et al., 2009). The appropriate choice of production system affected can depend on both the scale (i.e. whether it is a large or a small change) and also on the time and place of the change (e.g. the electricity production may be different now compared with in a future system). The selection of affected production systems is done either by simple assumption or by a more thorough analysis. Simple assumption of an equivalent alternative product is often fossil-based. This method is rather common; e.g. a review by Mathiesen et al. (2009) found that most studies used coal-based electricity produced in combined heat and power plants as marginal electricity production. Alternatively, a more thorough analysis of the market response to increased production can be made using e.g. economic models (Weidema, 2003; Earles & Halog, 2011).

One advantage with system expansion is that it is a suitable method to use if products with different applications and features are produced, as it can be difficult to find an appropriate physical allocation base for partitioning e.g. between chemicals and electricity. However, as markets change, e.g. a high supply production of by-products from biofuel production could saturate the feed market, the assumptions regarding the system expansion will change. In other words, the results from system expansion are only valid for a certain production volume and time.

Avoiding allocation by system enlargement

In comparative studies, system boundaries can be expanded so that the systems compared encompass the same multiple functions. This application is sometimes called system enlargement (according to ILCD) or the basket-of-functions approach. This is very similar to avoiding allocation by choice of functional unit to 1 biorefinery or to a combination of all outputs, as described above. The difference is that in system enlargement we are doing comparative studies of similar production systems, or comparing a production system to a reference system which encompasses the same multiple functions.

System expansion and system enlargement do not study the same functions and do not yield the same quantitative results, but there are many similarities and the two methods are often confused (Heijungs & Guinée, 2007). The difference between system expansion and system enlargement can be illustrated as in Figure 5.1.

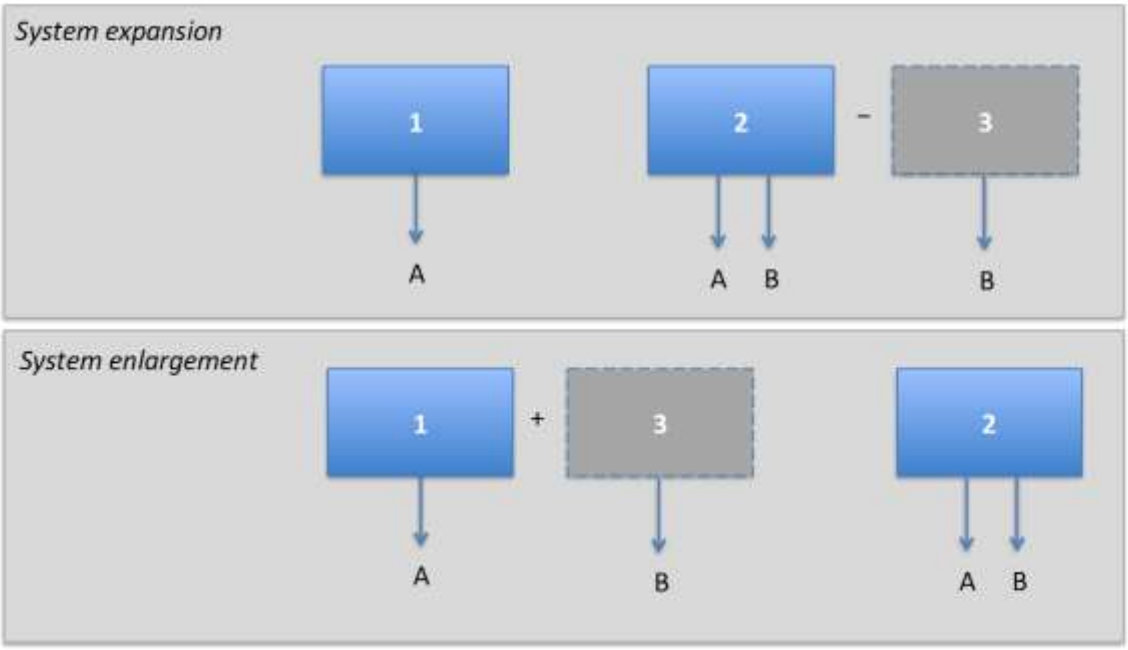

Figure 5.1. In comparative studies, system expansion or system enlargement can be applied. In system expansion the studied function is product A, while in system enlargement the studied function is product A and B.

In the system expansion, we are comparing product A, produced in system 1 or 2. System 2 is a multifunctional system also producing product B. To calculate the environmental impact of product A in system 2, we expand the system boundary and subtract the use of product B in system 3.

In system enlargement we are comparing production in system 1 or 2 of product A and B. The function is already fulfilled in system 2. In order to encompass the same function, we add production of product B in system 3. However, applying this method does not solve the original multifunctionality problem that arises with several output products from the biorefinery, but simply changes the functional unit and the reference flow. In fact, in the ISO standard 14044 (2006b), this method of enlargement is described in section 4.2.3.2 on function and functional units, which states that:

"Comparisons between systems shall be made on the basis of the same function(s)… As an alternative, systems associated with the delivery of this function may be added to the boundary of the other system to make the systems more comparable."

Note also that changing the functional unit from e.g. 1 MJ ethanol to 1 biorefinery will yield very different results and may not be able to answer the original research question.

Allocation

Allocation can be made based on physical relationships such as mass or energy properties, or on economic value; all methods have their (dis)advantages. For biorefineries producing a diverse set of products, it can be difficult to find a common criterion that is appropriate as an allocation basis. For example, mass-based allocation can be useful in some cases, but the mass of a substance does not give any information on the composition of a product; 1 kg of sand would be treated as exactly similar to 1 kg of ethanol (De Meester, 2013).

Allocation based on energy can also be problematic to justify, since not all co-products are produced for energy purposes (Singh et al., 2010; Cherubini et al., 2011b). Furthermore, using the lower heating value as the basis for allocation (as in the RED methodology) can be problematic, since wet materials, heat and steam have very low and sometimes even negative lower heating value. Some of these issues can be resolved with the use of exergy as the basis for allocation (exergy can be defined as the portion of the total energy of a system that is available for conversion to useful work), but exergy also has limitations, e.g. the practical utility of products (e.g. plastics or wood products) is overlooked (De Meester, 2013).

Allocation based on economic value could be problematic due to price variations, subsidies etc. (Luo et al., 2009). However, as Tillman (2000) points out, economic profit from a system is one of the reasons a system exists, and it has been proposed that gross sales value be used as a basis for allocation. To be more precise, the reason a system exists is typically the expected economic profit. This fluctuates less over time than the actual price. When all major costs are common to all products from the process, each product can often be assumed to contribute to the expected economic profit in proportion to an average of the gross sales value over, e.g., five years.

For biorefinery systems, it is useful to distinguish between processes that have an underlying physical relationship between the output products and the emissions and processes that do not. In ISO standard 14044 (2006), this is reflected in section 4.3.4.2 on allocation:

"Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system."

"Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products."

While the difference between these two types of situations is a key point for allocation of emissions over biorefinery products, it is also quite difficult to grasp. We therefore investigate the connection between the physical relationship of products and emissions further in the discussion.

Mixing different methods of handling multifunctionality

In some studies, allocation is done for the biomass inputs, but system expansion for output products. This can be seen e.g. in a study included in the literature review, in which Uihlein and Schebek (2009) studied the impact of a biorefinery using straw as feedstock, applying economic allocation for partitioning the impact between cereals and straw. For the output products (lignin, ethanol and xylite), system expansion was used.

When system expansion is performed, it can introduce new multifunctional problems since the avoided products are often part of other systems. Imagine e.g. that a co-product from a biorefinery (co-product A) replaces another co-product on the market (co-product B). The main product in the system where co-product B is produced will then be affected, giving effects on e.g. the market for product C, and so on. However, according to a theory by Weidema (2000), each time the system expansion process is repeated, the economic value and the volume of the displaced product tend to decrease, meaning that at a certain point, a cut-off will have little influence on the results. Another way to deal with this “second step” multifunctionality issue is to mix methods, e.g. by performing an economic allocation for co-product B in the example above (i.e. the avoided burden of co-product A is the environmental impact caused by co-product B, which is calculated with economic allocation).

Yet another common way of mixing methodologies is to increase the level of detail by using a sub-process approach, but to switch over to another methodology when this is no longer possible.

In the study by Cherubini et al. (2011b), a hybrid approach is illustrated in which the allocation is based on the GHG reduction potential of the replaced functions. In other words, a combination of system expansion and allocation is used. Depending on the particular goal of the study, the authors suggest that other environmental impact categories can be used (e.g. toxicological impacts, acidification, primary energy consumption) as the basis for the allocation factors.

5.3.2 Handling of the issue in the literature on biorefinery LCA

In the literature review, we found that system expansion and its version of substitution was the most common method in LCAs of biorefineries, followed by allocation (based on economic value and energy content). Recognising that this particular methodological choice is significantly important, some studies also included sensitivity analysis applying different methods.

5.3.3 Summary of requirements/recommendations on key issue in standards and guidelines

According to the ISO 14040 and 14044 standards, allocation should be avoided if possible. This can be done by increasing the level of detail in the modelling (identifying product-specific flows) or by system expansion. If allocation cannot be avoided, the multifunctionality problem may be handled in the first instance by allocation based on physical relationships between the environmental burdens and the functions, i.e. how the burdens are changed by quantitative changes in the functions delivered by the system. If that cannot be done, allocation should be based on other characteristics, such as economic value.

The ILCD Handbook roughly follows the method hierarchy of the ISO standards, stating that firstly, allocation is preferably avoided (subdivision); secondly, system expansion or substitution should be applied; and thirdly, allocation should be applied. The three different types of goal situations used in the ILCD Handbook (described in key issue 1) are used as a basis for the guidance regarding allocation choices. For Situation A, it is recommended that system expansion be used to solve multifunctionality problems when the degree of detail in modelling cannot be increased (even though attributional modelling is recommended for Situation A), otherwise allocation may be used. The same order of priority for methods is recommended for Situation B and Situation C1. For Situation C2, it is recommended that multifunctionality be solved with allocation.

The PEF guide is in accordance with ISO, but gives more specific examples of how to proceed when determining the allocation procedure. For example, system expansion should only be applied if a direct substitution effect can be robustly modelled, i.e. if there is a direct, empirically demonstrable substitution effect and the substituted product can be modelled in a directly representative manner. Avoiding allocation (by increasing the level of detail or system expansion) is advised as a first priority, and is not connected to the goal of the study.

The PCR for basic organic chemicals states that if possible, allocation should be avoided by applying a more detailed system description. In other cases, allocation based on underlying physical relationships should be used. Only as a last option should allocation based on economic value be used. Note that system expansion is not allowed!

The RED states that allocation by portioning should be used, based on the lower heating value of the products.

5.3.4 Discussion and recommendations

How to treat multifunctionality problems is one of the most widely discussed methodological aspects of LCA (Finnveden et al., 2009). Here we briefly summarise some findings from the literature.

Tufvesson et al. (2013) provide an overview of key parameters and methodological concerns for LCA in green chemistry. For bulk chemicals, those authors recommend system expansion, since it is important to include the benefits from the by-products (including by-products from cultivation, e.g. straw, and from the biorefinery). For fine chemicals, the use of economic allocation is recommended, since the by-products carry a relatively low value compared with the main product. It should be noted that this is in contrast to the PCR for basic organic chemicals, which does not allow system expansion and recommends physical allocation over economic allocation.

Pawelzik et al. (2013) provide some recommendations on LCA of bio-based materials produced in biorefineries, concluding that allocation based on mass can generally be considered appropriate when the economic value of the product and co-product is similar. However, when there is a substantial difference in price between products and co-products, allocation based on economic value is generally preferred. Energy allocation may be done if the energy content of both product and co-products is critical for the goal of the LCA. In other words, Pawelzik et al. (2013) in some cases relate the choice of functional unit to the goal of the study, and sometimes to the properties of the end products.

Cherubini et al. (2011b) compare different allocation methods for a biorefinery producing a diverse set of co-products. As a result of this comparison, they suggest that a suitable basis for allocation for dealing with co-products with different characteristics (such as both energy and materials) is an economic, exergy or hybrid approach of system expansion and allocation, and so is not connected to the aim of the study. De Meester (2013), on the other hand, argues that there is a strong link between the goal of the study and the choice of handling multifunctionality. When applying system expansion, more functions automatically become involved, meaning that the functional unit of the system is expanded from one product to an assessment of more aspects of the complete economy. This choice in allocation procedure thus changes the research question from: “What is the impact of this product?” to “What is the impact of this activity on the economy?”

Furthermore, there is no stringent recommendation on how multifunctionality should be related to the goal of the study (De Meester, 2013). The reason could be that it is not always easy to connect the choice of handling multifunctionality to the goal of the study. Even in a clear situation, as with the research question: “What is the environmental impact from this biorefinery product?”, with the intended audience of end consumers and the application of carbon footprint labelling, the methodological choices are not straight-forward. In this case, both system expansion and allocation are applicable (see e.g. Finkbeiner, 2009; Zamagni et al., 2012).

Although there are differences between the various standards and guidelines, most adhere to the ISO recommendations. The exceptions are PCR and RED, which have a clear focus on attributional LCA. For CLCA, the general recommendation is to use system expansion where possible, whereas for ALCA there are different recommendations.

Small, non-determining products

One special type of system expansion applies to cases where the product studied is small in quantity, or of less importance for the overall existence of the biorefinery, i.e. a product which is not determining for the process. In the “normal” case, where the product investigated is the main product of a biorefinery, system expansion should be applied to all co-products. However, if the product investigated is a small part of the total production volume, system expansion of all the other co-products can give large negative values.

Pettersson and Grahn (2013) also highlighted this problem, using the following example: If system expansion is used for a system with a relatively low biofuel output and a large output of a co-product, such as electricity, a high GHG emissions reduction potential may be erroneously attributed to the properties of the biofuel, when it is really an effect of a large electricity output. They suggest solving this problem by expanding the functional unit to include all output products. However, changing the functional unit from e.g. 1 MJ ethanol to 1 biorefinery will yield very different results and may not be able to answer the original research question. Furthermore, as the authors point out, the reference system becomes more difficult to define.

Weidema et al. (2009) discuss this issue and conclude that if the product investigated is a small, non-determining product for the process, the biorefinery process should not be included in the LCA because the process is not affected by the use or demand for the co-product. According to those authors, the LCA in these cases should instead include the alternative use (or possibly waste management) of the co-product.

Some products that are small in quantity output from the biorefinery can represent a large share of the economic output. In these cases, economic allocation could be a viable option when performing an ALCA.

Physical relationship between output products

As previously mentioned, the ISO standard distinguishes between processes with or without physical relationships between output products and the emissions. We explore this further. There are two types of process in question; processes that have an underlying physical relationship between the output products and the emissions (case (a)) and processes that do not (case (b)). In case (a), the ratio between the output products are fixed and cannot be changed. In case (b), the ratio of the output products is flexible and can be changed according to what the producer finds most economically suitable.

In theory this means that in case (b), the emissions from the process could be measured while the product output is changed. This relationship between the output products and the emissions can be expressed in mathematical terms and can form the basis for allocation. In case (a), there are several products but the ratio between these cannot be changed. The classical example is the production of chlorine and NaOH through electrolysis. Their relative proportions are decided by the chemical stoichiometrics of the reaction and the output ratio cannot be changed. The significance of this difference is that in case (a) there is no physical or chemical relationship between the production of one of the products and the emissions. There is therefore no physical relationship on which to base allocation, so any choice of physical parameter will be arbitrary.

In case (b), on the other hand, there is a relationship between the emissions and the output of the products and this can be the basis for allocation. Finding this relationship, or a reasonable approximation of it, is then a scientific question. Choice of a physical parameter in this case is therefore not arbitrary, but can be based on a scientific discussion. To summarise:

- In case (a), there are several products but the ratio between them cannot be changed. Here there is no underlying physical relationship between products and emissions on which to base allocation.
- In case (b), the ratio of the output products is flexible and can be changed according to what the producer finds most economically suitable. Here there is an underlying physical relationship between products and emissions on which to base allocation.

When modelling a change in demand, as in CLCA, the distinction between cases (a) and (b) is also of importance. In case (a), when the output of the co-products cannot be independently varied, a change in demand for one of the co-products may lead to an increase in the total production volume of the biorefinery. The overall production volume of the biorefinery process is typically determined by the combined revenue from all the co-products, implying that any change in revenue for any co-product may affect the production volume and these effects must be modelled.

So, in case (a) when the output of the co-products cannot be independently varied, a change in demand for one of the co-products may lead to an increase in the total production volume of the biorefinery. However, because of the inflexibility of the process, an increase in demand for a <u>small</u>

product might not trigger a reaction in the biorefinery process; the plant owner would perhaps not find it worth the investment to change the process setting or production volume. In that case, an increase in demand would be supplied from elsewhere. In case (b), on the other hand, a change in demand for a small product might not lead to a change in the total production volume from the biorefinery, but rather the combination of output products. For further reading on the issue of co-products in CLCA, see e.g. Weidema et al. (2009).

Recommendations

We advise LCA practitioners to follow the general recommendations in the ISO standard regarding allocation issues, meaning that as a first option allocation should avoided by increasing the level of detail. However, this kind of detailed process information might not be available and assessments of individual process energy and input demand might be very difficult to obtain. Furthermore, one can seldom solve the multifunctionality problem completely by a sub-process approach and some allocation issue usually remains (e.g. one process reactor could yield more than one product), which needs to be addressed with another methodology. This implies that a sub-process approach is seldom relevant in CLCA.

ISO does not give specific recommendations related to different types of modelling or different types of situations. Generally speaking, system expansion is often used in CLCA studies, since CLCA aims at describing the impact of change on surrounding systems, while allocation is often claimed to be more suitable for ALCA (Baumann & Tillman, 2004). However, Finnveden et al. (2009) suggest that system expansion can be done in ALCA as well, but then with the use of average data.

Avoiding allocation by choice of functional unit is not a good way to handle multifunctionality; choice of functional unit should instead be a consequence of the research question under study and not a way to “escape” difficult multifunctionality problems. However, this functional unit can be very suitable for certain types of research questions.

If the choice is for allocation, it is useful to distinguish between processes with or without physical relationships between output products and the emissions. As described above, in case (a) there are several products but the ratio between them cannot be changed, so there is no underlying physical relationship between products and emissions. In case (b) the ratio of the output products is flexible and can be changed for economic reasons, so there is an underlying physical relationship between products and emissions to use in allocation.

For case (a), any choice of physical parameter will be arbitrary. Furthermore, with a large variety in output products with different characteristics, it can be problematic to find a common physical characteristic of the co-products on which to base allocation. Therefore economic allocation is a preferred option in ALCA, although as discussed above this method also has its limitations. System expansion could be another option to solve this problem, for both ALCA and CLCA.

The above discussion leads us to the following recommended order of priority in how to handle multifunctionality in biorefinery systems:

- Avoid allocation by increasing the level of detail with a sub-process approach (applicable mainly for ALCA)
- Avoid allocation by system expansion (applicable for both ALCA using average data and CLCA using marginal data)
- Avoid allocation by choice of functional unit/system enlargement, if this is compatible with the aim of the study and the results can give answers to the research questions posed (applicable for both ALCA and CLCA). *NOTE: There is no order of priority between system expansion and system enlargement!*
- If the ratio of the output products is flexible (case (b)), use physical causation or a reasonable approximation of it (applicable for ALCA)
- If the ratio between output products cannot be changed (case (a)), use economic allocation. If this is not possible due to lack of information, make an arbitrary choice of a physical parameter (applicable for ALCA).

There could be several reasons to diverge from this list of priorities. We advise LCA practitioners to acknowledge the importance of choice of method for handling multifunctionality and, for each study, to think through carefully whether the method is in line with the intended audience, the intended application and the research question under study. We also advise LCA practitioners to be consistent and transparent about their choices.

Testing different methods of handling multifunctionality in the sensitivity analysis is advisable. In addition, if there are uncertainties regarding the basis for allocation, e.g. an arbitrary choice of a physical parameter such as in case (a) or assumptions made in economic allocation, this should be highlighted in the sensitivity analysis.

5.4 KEY ISSUE 4: ALLOCATION ISSUES IN THE PRODUCTION OF BIOMASS FEEDSTOCK

5.4.1 Introduction

Biomass feedstock, which is used as input to biorefineries, can originate from multi-output systems such as agricultural or forestry. Upstream burdens to this feedstock may be handled in different ways. Therefore, just as for the multi-output biorefineries, this creates a multifunctionality problem in LCA of biorefinery systems.

When discussing allocation issues for biomass, a feedstock classification could be useful. Wiloso et al. (2012) classify feedstock as follows: *Dedicated energy crops* are grown primarily for energy use and the whole or the majority of the crop is used. *Biomass residues* are crop residues and forest residues that may have economic value and other potential uses (soil protection, maintaining soil quality, soil carbon stocks etc). *Biomass waste*, on the other hand, has no economic value or functional uses, is available in excess and requires treatment or disposal.

5.4.2 Handling of the issue in the literature on biorefinery LCA

In the studies included in the literature review, some used dedicated energy crops, such as switchgrass (Cherubini & Jungmeier, 2010) or palm oil (Lim & Lee, 2011). Studies that included collection of the feedstock from multifunctional systems either assumed that it is the main product (often a crop) that carries all the environmental burden (Cherubini & Ulgiati, 2010) or applied economic allocation (Uihlein & Schebek, 2009). System expansion was applied in a few of the studies for handling multiple output systems in the feedstock production system, considering the alternative fate of the feedstock, e.g. involving leaving the straw or maize cobs on the field (Cherubini & Ulgiati, 2010) or even considering market-triggered changes in land use (Tonini & Astrup, 2012).

5.4.3 Summary of requirements/recommendations on key issue in standards and guidelines

In several of the standards and guidelines reviewed, e.g. ISO and ILCD, how to handle input to system multifunctionality is not explicitly mentioned, but in general the recommendations on allocation for multiple output and end-of-life should apply.

The PEF handbook gives special advice on recycled materials. When recycled materials are used as raw material input, only the conversion of recycled materials should be included in the inventory. From this, one may conclude that zero burdens should be allocated to recycled materials from previous life cycle stages.

The RED mentions that wastes and agricultural residues should be considered to have zero life cycle GHG emissions up to the process of collection of those materials.

5.4.4 Discussion and recommendations

Wiloso et al. (2012) recommend different allocation methods for different feedstocks. Dedicated energy crops should be attributed most of the environmental burden generated during primary production. Biomass waste should not be allocated any environmental burden, and in fact it could be relevant for the biorefinery to be credited with the avoided waste treatment of the biomass waste. Regarding biomass residues the allocation method is less straightforward. Referring to the Clean Development Mechanism (CDM) and Singh et al. (2010), Wiloso et al. (2012) suggest that economic allocation should be used. On using economic allocation, the biomass residue is attributed a share of the environmental burden in between that of dedicated energy crops (all the burden) and biomass waste (no burden).

Luo et al. (2009) compared the environmental impact of ethanol produced from maize stover by applying different allocation methods. Mass/energy and economic allocation was applied to allocate the environmental burden between maize and stover. Economic allocation credited the lowest environmental impact to the ethanol, since the economic value of stover was significantly lower than that of maize. The mass/energy ratio was 1:1, resulting in a higher environmental burden being credited to the stover and consequently the ethanol. Luo et al. (2009) argue that since the market demand for lignocellulosic material is growing the price of stover could increase, which would shift the ratio of the economic allocation.

Another way to handle biomass input is to expand the system by studying the alternative use of the feedstock. For example, Melamu and von Blottnitz (2011) studied the consequences of using bagasse (residue from sugar cane plantation) for biofuel production, where the bagasse previously utilised for boiler steam was replaced by coal, giving the biofuel a very high GHG profile.

We advise LCA practitioners to follow the general recommendations in the ISO standard regarding allocation issues. However, as the ISO standards do not give specific recommendations related to different types of modelling or for different types of situations, we make some more specific recommendations below. As previously pointed out, making recommendations always involves a certain measure of subjectivity. Thus the recommendations given below should not be seen as some universal truth, but rather as a reflection of the authors’ opinions.

In ALCA, including the environmental impact of cultivation of a dedicated energy crop should be pretty straight-forward. Any co-products or residues can be treated by allocation. If co-products or residues are used as feedstock, they can also be attributed an environmental impact by use of allocation. If the removal of residues from agriculture or forestry leads to soil carbon losses, these should be accounted for and allocated fully to the residue. If the input to the biorefinery has a negative value, i.e. if the biorefinery gets paid to receive it (e.g. as for certain waste), the waste treatment is part of the functions of the biorefinery. In this case, the environmental impact can be allocated between the biorefinery products and the treatment of waste, e.g. in proportion to their economic value, if performing an ALCA.

Taking a more consequential approach, it is relevant to expand the system by studying the alternative use of the feedstock, and the consequences of redirecting this feedstock to the biorefinery. For residue feedstock, the alternative use could be to leave it in the field, or to harvest it for another use. For waste feedstock, an alternative fate could be a relevant system expansion, e.g. land fill or incineration. For a dedicated biorefinery crop, a consequential approach implies including market-triggered changes in land use, which is also treated as a separate key issue. Furthermore, any co-products or residues can be treated by system expansion.

There could also be a need for allocation within a crop rotation. For example, if a nitrogen-fixing crop is used, it can have positive effects on the following crop, in other words it has a multifunctionality that needs to be addressed, e.g. by including a reduced need for fertilisers and/or increased yield of the following crop.

There are thus a number of methods for dealing with biomass input multifunctionality problems when performing an LCA. Similarly to other methodological choices, the most suitable method is connected the aim of the study. We advise LCA practitioners to acknowledge the importance of choice of method for handling multifunctionality.

We also recommend using the same method for handling multifunctionality for both the inputs and the outputs of the biorefinery system. If a mix of methods is used, this should be clearly stated together with a justification for this choice.

5.5 KEY ISSUE 5: CHOICE OF DATA

5.5.1 Introduction

Performing an LCA requires collection of many data, which can be one of the most time-consuming parts of the LCA work. In this report, we do not go into the choice of specific data needed for the LCA of biorefineries, but only the methodological aspects of data collection. There are a number of methodological aspects related to choice of data, e.g.:

- Marginal or average data
- Scale of change
- Limitations in time and space
- Current and future performance of technology.

These aspects concern both biorefinery processes and the background systems, e.g. the energy system and the supply of raw materials, but also the reference system if comparisons are made.

Concerning the choice between *average or marginal* data, it is sometimes argued that marginal data should be used for CLCA studies and average data for ALCA studies (Tillman, 2000). However, this can be considered a simplification, as CLCA can be considered more as a concept than a methodology (Zamagni et al., 2012), encompassing much more than just choice of data or the use of system expansion (Ekvall and Weidema, 2004). Rather, marginal data should be used where relevant to describe the aim of the study. For example, if the aim is to study an increase in the production of a product, it can be argued that the relevant electricity emissions factor should be for the grid margin, i.e. the carbon intensity of the additional electricity which is generated to manufacture the product, not the grid average (Brander et al., 2009).

The anticipated *scale of change* that is modelled can also influence the choice of data. For instance, it has been argued that marginal data should be used in CLCA when marginal effects are modelled, which is true for many CLCA as many decisions have marginal effects on large production systems (Ekvall et al., 2005). Another argument brought forward by Azapagica and Clift (1999) is that average data should be used when modelling fundamental changes in production systems that would affect or even displace a large number of technologies.

If the choice is to use marginal data, then how are marginal data identified? This can be of major importance for the outcome of a study. A number of methods and energy prediction models are available to establish the marginal energy production, but it tends to be very difficult to reflect the effects in a proper way and the results are therefore highly uncertain (Mathiesen et al., 2009). It can also be done in a more simplistic way by assuming a single marginal technology. In a review of consequential LCA studies, Mathiesen et al. (2009) found that most studies identified coal combined heat and power as the marginal production for electricity, whereas the results for heat were more varied.

The *limitations of data in time and space* are also of major importance, both for average and marginal data. For average data, it is e.g. important to decide over how many years the average should be calculated and over what geographical region. This is important e.g. for emissions factors for an electricity mix or for the emission factor for biomass input to a biorefinery. Even for biomass material of the same type, it will comprise a mix of crops from different locations, which can have large effects on the data (see e.g. Ahlgren et al., 2012). For marginal data, a distinction between long-term or short-term marginal change is often made. Short-term marginal production can be distinguished as the last unit to be taken into production when demand increases on an hourly or daily basis, and will be the unit with the highest operating costs. The long-term marginal production involves changes in capacity, i.e. instalment of new plant as a response to a change in demand from consumers (Kimming, 2011). Furthermore, the geographical location is also important for the choice of marginal data if there are physical limitations to market exchange, e.g. when heat production or consumption is involved, or when bottlenecks exist in the electricity transmission system (Mathiesen et al., 2009). In addition, regulatory systems (such as the EU CO_2 cap) can have an influence on marginal electricity production (Finnveden, 2008).

Data can be based on *current or future performance* of a technology. As the biorefinery technologies are developing and the possibility to use different biomass feedstock is explored, it is likely that many upcoming LCA studies will be based on future technologies and hypothetical cases. In a review of LCA studies on bioethanol, Wiloso et al. (2012) concluded that many studies apply data on best available technique for figures such as ethanol yield. They argue that these technologies not are commercially feasible yet and that caution is needed regarding input data on a technology level. Therefore those authors suggest that a sensitivity analysis could be performed for different technology levels. Similarly, Ekvall & Weidema (2004) point out that it can be risky to take future technological advances into account in an environmental assessment of future systems, since these types of assumptions are very uncertain. Those authors suggest that uncertainty can be dealt with through the development of different scenarios based on various assumptions regarding technological development.

5.5.2 Handling of the issue in the literature on biorefinery LCA

Most of the studies included in the literature review use average and site-specific data, while two studies, both of which define themselves as CLCA, apply marginal data (Kimming et al., 2011; Tonini & Astrup, 2012). Some studies use different allocation methods for the input biomass than in the rest of the study, e.g. Uihlein & Schebek (2009) apply economic allocation for input straw biomass, but system expansion for other parts of the system.

5.5.3 Summary of requirements/recommendations on key issue in standards and guidelines

The ISO 14040 and 14044 standards give no explicit methodological guidance on choice of data, but only generic guidelines, e.g. that the data selected for an LCA depend on the goal and scope of the study. Data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data.

The ILCD Handbook (JRC, 2010) gives more detailed recommendations on choice of data, depending on the type of goal situation (described in key issue 1). For small changes (Situation A) use of average data is recommended, i.e. the average market mix. However, in system-system relationships when the system under study has a direct effect on another system and no market effects are involved, then short-term marginal data should be used. Larger changes (Situation B) should be modelled using long-term marginal data. For Situation C, which is only for descriptive purposes, average data should be used.

The other standards and guidelines reviewed here give no guidance on choice of data, except that the RED requires average values to be used in GHG calculations.

5.5.4 Discussion and recommendations

Collection of data is a cumbersome part of LCA work. A number of databases have been set up over the years to facilitate data collection, but much of the material in these LCA databases is average data (Finnveden et al., 2009).

In the standards and guidelines reviewed here, we could find no clear consensus on choice of data taking into account the differences in ALCA and CLCA modelling, marginal or average data, scale of change, limitations in time and space, and current and future performance of technology.

For example, Lindfors et al. (2012) point out the contradictory conclusions drawn by Azapagic & Clift (1999) and the ILCD Handbook concerning scale of change and choice of data. According to Azapagica & Clift (1999), average data should be used when the change involves a complete elimination or change of a production system and changes that affect not the full production system, but a significant share of the production volume, should be modelled using scale-dependent, incremental data. The ILCD Handbook, in contrast, requires that average data be used to model small changes, with marginal data being used only to model changes that are large enough to have a direct, large-scale effect on the production capacity of the system. Lindfors et al. (2012) did not find an upper limit to the use of marginal data, which could be interpreted such that marginal data should be used even to model complete changes of production systems.

Our recommendation is that average or marginal data relevant to describe the aim of the study should be chosen. In general this means that average data are used for ALCA. For CLCA the choice depends on the scale. For small changes, marginal data are relevant for the time and place that is relevant for the study. If some parts of the study include larger changes, e.g. introduction of a new technology, marginal data may not be relevant and instead average data for this new technology would best reflect the change. Be aware that much of the data in LCA databases are average data! However, there is a possibility to perform specific consequential modelling with the use of marginal data in some databases (http://www.ecoinvent.ch/). Furthermore, we do not recommend mixing average and marginal data in a study unless there is an obvious reason, which in that case should be clearly stated.

If the choice is for average data, for the most important input data it should be specified how many years the average is calculated over and what geographical region is assumed. If the choice is for marginal data, it should be specified how the marginal production was chosen and what time frame is assumed (e.g. short-term or long-term). To highlight the uncertainty in assumptions of marginal production, Finnveden (2008) recommends that two scenarios be used in LCAs, one high CO_2 emissions marginal alternative and one with low CO_2 emissions. This is a recommendation we endorse. Note also that marginal data in some cases have volumetric limits, i.e. the market for a specific product can become saturated. Marginal data are therefore in some cases only valid to a certain extent!

While following these recommendations is not an easy task, reflecting on choice of data will increase the relevance of the LCA study. Overall, input data that are uncertain and have a major impact on the results should be highlighted in a sensitivity analysis.

5.6 KEY ISSUE 6: LAND USE

5.6.1 Introduction

Following the definition of a biorefinery, one or several types of biomass are used as feedstock. Using biomass often implies that some sort of land use is involved. A distinction can be made between land use (LU) (also referred to as "land occupation") and land use change (LUC) (also referred to as "land transformation"). Land use can be expressed in units of area and time (e.g. m^2 per annum), while land use change is measured as area of converted land (e.g. m^2 forest converted to arable land; see also Mattila et al., 2011).

Furthermore, land use change can be divided into two groups: direct land use change (DLUC) and indirect land use change (ILUC). The direct changes are connected with the location of the raw material production itself, while indirect changes are market-induced effects elsewhere due to the raw material production system studied. Indirect land use change occurs when an increased demand for a product leads to displacement or intensification of agricultural production. As most agricultural and forest products are internationally traded, indirect land use change can occur anywhere on the globe. In particular, ILUC connected to biofuel production has been heavily debated in e.g. research, policy and media, with some studies showing that biofuels have a larger climate impact than fossil fuels when emissions from ILUC are taken into account. Therefore, this is an important key issue for biorefinery LCA studies.

Quantification of environmental impacts due to indirect land use change are very different from quantifications of those due to direct land use change, as the theory of indirect land use change is based on expected market reactions to increasing demand for a product, whereas quantifying direct changes relies more on natural science (e.g. modelling carbon stock changes at a specific location). Indirect land use changes are not observable. A farmer in Europe starting to grow wheat for bioethanol cannot see any indirect effects and it can never be proven that a certain land use, e.g. in Brazil, is the effect of a the farmer's change from producing wheat for food into wheat for ethanol. The linkages are complex and impossible to track down to a certain field.

The only way to quantify indirect land use change is by using models. Such quantification is commonly based on global or regional economic equilibrium modelling and the results from studies show extremely large variations. For example, the ILUC emissions from wheat-based ethanol have been estimated to range between 176 and minus 53g CO_2-eq/MJ (Di Lucia et al., 2012) (compared with life cycle emissions from fossil fuels of 83.8 g CO_2-eq/MJ in the RED). Some of the variation in estimates of ILUC stems from uncertainty, which in the future can be reduced with better models and better data. However, due to the complexity of the global economy, so-called epistemological uncertainty (connected with lack of knowledge of system behaviour) is a major contributor to the uncertainty, and it is not likely that these uncertainties will be reduced soon (Plevin et al., 2010). Furthermore, ILUC depends not only on market reactions but also agricultural and trade policies in different parts of the world. Since future decisions of future policymakers are unknown and may include surprises, future indirect land use change is intrinsically unknown.

The integration of land use into LCA procedures has been discussed in several methodology papers, with the main focus on how to handle the climate impacts. Much attention has also been given to land use connected with bioenergy and biofuel production in particular, see e.g. overview in Berndes et al. (2012). Definition of indicators to assess impacts on biodiversity and soil quality due to ILUC has been given increasing attention (see e.g. special issue *Global Land Use Impacts on Biodiversity and Ecosystem Services in LCA* in the International Journal of LCA Volume 18, Issue 6, July 2013). Integration of other land use-related impact categories (e.g. water use, pollution and effect on quality) in LCA has also been discussed (Pfister et al., 2009; Boulay et al., 2011; Kounina et al., 2013). The way in which indirect land use change is included in case studies varies greatly. A review of CLCA studies by Earles & Halog (2011) showed that only 11 of the 26 studies reviewed included ILUC in the modelling. Some studies have simply added indirect land use change GHG emissions generated from economic modelling on top of the LCA results (sometimes referred to as 'ILUC factors'). Others have tried to integrate economic models with LCA in a more advanced way.

5.6.2 Handling of the issue in the literature on biorefinery LCA

Since the majority of the studies included in the literature review do not specify whether the study is question is an accounting or consequential LCA, the inclusion of land use effects can rarely be connected with the type of LCA performed. When the type of LCA is specified, different approaches for handling land use change are applied. In general, it seems that the type of raw material used in the biorefinery has the highest influence on whether to include land use change or not.

In general, there is more focus on land use change issues in studies where the raw material for the biorefinery under study comes from agriculture than if forestry-based raw materials are used (Pettersson and Harvey, 2010; González-García et al., 2011; Mason Earles et al., 2011). If residues or wastes are used as raw material, land use change effects are not included in the studies we reviewed (Kimming et al., 2011; Seabra & Macedo, 2011; Tonini & Astrup, 2012; Pourbafrani et al., 2012), with the exception of Cherubini & Ulgiati (2010). Some studies, e.g. Ekman and Börjesson (2011) and Lim & Lee (2011), include land use change in a sensitivity analysis, but not in the base case of the study. If dedicated energy crops are used as raw material, as in Cherubini & Jungmeier (2010) and Souza et al. (2012), direct land use change is included in the LCA but indirect land use change is not. Indirect land use change is not included in any of the studies, mostly with lack of methodology stated as the major reason.

5.6.3 Summary of requirements/recommendations on key issue in standards and guidelines

Direct land use change is not mentioned on the ISO 14040 and 14044 standards, but must be taken into account according to most of the other standards and guidelines, e.g. PAS 2050, ISO 14067, ILCD and RED.

The ILCD Handbook recommends that impacts of land use change be included by means of modelling. If these impacts are not included, a justification for excluding them should be presented. It is recommended that the carbon dioxide impacts of direct land use change be modelled following IPCC (2006) emission factors (unless more accurate, specific data are available). Other GHG impacts of land use (e.g. from burning of litter, soil erosion, nutrient losses) should also be quantified. These recommendations are the same for attributional and consequential models. The ILCD Handbook does not recommend including indirect land use change, since there is no methodology available for how to deal with such change. However, it could be included in the future if such methodology were to be developed.

According to the PEF guide, GHG emissions that occur as a result of direct land use change should be included using the IPCC default values table (unless more accurate, specific data are available). Furthermore, the PEF states that as there is no widely accepted provision existing for the calculation of emissions resulting from indirect land use change, these should not be assessed in a PEF study.

In the RED, direct land use change must be accounted for, but only under certain conditions e.g. if the land use change takes place on land that was not classified as farmland in January 2008. Here too, IPCC methodology must be used for the calculation of direct land use change. At present, there are also discussions on whether indirect land use change should be included in the RED.

5.6.4 Discussion and recommendations

Including land occupation as an impact factor is not so problematic and has been done in several studies over the years, but including land use changes is more problematic. If there is a direct land use change in the system under study, it is important to establish the land status before and after the change; the question can also be framed as “What is the reference land use?”. The carbon changes connected to direct land use change can be established by direct measurements, collecting data from the literature, or by the use of soil carbon models. Changes in standing biomass can also be accounted for. Changes in soil and aboveground carbon can have substantial effects on the climate impact in LCAs of e.g. biofuels (Hoefnagels et al., 2010). At the same time, the uncertainties regarding the data are large due to difficulties in establishing the status of land and due to uncertainties in quantification of carbon changes, which are variable and site-specific. Another uncertainty connected to direct land use change is how to allocate the emissions over time. If a piece of land is converted from forestry to agriculture, how many years of cropping should the emissions be distributed over? This is further discussed in key issue 7, section 5.7

Including indirect land use change effects can be considered one of the most difficult and controversial issues to be dealt with in LCA (Mattila et al., 2011), as it requires economic, casual descriptive or other types of models or assumptions to be integrated with LCA models. There are a number of aspects that need to be considered when combining models; there can be differences in assumptions regarding time, allocation procedures, data collection etc. When combining economic models with LCA models (or adding results from the two types of models), there are also some fundamental differences that need to be considered:

- While LCA is process-specific, economic models study changes on a regional or global level, after which impacts are allocated over single products. A typical question an economic indirect land use change model aims to answer is: “What is the global land use change due to the implementation of a biofuel policy?”
- While LCAs can be both of accounting and consequential types, economic models have a consequential perspective, looking into future changes of an *increased demand* for a product on the market, modelling *marginal effects*
- While LCA models do not optimise, most economic models optimise something, often the profit of companies or a welfare function.

Even though direct land use change implies a *change* in land use, it seems logical that this change be included in both attributional and consequential LCA, as it is a change within the studied system boundary. If there is a direct land use change, we recommend always including this in the study.

However, indirect land use change occurs outside the system boundary, implying it is more suitable to include in a consequential LCA. The economic models utilised to quantify indirect land use change also have much more in common with CLCA, as economic models study increased demand on a market. However, due to the uncertainties in economic modelling, a strict recommendation to always include indirect land use change can currently not be made. Examination of this factor in sensitivity analysis is encouraged, however.

In principle, indirect land use change should not be included in an ALCA, since indirect land use change models quantify marginal effects.

5.7 KEY ISSUE 7: BIOGENIC CARBON AND TIMING OF EMISSIONS

5.7.1 Introduction

In many LCA studies it is assumed that the carbon dioxide (CO_2) from biogenic sources has no climate effect. However, when evaluating the climate benefits of bio-based systems this could be too much of a simplification, since there is a time lag between uptake and release of CO_2, especially for biomass with long rotation periods (Brandão et al., 2012). A specific feature of biorefineries is also that bio-based materials can be produced. This means that not all products from a biorefinery are immediately combusted; there will be a period of carbon storage in e.g. plastic or woody material. This is also the case if some of the biorefinery biogenic waste ends up in a long-term landfill or, if carbon capture and storage (CCS) technology is utilised in the future, CO_2 emissions being stored underground for a long time.

Global warming potential (GWP) using a 100-year time horizon is one of the most commonly used characterisation factors for potential climate in LCA. Characterisation factors are used to convert net emissions of different GHG to a common, unitless indicator value, CO_2-equivalents. This is equivalent to accounting all emissions occurring throughout the study period as if occurring in the same year (Peters et al., 2011) and thus it cannot capture the timing of emissions (there are several other arguments in the discussions for and against using a 100-year time horizon, see e.g. Brandão et al., 2012).

In order to reflect the climate impacts in relation to the temporal distribution of emissions, other methods are needed. Several approaches have been proposed in order to account for the timing of emissions and sequestration, in the context of both carbon accounting and LCA (see review by e.g. Peters et al., 2011; Brandão et al., 2012. Examples that can be mentioned include the use of dynamic characterisation factors by Levasseur et al. (2010), Global Temperature Potential (GTP) by Shine et al. (2005), time-adjusted warming potentials by Kendall (2012), the Lashof-method by Fearnside et al. (2000), the fuel warming potential proposed by O'Hare et al. (2009) and the GWPbio characterisation factors suggested by Cherubini et al. (2011a). Some of the standards and guidelines also have their own methodology (see section 5.7.3).

All this makes accounting of biogenic carbon and timing of emissions an important key issue for biorefinery LCAs.

In the following, we explain some methodological issues connected to biogenic carbon in LCA of biorefinery systems, divided into three categories:

- Carbon cycle in biomass production
- Biogenic carbon and other GHG from land use change (emissions or sequestration)
- Storage of biogenic carbon in products/wastes/carbon capture and storage etc.

Carbon cycle in biomass production

As mentioned, common practice in energy LCAs is that no explicit biogenic carbon balances are made, but that CO_2 fixation during crop growth for bioenergy is set to zero and the CO_2 emissions from e.g. fermentation, digestion and incineration of the biofuel are also set to zero (Guinée et al., 2009).

Rabl et al. (2007) recommend that emissions and removal of CO_2 be counted explicitly at each stage of the life cycle. For example, in a study of a biomass fuel chain (where biomass is grown as fuel to be burned in a power plant), the removal of CO_2 should be counted explicitly for the biomass plantation, and the emissions of CO_2 explicitly for the power plant. The net effect in that example will be zero, but for e.g. an LCA of waste treatment the system boundaries change and the CO_2 emitted during incineration has to be counted fully, although perhaps not for landfill. Guinée et al. (2009) also suggest that in LCAs of agricultural products, a distinction between “negative” and “positive” emissions may be relevant, i.e. viewing the emissions as genuine cycles and, at the systems level, subtracting the fixation of CO_2 during tree growth from the CO_2 emitted during waste treatment of discarded wood and quantifying the methane emissions. It is important to note that some databases distinguish fossil CO_2 from biogenic CO_2, but these do not automatically balance one another and therefore cannot be cancelled out (Guinée et al., 2009).

However, in recent literature the relationship between carbon neutrality and climate neutrality has been questioned. In fact, it is argued that the flows of carbon to and from the atmosphere during the life cycle are very important when evaluating the climate benefits of bio-based systems, i.e. even though the carbon balance is zero over a longer time, the carbon could give climate effects while in the atmosphere. This is especially important when there is an extended time lag between capture and release of CO_2, e.g. for perennial biomass (Brandão et al., 2012). By applying the method suggested by Guinée et al. (2009) and Rabl et al. (2007), the timing of emissions and its impact on climate are neglected. As mentioned, metrics other than the GWP are needed to reflect this. For example, Ericsson et al. (2013) study a willow biomass-to-heat system, and express the results as global mean temperature change over time.

It is important to note that the importance of biogenic carbon accounting differs between different types of feedstock. For annual crops, it can be expected to be of less importance since the carbon cycle is very short. For forest logging residues and stumps, the difference between leaving the remains in the woods to naturally decay and removing them is interesting to study. If using stem wood for bioenergy, the accounting method becomes more important. One must take into account the time it takes for the carbon to be bound into new trees, which involves assumptions about growth. In addition, the spatial perspective is important. Eliasson et al. (2013) describe two different spatial perspectives: stand level and landscape level. If studying one single stand, the amount of carbon in standing biomass will vary over time as the trees grow and are eventually harvested.

However, looking at the whole landscape, where different stands are harvested on different occasions, the average carbon stock in biomass will remain rather constant over time.

Furthermore, if the evaluation is done at the stand level, it is important to determine whether the calculations begin with the burning of a tree, i.e. if there will be a “carbon debt” or a certain “payback time”, since it will take many years before the CO_2 emitted during combustion has been taken up by the new forest biomass; or whether the calculations start with a tree being harvested, i.e. CO_2 emissions from combustion can be counted as zero because the tree has already taken up the same amount of CO_2 from the atmosphere during its growth. This becomes less important if a landscape perspective is applied, as there is continuous sequestration and emissions of CO_2 in the system.

Biogenic carbon and other GHG from land use change (emissions or sequestration)

When assuming direct or indirect land use change, such as the shift from forest or permanent pasture to annual crops, there can be substantial initial carbon losses and emissions of other GHG. This is an impulse emission to the atmosphere, and the carbon released will not be sequestered as long as the land is not returned to its original state, and can be treated in the same way as fossil fuel emissions. However, as the land will continue to produce crops for several years, carbon losses should be allocated over time. In most studies, the GHG emissions are allocated over 20 or 30 years. This probably originates from the IPCC estimated average time for a soil to reach a new steady state or, alternatively, from the estimated average life of a bioenergy plant (Khanna et al., 2011).

Müller-Wenk and Brandão (2010) argue that emissions from land use change should be compared with the potential natural vegetation as a baseline. In the absence of any subsequent land occupation, relaxation toward the potential natural vegetation starts immediately after the initial land transformation. However, if a series of land occupations (e.g. planting of agricultural crops on a former forest area) follows land transformation, the relaxation is postponed by a number of years, which needs to be taken into account. Lamers and Junginger (2013) also bring up the subject of reference land use, but claim that in the land-constrained world we live in today, a reference scenario with natural vegetation or protected forest is a questionable assumption.

Another method is proposed by Kløverpris and Mueller (2013), where the emission of GHG from indirect land use change are treated as impulse emissions and recalculated to radiation forcing and then to CO_2-equivalents. Kløverpris & Mueller (2013) also take into account the part of the world in which expansion of land is taking place. In parts of the world where there is an expansion of arable land, the emissions from indirect land use change are assumed to be immediate, while in parts of the world where there is a decline of arable land the emissions from indirect land use change are treated as delayed regrowth. The results from that study indicate that the climate impact of indirect land use change calculated in this way may be significantly less than previously estimated, about one-third of the CO_2-equivalents compared with studies by e.g. Searchinger et al. (2008) and Hertel et al. (2010).

A land use change can also mean sequestration of carbon, e.g. Ericsson et al. (2013) investigated the climate impacts of growing short rotation forestry on farm land and concluded that soil carbon sequestration had a major impact on the evaluation of short rotation forestry as an energy crop, as well as carbon in standing biomass. In total, the system showed a negative temperature effect (cooling), even without including the substitution of fossil fuels in the energy system.

Storage of biogenic carbon in products/residues/wastes/CCS etc.

Besides energy, a biorefinery can also produce products which are not immediately combusted, e.g. chemicals, plastics, wood products for construction, pulp, paper, fibres, which will store carbon for a period of time. This is also the case if some of the biorefinery products, residues or wastes are recycled to cropping (e.g. digestate from biogas production), end up in a long-term landfill, or if carbon capture and storage technology is applied in the future, storing CO_2 emissions underground for a long period of time.

Brandão et al. (2012) argue that despite significant efforts to develop robust methods, there is currently no consensus on how to account for temporary removals of carbon from the atmosphere in LCA. The authors present five method alternatives to GWP for accounting for the potential climate impacts of carbon sequestration and temporary storage of biogenic carbon in LCA and carbon footprinting; basically these are also used for accounting for emissions of GHG. Brandão et al. (2012) do not recommend a particular approach, but point to further research needs.

Pawelzik et al. (2013) also recognise that although controversial, the treatment of biogenic carbon storage is critical for quantifying the GHG emissions of bio-based materials in comparison with petrochemical materials. The authors recommend that a credit for carbon storage should be given to bio-based materials depending on product-specific life cycles and the likely time duration of carbon storage. Further, they highlight that co-product allocation can be complicated when including biogenic carbon, and should be chosen with care in order to ensure that carbon storage is assigned to the main product and the co-product(s) in the intended manner, and that stored carbon is not double counted.

5.7.2 Handling of the issue in the literature on biorefinery LCA

In the studies reviewed for the literature review, carbon cycle emissions are considered when they are a result of land use change (Cherubini & Jungmeier, 2010; Cherubini & Ulgiati, 2010; Lim & Lee, 2011; Souza et al., 2012). Emissions that are formed when the use of land is changed usually result from the decomposition of biomass above and below ground, as well as in the soil. In the studies where this is considered the most common time frame was around 20 or 30 years. The reason for this was that it was either based on recommendations by the IPCC (Cherubini & Jungmeier, 2010; Cheubini & Ulgiati, 2010), or it was the approximate life time of a certain energy crop (Souza et al., 2012). The studies that do not consider land use or land use change also do not consider the carbon cycle emissions, even when woody materials are used and there is a time lag between the capture of CO_2 in plants and its release to the atmosphere caused by the combustion of products (such as ethanol). Several studies conclude that one of the most important factors that contribute to GHG emissions is the reference land use scenario where planting energy crops on peat soils contributes to increased emissions (Lim & Lee, 2011; Souza et al., 2012). However, if degraded forest or degraded land is used for plantation of energy crops, positive effects can be seen (Cherubini & Jungmeier, 2010; Lim & Lee, 2011).

The majority of studies have fuels or other energy carriers as the main products. In the cases where bio-based chemicals are also produced, the storage of CO_2 in the products is not considered and they are treated as fuels even though their final use is not specified.

Some of the studies specify that GWP is calculated over a 100-year perspective (Souza et al., 2012), but without any further discussion about this. Other studies, e.g. those by Piemonte (2012) and Uihlein & Schebek (2009) use predefined models for impact assessment and thus the time perspective is not discussed explicitly.

5.7.3 Summary of requirements/recommendations on key issue in standards and guidelines

There are no methodological recommendations in the ISO 14040 and 14044 standards explicitly related to biogenic carbon. However, ISO/TR 14047 includes an example of impact assessment for LCA of systems including carbon sinks; carbon sequestration in this case is handled as a separate impact category.

The ILCD Handbook states that biogenic and fossil CO_2 and methane emissions and removals must be reported separately in the inventory results. Land use change-related CO_2 emissions from soil, peat etc. in all cases and from biomass and litter of virgin forests must be inventoried as "Carbon dioxide (fossil)". Emissions from biomass and litter of secondary forests must be inventoried as "Carbon dioxide (biogenic)". Uptake of CO_2 must e.g. be inventoried under “Resources from air”. Both the uptake of CO_2 from the atmosphere and the release of biogenic CO_2 are assigned characterisation factors for the impact assessment. Temporary carbon storage in e.g. products within the first 100 years from the time of the study should only be considered quantitatively if this is explicitly required to fulfil the goal of the study. For storage of carbon in e.g. wood products, the ILCD Handbook applies a “correction flow for delayed emission of biogenic carbon dioxide” (within the first 100 years) of -0.01 kg CO_2-eq. per kg and year. This means that if a wood product stores 1 kg of CO_2 for 80 years, it will result in -0.8 kg CO_2-eq in the impact assessment (1 x 80 x - 0.01).

In the PEF Guide, reporting of biogenic and fossil carbon is also done separately in the inventory. Furthermore, carbon removed from the atmosphere, e.g. as part of the process of growing wood, has a characterisation factor of -1 CO_2-eq. for global warming, while carbon released during the burning of wood has a characterisation factor of +1 CO_2-eq. Credits associated with temporary (carbon) storage or delayed emissions should not be considered in the calculation of the PEF for the default impact categories, unless otherwise specified in supporting PEF Category Rules. However, credits associated with temporary (carbon) storage or delayed emissions may be reported under “additional environmental information” if foreseen and justified in the goal/scope of the PEF study.

The PAS states that for food and feed, emissions and removals arising from biogenic sources that become part of the product may be excluded. However, emissions and removals of biogenic carbon used in the production of food and feed (e.g. in burning biomass for fuel), where that biogenic carbon does not become part of the product, must be accounted for. Non-CO_2 emissions arising from degradation of waste, enteric fermentation and biogenic component in material that is part of the final product, but is not intended to be eaten (e.g. packaging), must also be accounted for. For storage of carbon in products, the PAS suggests a rather complicated framework that may be used. If all the carbon emissions occur within the first year, the weighting factor is 1. If all the carbon emissions occur as a single emissions event between 2 and 25 years after the manufacture of the product, the weighting factor is calculated by multiplying the number of years of full carbon storage by 0.76 and dividing it by 100 years. In all other situations, the weighting factor is in principle the same as proposed by the ILCD Handbook (Pawelzik et al., 2013).

Some of the more specific guidelines also treat the biogenic carbon issue to a certain extent. For example in the PCR for basic organic chemicals, GHG emissions must be reported in two separate categories: (1) Excluding emissions of biogenic CO_2 and CO_2 sequestration or (2) excluding emissions of biogenic CO_2, but including CO_2 sequestration. In the RED, emissions of CO_2 from the fuel in use must be taken as zero for biofuels and bioliquids. However whether to include sustainability criteria for solid bioenergy in the RED is under discussion and the Joint Research Centre under the European Commission is initiating several workshops and studies on how biogenic carbon can be handled in such a framework (Agostini et al., 2013).

5.7.4 Discussion and recommendations

Some of the standards and guidelines reviewed have covered carbon in products, but not carbon accounting methods to capture the timing of emissions or carbon taken up in the biomass carbon cycle and how it should be treated in LCA.

Several research studies on temporal aspects of carbon in bioenergy systems have been conducted. A review of 18 recent studies by Lamers & Junginger (2013) concluded that many studies are full LCAs, that most of them include post-harvest carbon cycling (e.g. fossil fuel replacement or carbon storage in products), and that almost all use cumulative CO_2 as the metric for evaluation, i.e. not considering climate responses. However, it is unclear from that paper how the LCAs deal with e.g. choice of functional unit or handling of multifunctionality.

In policy, there is much debate about the carbon debt. In the US, there already is a suggested framework for biogenic carbon accounting (US EPA 2013). In the EU, there are discussions to incorporate biogenic carbon accounting for solid bioenergy into the RED. As the present method of accounting in the RED is very much ALCA, this will be an interesting challenge.

All of this points to the necessity of considering biogenic carbon in LCA related to land use change and carbon in products – the question can no longer be ignored. However, there is still no agreed method. As mentioned, GWP may not be the best method to reflect the climate impact due to timing of emissions. It may be necessary to consider other indicators for climate change impact assessments in addition to, or instead of, GWP. However, it will require time and resources for research to develop new indicators. Furthermore, the use and acceptance of the 100-year GWP as a metric is international and difficult to change (Brandão et al., 2012).

There are many different types of disciplines involved in the research on biogenic carbon, e.g. forest carbon models, climate models, LCA models and even economic models have been used to capture market dynamics. Also involved in the debate on biogenic carbon are e.g. NGOs, industry and policymakers. All of these researchers and stakeholders have different backgrounds against which they reflect upon the issue and can draw very different conclusions. It is indeed a major challenge to communicate across different groups and to get a full grip of all the different perspectives. Furthermore, the discussions on biogenic carbon accounting have brought to the agenda more questions which are important for LCA, such as differences in accounting method between different types of feedstock (e.g. residues vs. stem wood), stand vs. landscape level, what the reference land use should be, and market effects in the forestry sector.

Considering this, it is not easy to provide recommendations on how biogenic carbon and timing of emissions should be handled in LCA of biorefinery systems at the moment. However, there are a few conclusions we can draw that can be of use for LCA practitioners:

- Some databases distinguish fossil CO_2 from biogenic CO_2, but these do not automatically balance and do not provide sufficient data to capture timing of emissions
- The GWP metric has certain limitations in ability to reflect timing of emissions. However, as GWP is a widely accepted metric and there is no other standardised metric, we advise using GWP in the meantime.
- For delayed emissions due to storage of biogenic carbon in products, residues, wastes, carbon capture and storage etc., there are several different methods to choose from which can be incorporated within existing LCA methodology and the GWP metric. If there are significant differences in the emissions of CO_2 compared with the uptake in the system under study, this should not be ignored. At a minimum, this should be discussed in the study and efforts to quantify the impact should be made.

6 GENERIC BIOREFINERY EXAMPLE

To illustrate the consequences of different choices in an LCA study, we use the example of a hypothetical and very simplified generic biorefinery. Since this is not a case study, the results should not be interpreted as representative for a biorefinery; the figures are merely given to illustrate the LCA methodology.

As was concluded in previous sections of this report, many of the methodological choices necessary when performing an LCA of a biorefinery system are decided by the aim of the study. In this example, we do not connect the methodological choices to an aim, since we are not performing a case study, but simply illustrating how different methodological choices can change the outcome of the results. This gives us flexibility to show the results from different angles. Had we chosen to do a case study with a specified aim, we would have been restricted to certain methodological choices (e.g. if we had the aim of calculating the carbon footprint of a biorefinery product, it would be contradictory to use an input-based functional unit).

6.1 ASSUMPTIONS

Please note again that this is not a case study, but merely an example to illustrate some of the key issues regarding the LCA methodology, so the results should not be interpreted as representative for a particular biorefinery. The key issues illustrated by this biorefinery example are choice of functional unit, handling of multifunctionality and choice of data.

The biorefinery in this study is assumed to be self-sufficient in process energy and thus there is no extra input of energy to the biorefinery. The output products are biofuels, fine chemicals, electricity and heat (Figure 6.1).

Figure 6.1. Example of a generic biorefinery. The biorefinery is assumed to be energy self-sufficient, i.e. the required process energy is produced internally from biomass and/or via energy recovery within the plant. All numbers are for illustrative purposes only and are not intended to reflect a real situation.

For the calculations, a number of data were chosen, see Table 6.1 and Table 6.2.

Table 6.1. Input data on greenhouse gas emissions used in the biorefinery example, with specification of assumptions regarding average/marginal.

	Average	**Marginal**	
Emissions from production of inputs (average/marginal):			
Biomass (without/with carbon stock change)	0.5	2	kg CO_2-eq/kg
Refinery inputs (high/low estimate)	5	10	kg CO_2-eq/kg
Emissions reduction potential from replacing products (average/marginal):			
Biofuels replace fossil fuel (high/low estimate)	3.7	7.4	kg CO_2-eq/kg
Fine chemicals replace fossil-based chemicals (high/low estimate)	5	10	kg CO_2-eq/kg
Electricity replaces electricity (Swedish mix/fossil)	0.04	1	kg CO_2-eq/kWh
Heat replaces heat (Swedish mix 90% bioenergy/ 10% fossil)	0.09	0.2	kg CO_2-eq/kWh

Table 6.2. Prices of input materials and output products used in the biorefinery example.

	Price	**Units**
Input		
Biomass	160 000	SEK/GWh
Outputs		
Biofuel	8000	SEK/tonne
Fine chemical	20 000	SEK/tonne
Electricity	550 000	SEK/GWh
District heat	280 000	SEK/GWh

6.2 FUNCTIONAL UNIT

The functional unit can be based on either input or output products. In this example, three different output-based functional units are tested; 1 kg fuel, 1 kg fine chemicals, and 1 kg fuel and 0.167 kg fine chemicals. These are illustrated for both energy allocation and system expansion (Figures 6.2 and 6.3). For the calculations used to demonstrate the differences in functional units, average data are used. We do not show any input-based functional units, since we believe those answer questions that are broader than just biorefining, e.g. best use of land or feedstock, and here we want to focus on the biorefinery aspects.

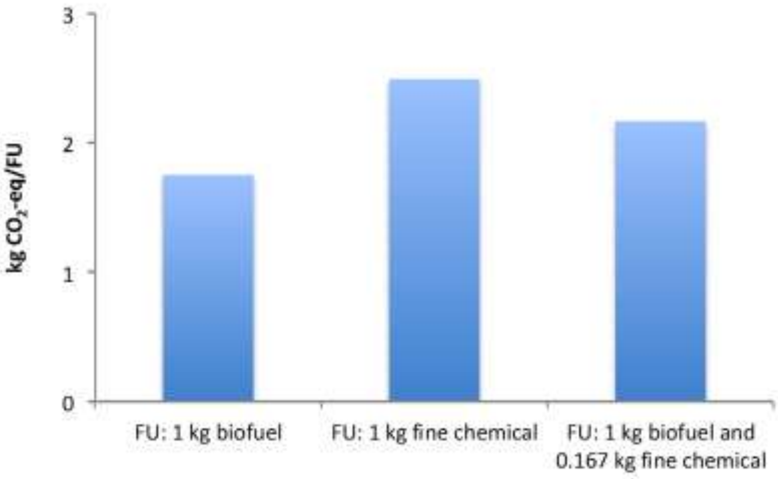

Figure 6.2. Greenhouse gas emissions when using different functional units for the biorefinery example (energy allocation).

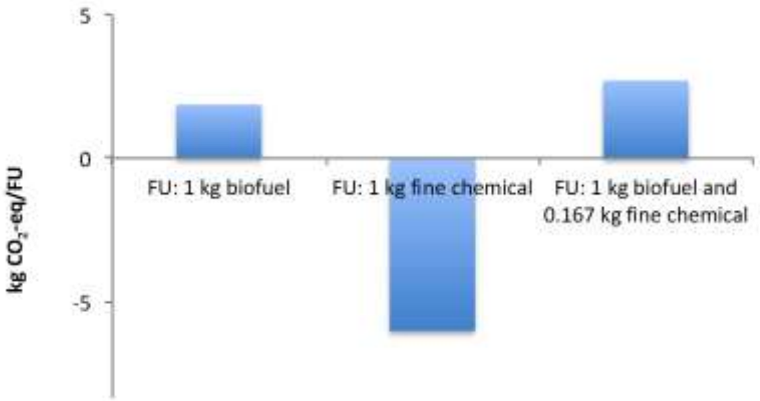

Figure 6.3. Greenhouse gas emissions when using different functional units for the biorefinery example (system expansion).

In this biorefinery example, the biofuel is a clear main product since it is produced in a large amount and contributes most to the total economic income. However, depending on the aim of the study, using the fine chemicals as the functional unit is also an alternative, e.g. for calculating the carbon footprint of the chemicals. As can be seen, the results are dependent on both the functional unit but to a high degree also on the how to handle multifunctionality. Choosing energy allocation means that the difference between the functional units is less, e.g. 1 MJ lower heating value of whichever product gets the same amount of emissions allocated to it (in Figure 6.2 the functional unit is mass-based, which explain why the functional units have different emissions). However, using system expansion requires more consideration, as discussed in the following section.

6.3 HANDLING OF MULTIFUNCTIONALITY

Figure 6.4 shows the GHG emissions for different methods of handling multifunctionality, divided over different types of functional units.

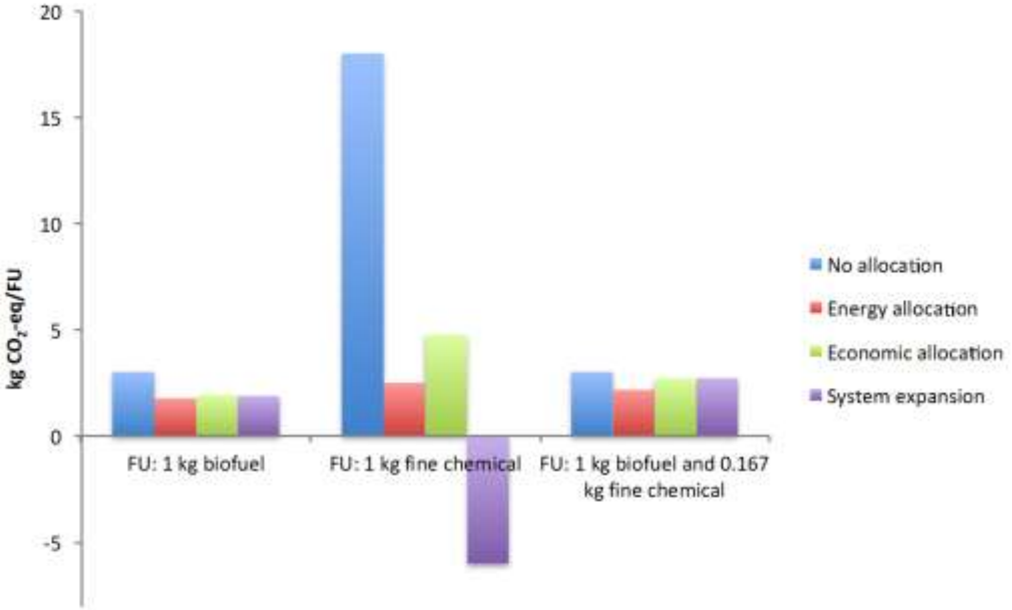

Figure 6.4. Greenhouse gas emissions when using different allocation methods for different functional units in the biorefinery example.

As can be seen from the diagram, for the functional unit 1 kg fine chemicals the choice of allocation method has a high impact on the results, while the other functional units show less sensitivity to choice of allocation method in this specific example. If 1 kg biofuel and 0.167 kg fine chemicals is used as the functional unit, there is little difference between the different allocation methods, including compared with no allocation.

If a product that is a smaller output from the biorefinery (in terms of quantity) is chosen as the functional unit, one should be aware that the results are very sensitive to the choice of whether to allocate or use system expansion through substitution and the choice of the avoided system. Consider e.g. the fine chemicals; if the quantity of fine chemicals is reduced and the other products increase, the minus value for fine chemicals will increase as there are more products that can replace other products. In other words, the lower the output, the better the environmental performance of the fine chemicals.

However, some products that are small in terms of quantity of output from the biorefinery can represent a large share of the economic output. In these cases, revenue would increase with increased production of the fine chemicals. Using system expansion with substitution would then show the trade-off between environmental and economic aspects and is therefore of interest. Economic allocation could also be a relevant choice in this case. Of course, using economic allocation introduces the uncertainty of choosing a representative price (Figure 6.5).

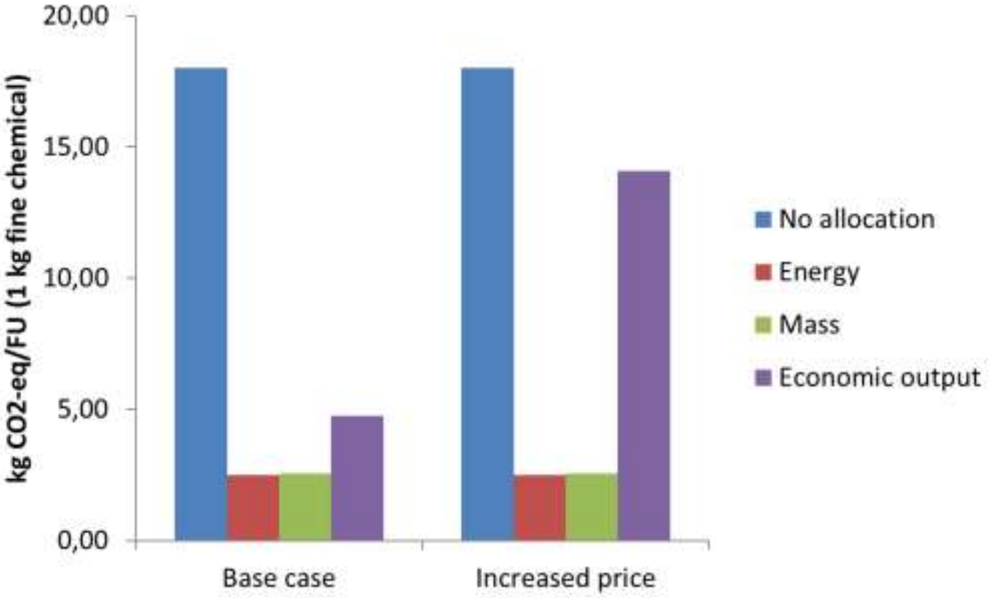

Figure 6.5. Greenhouse gas emissions from 1 kg fine chemicals in the biorefinery example when the price increases from 20,000 SEK/tonne (Base case) to 200,000 SEK/tonne (Increased price).

Besides the common approaches to handle multifunctionality (avoiding allocation, economic allocation, mass- and energy-based allocation) other non-standardised methods were mentioned earlier, such as allocation based on the potential for emission reduction, sub-process allocation and mixed methods.

The environmental load allocated to the different products for allocation based on GHG reduction potential and sub-process allocation compared with standard energy allocation is shown in

Table 6.3. In all scenarios, average data are used.

Table 6.3. Loads allocated to different products with different allocation methods. Note this is allocation to the total amount of products from the biorefinery example, e.g. in the energy allocation the products would carry equal amounts of the emissions if expressed per MJ product.

Product	**Energy allocation**	**GHG reduction potential**	**Sub-process allocation**
Biofuel	58%	76%	59%
Fine chemicals	14%	17%	16%
Electricity	6%	1%	5%
Heat	22%	6%	19%

As can be seen, the allocation load to the different products varies greatly between the methods (

Table 6.3). This suggests that choice of allocation method is very important and needs to be carefully considered in each LCA study.

6.4 CHOICE OF DATA

Another important key issue is the choice of data (average or marginal data), which can have a large impact on the results of a study. Figure 6.6 presents the results for different types of data when using different functional units and using system expansion.

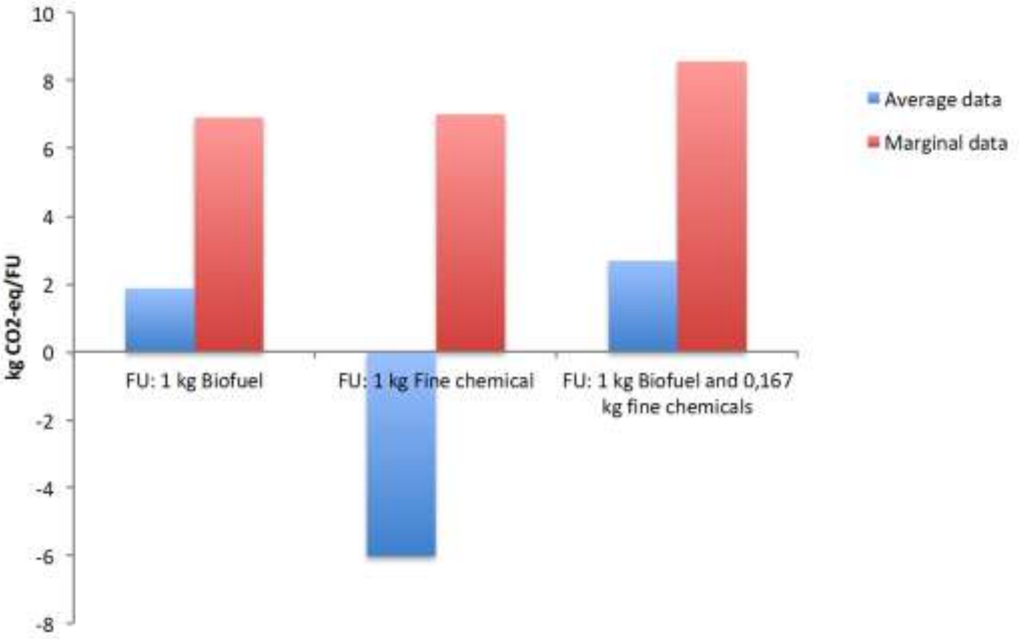

Figure 6.6. Greenhouse gas emissions using system expansion for the functional units studied in the biorefinery example when different types of data are assumed.

As can be seen, choice of data has a large impact on the results for all functional units when using system expansion. Again, we can also see that if the functional unit is not the main product in terms of quantity, e.g. fine chemicals, and if system expansion is used, the results are sensitive.

6.5 DISCUSSION AND CONCLUSIONS FROM THE BIOREFINERY EXAMPLE

The biorefinery example above shows how large the differences in results can be depending on a few methodological choices. Hypothetical data are used for the example and the results should only be seen as illustrations of principles and not as actual values for emissions. The key issues modelled are choice of functional unit, methods to handle multifunctionality and choice of data.

With this example, we illustrate that there can be great variation in the results caused by methodological choices. However, no general conclusions, e.g. that a certain type of methodological choice leads to certain outcomes, can be drawn. For example, it cannot be concluded that system expansion, marginal data or a particular functional unit always result in more or less favourable results, since this depends both on the biorefinery and reference systems under study. In other words, it cannot be concluded that system expansion always results in lower emissions than e.g. economic allocation.

As mentioned in section 5.3.4, one special type of system expansion applies to cases where the product studied is small in quantity, or of less importance for the overall existence of the biorefinery, i.e. a product which is not determining for the process. In a “normal” case where the product investigated is the main product of a biorefinery, system expansion should be applied to all co-products. However, if the product investigated is a small, non-determining product, the biorefinery process should not be included in the LCA because it is not affected by the use of the co-product. According to Weidema et al. (2009), the LCA should in these cases instead include the alternative use (or possibly waste management) of the co-product. Some products that are small in terms of quantity of output from the biorefinery can represent a large share of the economic output. In these cases, economic allocation could be a viable option if performing an ALCA. In our biorefinery example, this is clearly illustrated by the functional unit of 1 kg fine chemicals, which results in a large co-product credit when using system expansion (Figure 6.4) giving a large negative value.

7 DISCUSSION AND CONCLUSIONS

The main aim of this report was to identify key methodological issues for LCA of biorefinery systems, with the focus on energy and climate impacts. These key issues were then described and discussed in relation to a literature review of LCA case studies of biorefinery systems, and existing standards and guidelines.

We can conclude that the case studies reviewed here suffer from major inconsistencies in methodological choices, e.g. the functional unit is often not connected to the aim of the study. The problem is further exacerbated by the lack of proper documentation of assumptions in many studies. Furthermore, the large differences in methodological choices make comparisons among studies difficult.

We can also conclude that many of the standards and guidelines reviewed here provide general methodological recommendations. Some standards and guidelines give more specific methodological recommendations, but these often differ between the standards.

A second aim was, when possible, to make methodological recommendations on how to handle the key issues identified. Methodological recommendations can be of different types; they can be general or specific level and they can be based on philosophical/logical arguments (as often done in the scientific literature) or simply stated (as done in several standards and guidelines). In this report, we try to base all recommendations on logical argumentation and we make both general and (to a lesser extent) specific recommendations.

Providing specific recommendations for each key issue is difficult, since there are several plausible goals and intended applications of biorefinery LCA and methodological choices should always be connected to these. Furthermore, giving specific recommendations is complicated by the fact that several of the key issues are interconnected. In addition, there is a difference between general LCA issues and issues that are specific for biorefinery systems, and it is difficult to talk about one without the other. However, even though not all discussions and recommendations are biorefinery-specific, we do believe they are all relevant when performing LCAs of biorefinery systems.

It should also be noted that even when based on logical arguments, recommendations always involve a certain measure of subjectivity. The recommendations given here should in other words not be regarded as a universal truth, but rather as a reflection of the authors’ considered opinions.

Based on the review of existing standards and guidelines in Chapter 3, the literature review in Chapter 4, the discussions of the key issues in Chapter 5 and the hypothetical biorefinery example in Chapter 6, below we summarise the general and specific recommendations and some conclusions that we have drawn for each key issue, which can be helpful to consider while performing an LCA of a biorefinery system:

Key issue 1: Goal definition

- Specify the intended audience and intended application
- Specify the time horizon of the study. Note that there are several different kinds of time horizons in the same LCA: how long the results are valid for, how far into the future the analysis of the socio-technical system extends, how long a time horizon is used to calculate emissions

from landfills and the climate impact of greenhouse gases, etc. Ideally, all of these time horizons should be specified in the study's goal and scope definition

- Specify the research question and type of modelling approach (e.g. ALCA or CLCA). These two are linked, although this link is not always straight-forward in practice. It can be noted that what appear to be limited changes in the formulation of the research question can change an ALCA into a CLCA and vice versa.

Key issue 2: Functional unit

- The functional unit should be well chosen in relation to the research question.
- In comparative studies, it is important that the compared products have comparable functions.
- Several functional units can be applied in a study, but be aware that different functional units will give answers to different types of questions.

Key issue 3 and 4: Multiple outputs from biorefinery and feedstock production

- We recommended the following order of priority in how to handle multifunctionality of output products from biorefinery systems:
    - Avoid allocation by increasing the level of detail with a sub-process approach (applicable mainly for ALCA).
    - Avoid allocation by system expansion (applicable for both ALCA using average data and CLCA using marginal data).
    - Avoid allocation by choice of functional unit or system enlargement, if this is compatible with the aim of the study and the results can answers the research questions posed (applicable for both ALCA and CLCA).
    - If the ratio of the output products is flexible, use physical causation or a reasonable approximation of it (applicable for ALCA).
    - If the ratio between output products cannot be changed, use economic allocation. If this is not possible due to lack of information, make an arbitrary choice of a physical parameter (applicable for ALCA).
- Use the same method for handling multifunctionality when possible for both for the inputs and the outputs of the biorefinery system. If a mix of methods is used, this should be clearly stated, together with a justification of this choice.
- When calculating environmental load for biorefinery output products that are small in quantity, or of less importance for the overall existence of the biorefinery, i.e. products which are not determining for the process, the biorefinery process should not be included in a CLCA. Instead, the alternative use (or possibly waste management) of the co-product should be included. Some products that are small in terms of quantity of output from the biorefinery can represent a large share of the economic output. In these cases, economic allocation could be a viable option. If performing an ALCA, we advise LCA practitioners to acknowledge the importance of choice of method for handling multifunctionality and, for each study, to think through whether the method is in line with the intended audience, the intended application and the research question. We also advise LCA practitioners to be consistent and transparent about their choices

- It is advisable to test different methods of handling multifunctionality and underlying assumptions in the sensitivity analysis.

Key issue 5: Choice of data

- Data should be chosen relevant to describe the aim of the study. In general this means that average data are used for ALCA. For CLCA, the choice depends on the scale of change (for small changes marginal data, for larger changes average data could in some cases better reflect the change).
- We do not recommend mixing average and marginal data in a study unless there is an obvious reason (e.g. lack of data), which in that case should be clearly stated.
- If the choice is for average data, for the most important input data, it should be specified how many years the average is calculated over and what geographical region is assumed. If the choice is for marginal data, it should be specified how the marginal production was chosen and what time frame is assumed (e.g. short-term or long-term).
- Input data that are uncertain and have a major impact on the results should be considered in a sensitivity analysis.

Key issue 6: Land use change (LUC)

- If there is direct land use change, it should be included in both ALCA and CLCA studies.
- In principle, indirect land use change should be included in a CLCA. However, due to the uncertainties in economic modelling, a strict recommendation to always include it cannot currently be made. Use of this factor in a sensitivity analysis is encouraged, however.
- In principle, indirect land use change should not be included in an ALCA, since indirect land use change models quantify marginal effects.

Key issue 7: Biogenic carbon

- The global warming potential metric has certain limitations in terms of its ability to reflect timing of emissions. However, as GWP is a widely accepted metric and there is no other standardised metric, we advise using GWP in the meantime.
- For delayed emissions due to storage of biogenic carbon in products, residues, wastes, carbon capture and storage etc., there are several different methods to choose from which can be incorporated within existing LCA methodology and the GWP metric. If there are significant differences in the emissions of carbon dioxide compared with the uptake over time in the system under study, this should not be ignored. At a minimum, this should be discussed in the study and efforts to quantify the impact should be made.

A biorefinery LCA study is often more complex than a single product LCA. A general recommendation is therefore to perform a number of well-chosen sensitivity analyses and to include a comprehensive interpretation phase where the results are discussed. Since there are many methodological choices in a complex LCA, we also recommend being transparent and clearly stating all methodological and important data choices when performing a biorefinery LCA.

Besides the methodological key issues investigated in this report, there are several other issues to be dealt with when performing a biorefinery system LCA, e.g. choice of data is often critical since studies of biorefinery systems are often of a future-based character. Pettersson and Grahn (2013) identify a number of critical data choices when evaluating biorefinery systems: soil carbon dynamics, emissions related to handling and transport of feedstock, data for GHG intensity of electricity, utilisation degree and GHG intensity of excess heat, market restrictions of co-products, introduction of carbon capture and storage technology and type of fuel replaced in the case of biofuel production.

Pettersson and Grahn (2013) also point out the importance of choice of reference system. Those authors state that in systems analyses with the purpose of assessing global fossil GHG emissions, a baseline or reference system must be defined, based on an estimation of what would have occurred in the absence of the technology. This reference system should include alternative pathways for the production of all the co-products. Furthermore, alternative land use must also be included in the reference system, as well as demand-driven land use change, e.g. indirect land use change. However, the authors also stress that the choice of reference system depends largely on the aim and time frame of the study. The reference system should constitute a close alternative to the system studied, adopting the same technology level, e.g. if studying a future system the reference system should incorporate projected best available technology for the same time frame, rather than presenting average technology.

This report focused on energy and GHG emissions related key issues. However, there are many other sustainability issues connected to biorefinery systems. According to Sacramento-Rivero (2012), a biorefinery should be designed and operated in a sustainable way, i.e. environmentally benign, economically viable and socially responsible. For this purpose, Sacramento-Rivero (2012) developed a framework to evaluate the sustainability of biorefinery designs. The framework consists of five indicator categories covering issues of feedstock, process, oil-displacement capacity of products, environmental load and corporate commitment to sustainability (health, safety, social responsibility etc.). De Meester (2013) also proposes a larger framework for sustainability assessment of biorefinery systems, developing an indicator of sustainable development that weights the antropospheric benefit (quantified as satisfaction by a product or service and the labour quality and quantity), with the ecological burden (quantified as resource and emission impact). These factors are weighted with macro-scale aspects such as the human development index, unemployment rate and global ecological footprint. In an earlier publication, De Meester et al. (2011) developed a method to calculate the resource footprint of a bio-based product, integrating the trade-off between the carbon footprint of bio-based products and that of the land, water and minerals.

Pawelzik et al. (2013) looked into the critical aspects of bio-based materials, produced in e.g. biorefineries. They point out a number of important sustainability issues that should be included when evaluating these products: biogenic carbon storage, land use changes, soil degradation, water use, impacts on soil carbon stock and biodiversity. Those authors illustrate various approaches to account for these sustainability issues, but conclude that substantial methodological progress is necessary, although hampered by the complex and often case- and site-specific nature of impacts. Despite these difficulties, Pawelzik et al. (2013) recommend that LCA practitioners use preliminary approaches for including these impacts when evaluating bio-based materials.

The overall aim of this report was to identify and discuss key methodological issues for LCA of biorefinery systems and to make methodological recommendations on how to handle these key issues. The intention was to provide a better insight into the difficulties when performing LCA of biorefinery systems, help enhance consistency and comparability among future case studies and increase the credibility of the results. In this report we review much of the existing literature, standards and guidelines and attempt to clarify and make recommendations on a few of the key issues when performing a biorefinery LCA. We believe that if LCA practitioners have insights into these key issues, the quality of future LCA studies will be improved.

However, we can also conclude that many issues remain to be resolved. In this review, we found that the discussions on biorefinery systems and how they can be evaluated have brought many questions important for LCA to the agenda, including biorefinery-specific, biomass-specific and general LCA issues. For example, allocation problems are general for all LCA studies, but when studying biorefinery systems it becomes clear that there is more need for in-depth analysis of the methodological issues. Studying biorefinery systems also highlighted the need for more methodology development, e.g. on how to handle biogenic carbon. Our work is far from finished and we can expect a number of methodological advances to be made in LCA within the coming years.

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