HOW MUCH CAN BIOFUELS REDUCE GREENHOUSE GAS EMISSIONS?

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INTRODUCTION

The transport sector is today totally dominated by fossil oil-based fuels, above all gasoline and diesel. In order to decrease the fossil greenhouse gas (GHG) emissions from the transport sector, and the dependency on crude oil which is a scarce resource, one option is to introduce biomass derived motor fuels, here called biofuels. However, biomass is also a limited resource which makes efficient resource utilization essential. Therefore, the usage of biomass for biofuel production will have to be compared to other possible ways to use the limited biomass resource.

The biomass derived transportation fuels that are available today includes, for example, ethanol from sugar or starch crops and biodiesel from esterified vegetable oil. Biofuels based on lignocellulosic feedstock are under development. The two main production routes are gasification of solid biomass or black liquor followed by synthesis into, for example, methanol, dimethyl ether (DME), synthetic natural gas (SNG) or Fischer-Tropsch diesel (FTD), and ethanol produced from lignocellulosic biomass. Potential lignocellulosic feedstocks include forest residues, waste wood, black liquor and farmed wood. What feedstock will come to predominate in a country or region will very much depend on local conditions.

When evaluating the greenhouse gas emission balances or overall energy efficiency of introduction of new biomass-based technologies, it is important to adopt a life cycle perspective and consider the impact of all steps from feedstock to final product(s). There are a number of different approaches that can be used for this purpose, and different choices can be made for each step from feedstock to product. Thus, different studies can come to very different conclusions about, for example, the climate effect for a given product and feedstock. These issues have been heavily debated, particularly regarding evaluation of different biofuel routes. Parameters identified as responsible for introducing the largest variations and uncertainties are to a large part connected to system related assumptions, for example system boundaries, reference system, allocation methods, time frame and functional unit. The purpose of this chapter is to discuss a selection of these issues, in order to give the reader an improved understanding of the complexity of evaluating GHG emission balances for different biorefinery products, with biofuels used as an example.

ASSESSING GHG EMISSIONS FROM BIOFUEL SYSTEMS

The evaluation of energy efficiency and climate impact of biofuels and other transportation options is usually done from a well-to-wheel

(WTW) perspective. A WTW study is a form of life cycle analysis (LCA) that is normally limited to the fuel cycle, from feedstock to tank, together with the vehicle operation, and that typically focuses on air emissions and energy efficiency[1] (see also discussion in Chapter 1 and Figure 1.2). A WTW analysis generally does not consider the energy or the emissions involved in building facilities and vehicles, or end of life aspects. The main reason for this simplified life cycle analysis is that the fuel cycle and vehicle operation stages are the life cycle stages with the greatest differences in energy use and GHG emissions compared to conventional fuels. In this chapter, WTW analysis will be used to illustrate different methodological approaches and issues regarding the different steps from feedstock to product. However, the discussion can easily be generalized to apply to other products as well.

Figure 7.1 illustrates possible main energy and material flows between the main steps in a WTW analysis of biofuels. If biofuel is produced integrated with an industrial process, such as a pulp mill, the flows represented are net differences compared to a reference case representing the industrial process as it would have been non-integrated with the biofuel plant.

The first step in a WTW chain includes operations required to extract, capture or cultivate the primary energy source, in this case biomass feedstock. Thereafter, the biomass needs to be transported to the biofuel production plant. At the biofuel production plant, the biomass is processed into biofuel and possibly also other products such as electricity, heat or other co-products. The biofuel production plant may have a deficit of electricity. The biofuel production process may also have a net deficit of steam. However, this is usually handled within the plant by firing additional fuel, or by using internal co-products. Thus, the biofuel plant will not have a heat deficit. It could also be possible to capture CO_2 in the process (see further below). The produced biofuel is then distributed to refueling stations. The final step includes the vehicle operation where the biofuel is used to fuel the vehicle's powertrain. A well-to-tank (WTT) analysis includes the steps from feedstock to tank, and thus does not include the vehicle operation stage. This type of analysis could be used for example when comparing different ways to produce a specific biofuel. Most studies are focused on direct effects from physical flows in the WTW chain, but some studies also include an estimation of contributions to system change[2] (see also discussion in Chapter 1).

CO-PRODUCTS AND ALLOCATION PROBLEMS

How to allocate the distribution of environmental burdens between the different outputs of a process producing more than one product has been one of the most controversial and heavily debated issues of LCA methodology, as it can have significant impact on the results.[3] Several reviews of WTW studies of various biofuels show that co-product allocation is one of the key issues that influence the GHG and energy efficiency results.[4] (See also examples in Chapters 6 and 8 and the general discussion Chapter 1.)

Allocation can be done on the basis of physical properties (mass, energy content, volume, etc.)

1 MacLean, H.L and Lave, L.B. (2003). Evaluating automobile fuel/propulsion system technologies. Progress in Energy and Combustion Science 29(1):1-69. And Edwards, R. et al. (2007). Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c. JRC, EUCAR and CONCAWE.

2 See for example Sandén, B. A. and M. Karlström (2007). «Positive and negative feedback in consequential life-cycle assessment.» Journal of Cleaner Production 15(15): 1469-1481 and Hillman, K. (2008). Environmental Assessment and Strategic Technology Choice – The Case of Renewable Transport Fuels. PhD Thesis. Department of Energy and Environment, Division of Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden.

3 See for example Finnveden, G. et al. (2009). Recent developments in Life Cycle Assessment. Journal of Environmental Management 91(1):1-21.

4 Börjesson, P. (2009). Good or bad bioethanol from a greenhouse gas perspective – What determines this? Applied Energy 86(5):589-594.
Delucchi, M. (2006). Lifecycle analyses of biofuels. Draft report. Institute of Transportation Studies, University of California, Davis.
Larson, E. (2006). A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development 10(2):109-126.
Fleming, J.S., et al. (2006). Investigating the sustainability of lignocellulose-derived fuels for light-duty vehicles. Transportation Research Part D-Transport and Environment 11(2):146-159.

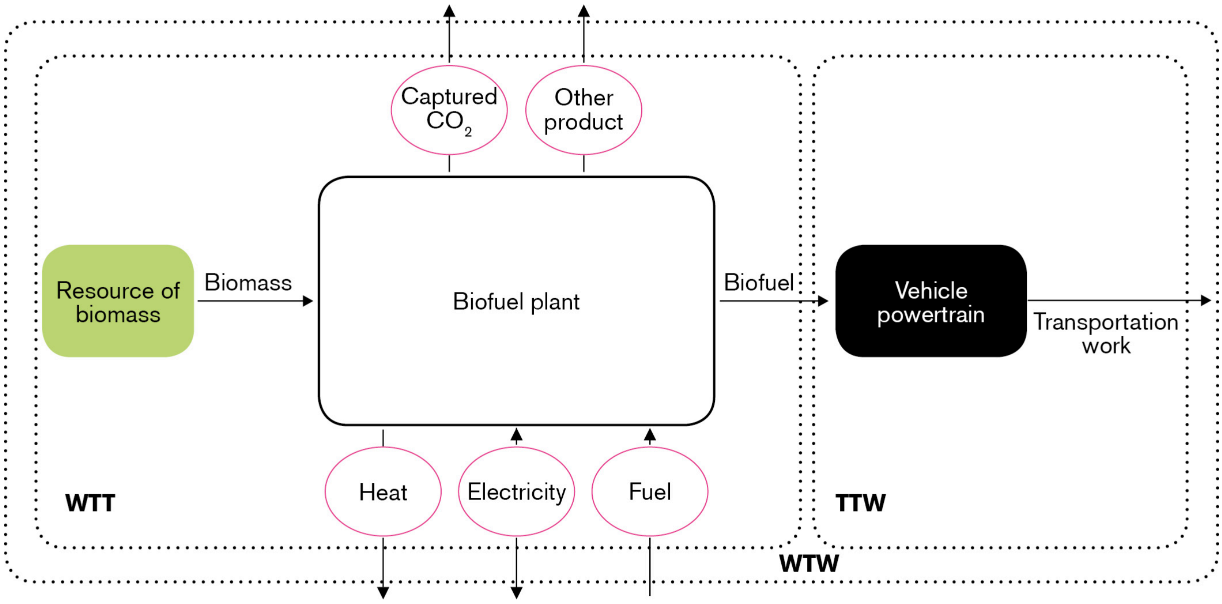

Figure 7.1 Simplified illustration of possible main energy and material flows between the main steps in a well-to-wheel (WTW) analysis of biofuels, where also the well-to-tank (WTT) and tank-to-wheel (TTW) parts are illustrated.

or on the basis of economic value. Allocation can also be avoided through system expansion or substitution, that is, expansion of the system's boundaries to include the additional functions of all co-products. Co-product credits can sometimes also be handled by recalculating co-product streams into the same raw material as used for the main product and then subtracting the calculated amount from the raw material usage.

Using physical or economic allocation, or recalculation of co-product streams, to handle coproduced electricity, heat or other co-products, may hide wider system implications. Furthermore, the size of certain co-product markets are limited and this also needs to be taken into consideration, especially for large scale technology implementation.[5] Therefore, to fully see the impact of a biofuel technology one has to estimate the impact of the co-products by using system expansion, as recommended by for example the ISO standard.[6]

5 Hillman, K. M. and B. A. Sandén (2008). "Time and scale in life cycle assessment: The case of fuel choice in the transport sector." International Journal of Alternative Propulsion 2(1): 1-12.
6 ISO, 2006. Environmental Management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006), European Committee for Standardization.

REFERENCE SYSTEM

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 technology's absence. The reference system should include alternative pathways for the production of transportation fuel as well as for electricity, heat, and other coproducts. If the feedstock production results in land-use change, an alternative land use must also be included in the reference system. Similarly, when the same feedstock is in demand for other purposes an alternative biomass use should be included, as the increased use of a resource with constrained production volume results in less of that resource being available for other parts of the system, which can cause important effects that may significantly affect the results.[7]

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 studied system, adopting the same technology level. Thus, if the study includes technology

7 Merrild, H. et al. (2008). Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. Resources Conservation and Recycling 52(12):1391-1398.

for which commercialization is not imminent, the reference system should incorporate projected best available technology for the same time frame rather than presenting average technology.

Several studies show that the reference system selected results in a large degree of variation in the WTW GHG emissions, and that it may have consequences for the ranking order of the studied biofuels.[8] This makes it reasonable to include several different reference systems (scenarios) in biofuel WTW studies, or studies of other biomass conversion systems, in particular when studies are made for a future situation.

FUNCTIONAL UNIT

In studies where different systems are compared, the functional unit must be carefully selected and defined. When biofuels are compared to each other and/or to fossil-based motor fuels, the service provided – such as the distance travelled – can be chosen as the functional unit.[9]

If biofuels are to be compared with other bioenergy applications, another functional unit must be chosen. Several studies emphasize the importance of considering the resource that will be limiting, for example in order to reach reduction of fossil GHG[10]. For bioenergy systems, this will typically be the available amount of biomass or the available land for biomass production. If the feedstock is the same in all considered cases, for example forest residues, the relative order of the results will of course be the same when reporting per ha and year as when reporting per unit biomass. When different feedstocks are compared, however, land use efficiency becomes increasingly important, since the land area available for biomass production is limited (see discussion in Chapter 1 on vertical system expansion and the different dimensions in Figure 1.2).

The choice of functional unit is associated with several methodological considerations. If, for example, the results are presented as driving distance per ha, adjustments of included processes need to be made by recalculation to the considered type of biomass. Thus, all flows leaving or entering the biofuel system are assumed to replace or originate from biomass-based technologies. This may lead to the inclusion of unlikely components in the system studied. For example, surplus heat from a biofuel system in current central Europe are more likely to replace fossil-based than biomass-based district heat.

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. To counter this problem, the functional unit can be expanded to include all energy carriers or products produced.[11] Using the method of an expanded functional unit, however, may lead to the inclusion of unlikely components in the system studied, since for example inclusion of stand-alone plants for production of products that are not produced in this way could be required in order for the systems to produce the same output or function. Furthermore, this approach is suitable when comparing only a few systems. With increasing number of systems, the difficulty to define relevant systems producing the same output or function increases (extensive horizontal system expansion, see Chapter 1).

8 See for example Hillman, K.M. and Sanden, B.A. et al. (2008). Time and scale in Life Cycle Assessment: The case of fuel choice in the transport sector. International Journal of Alternative Propulsion 2(1):1-12 Wetterlund E, Pettersson K. et al. (2010). Implications of system expansion for the assessment of well-to-wheel CO_2 emissions from biomass-based transportation. International Journal of Energy Research; 34(13):1136-1154.

9 See for example Edwards, R. et al. (2007). Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c. JRC, EUCAR and CONCAWE.

10 See for example Schlamadinger, B. et al. (1997). Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass & Bioenergy 13(6):359-375 and Gustavsson, L. et al. (2007). Using biomass for climate change mitigation and oil use reduction. Energy Policy 35(11):5671-5691.

11 See for example Schlamadinger, B. et al. (1997). Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass & Bioenergy 13(6):359-375. and Gustavsson, L. And Karlsson, Å. (2006). CO_2 mitigation: On methods and parameters for comparison of fossil-fuel and biofuel systems. Mitigation and Adaptation Strategies for Global Change 11(5-6):935-959.

CRITICAL ISSUES FOR SPECIFIC ENERGY AND MATERIAL FLOWS

Unless fallow land or waste biomass is used, both direct and indirect land-use changes associated with biomass usage can cause large increases of GHG emissions (see also Chapter 4). However, also for waste biomass, such as forest residues, soil carbon dynamics can have a substantial impact. When logging residues are removed from the forest, the soil carbon stock will in general be lower than if the residues were left in the forest to decompose, particularly if looked at over a short time period. The magnitude of the impact of the soil carbon decrease is, however, uncertain.[12]

How large emissions are and how much energy is needed for the transportation, handling and distribution of the feedstock, will depend on the type of biomass, the size of the production plant, and whether it is possible to supply the plant with biomass from the local region, or whether biomass must be transported from a larger area or even imported from another country.

A net deficit or surplus of electricity can be handled in different ways, as discussed. When the system is expanded to include the electricity grids, one can use the average GHG or energy intensity of the entire system, the build margin or the operating margin.[13] What is a relevant grid electricity mix or marginal technology to use is dependent on, for example, the time frame of the study, if one compare technical systems or impact of system intervention, and which cause-effect chains that are considered to be relevant in the given decision context (see discussion in Chapter 1). An electricity deficit or surplus can also be handled by assuming that the electricity is produced in a biomass-fired power plant. For production processes with a deficit of electricity, the calculated amount of biomass for electricity production is added to the amount of biomass feedstock, and vice versa for processes with a surplus of electricity. When doing this, the assumed biomass-to-electricity efficiency becomes important.[14]

Biorefinery excess heat could be used in district heating systems. However, in order for this to be possible the production plant has to be located within reasonable distance from a district heating system. The alternative district heating production is very much dependent on local conditions, such as the heat demand and availability of different fuels. For example, in a Swedish perspective a biomass CHP plant is often considered as a technique competing against industrial excess heat.[15] When excess heat replaces CHP heat, biomass is released for other uses. Thus, it is important to be able to attribute a GHG emission credit for the indirect contribution to a decreased use of biomass. In a European perspective, coal-based CHP could be considered as a technique competing against industrial excess heat[16]. (See Chapter 8 for a thorough discussion on the use of excess heat in district heating systems.)

Even if the markets for other possible co-products such as different chemicals, are not local – as is the case for heat – it is important to consider the size of the market (see Chapter 3). Different co-product credits could for example be given depending on the degree of market penetration of the studied biofuel and its co-products.[17]

12 Holmgren, K. et al. (2007). Biofuels and climate neutrality - system analysis of production and utilisation, Elforsk: Stockholm, Sweden.

13 See for example Kartha, S. et al. (2004). Baseline recommendations for greenhouse gas mitigation projects in the electric power sector. Energy Policy 32(4):545-566, Schlamadinger, B. et al. (2005). Optimizing the greenhouse gas benefits of bioenergy systems. 14th European Biomass Conference. Paris, France and Ådahl, A. And Harvey, S. (2007). Energy efficiency investments in Kraft pulp mills given uncertain climate policy. International Journal of Energy Research 31(5):486-505.

14 See for example Joelsson JM. et al. (2009) CO_2 balance and oil use reduction of syngas-derived motor fuels co-produced in pulp and paper mills 17th European Biomass Conference & Exhibition, Hamburg, Germany, 29 June – 3 July, 2009.

15 See for example Jönsson J et al. (2008). Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden – Part 2: Results for future energy market scenarios. Energy Policy 2008;36(11):4186-4197.

16 Axelsson, E. and Harvey, S. (2010). Scenarios for assessing profitability and carbon balances of energy investments in industry. AGS Pathways report 2010:EU1. AGS, The alliance for global sustainability. Pathways to sustainable European energy systems, Göteborg, Sweden, 2010.

17 See for example Hillman, K.M and Sandén, B.A. (2008). Time and scale in Life Cycle Assessment: The case of fuel choice in the transport sector. International Journal of Alternative Propulsion 2(1):1-12.

The possibility of CCS could affect the CO_2 emissions of a biofuel system, or other biomass conversion systems, both directly – if CO_2 capture is possible in the production process (see Chapter 2) and the plant is located near an infrastructure for CCS – and indirectly if, for example, CCS is implemented in coal power plants (lowering CO_2 emissions from grid electricity).

The final steps in the WTW chain include distribution, dispensing and usage of the biofuels. Today oilbased fuels, above all gasoline and diesel, totally dominate the transport sector and different biofuels are likely to replace these fuels. However, since crude oil is a considerably limited resource, the dominant transportation fuels of the future could be coal-based. For example, FTD produced via gasification of coal, with as well as without CCS, could be considered for the future reference transportation system. Most studies assume that produced biofuels replace gasoline and diesel, whereas other studies also consider replacement of other fuels.[18] These comparisons are still relevant also if electricity is used to a larger extent in the transportation sector. Pure electrical vehicles are primary an option for personal transportation, not for heavy vehicle, and can thus only be expected to cover a part of the transportation need. For heavy vehicles, plug-in hybrids using an internal combustion engine running on biofuels or fossil-based fuels to complement the electric drive train could be an option.

AN ILLUSTRATIVE EXAMPLE

As is apparent from the descriptions in this chapter, to be able to calculate the GHG emissions for biofuels a number of choices have to be made. In this section, an example of GHG emission balance for the use of DME will be presented that illustrate how different choices regarding perhaps the most critical issue, the reference system, affect the avoided GHG emissions from biofuels.

Figure 7.2 shows how the reduction of CO_2 emissions for two biofuel production processes producing DME via gasification varies dependending on assumptions about the future reference system.[19] The difference between the processes are that in Process 1 (blue bars) the production of DME is not maximized and the plant co-produces considereable amounts of electricity, resulting in a significant electricity surplus, while in Process 2 (red bars) the DME production is maximized, resulting in less produced electricity and in total an electricity deficit.[20] There is a possibility to capture and store CO_2 from both processes. Three reference transportation options are considered: oil-based transportation fuel (in this case diesel) and production of FTD via gasification of coal with and without CCS.[21] Four different electricity production technologies are considered: coal, NGCC (natural gas combined cycle), coal with CCS and a CO_2-neutral option (for example wind power).[22] As Figure 7. shows, the reduction of CO_2 emissions varies significantly depending on the assumptions about future reference transportation and electricity production systems.

Combinations that are considered to be less probable have been omitted from Figure 7.2. This significantly reduces the number of possible outcomes. If CCS is not implemented in the power sector with its very large emission point sources, it is assumed unlikely that an infrastructure for CCS is established. Thus, both CCS in the biofuel processes and in connection with motor fuels produced from coal are assumed less probable if the electricity production are coal or NGCC without CCS. On the other hand, if the electricity production in the reference system is coal with CCS, it is assumed unlikely that CO_2 is not captured in the biofuel processes and in connection with motor fuels produced from coal

18 See for example Andersson E (2007). Benefits of Integrated Upgrading of Biofuels in Biorefineries – System Analysis. PhD Thesis. Department of Energy and Environment, Division of Heat and Power Technology, Chalmers University of Technology, Göteborg, Sweden, and Edwards, R. et al. (2007). Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c. JRC, EUCAR and CONCAWE.

19 For a discussion on what it would take to commercialize such a technology see Chapter 9.

20 Process 1: 100 MW biomass input resulting in 34 MW DME and 13 MW electricity. Process 2: 100 MW biomass and 6 MW electricity input resulting in 65 MW DME. Possible to capture 46 kg $CO_2/GJ_{biomass}$ in each process at a cost of 70 MJ electricity.

21 Oil (diesel):77 kg CO_2/GJ_{fuel}, Coal with CCS (FTD): 92 kg CO_2/GJ_{fuel}, Coal (FTD): 166 kg CO_2/ GJ_{fuel}.

22 Coal: 201 kg CO_2/GJ_{el}, NGCC: 104 kg CO_2/GJ_{el}, Coal with CCS: 38 kg CO_2/GJ_{el}, CO_2-neutral: 0 kg CO_2/GJ_{el}.

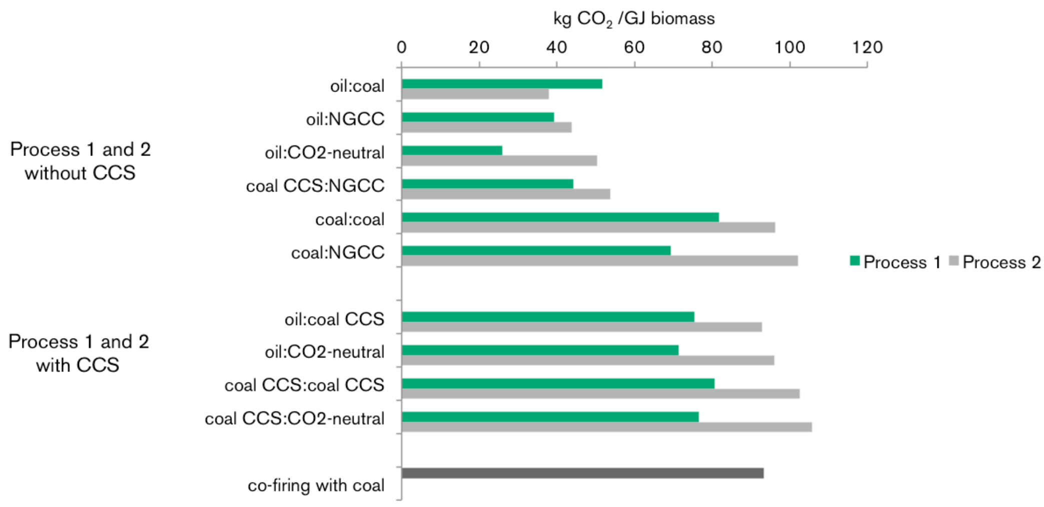

Figure 7.2. Reduction of CO_2 emissions for two biofuel production processes producing DME via gasification (see text for process descriptions). The impact of different assumptions regarding reference transportation and electricity production systems is illustrated (e.g. "oil:coal" refers to transportation based on oil and electricity based on coal). The potential CO_2 emission reduction if biomass is co-fired with coal is also shown.

since CO_2 in this cases are seperated as part of the processes. An electricity system dominated by CO_2-neutral technologies will probably be an indication of strong policy instruments promoting reduction of GHG in the atmosphere. Hence, if the electricity production in the reference system is CO2neutral, a reference transportation technology based on coal (without CCS) is considered less probable.[23]

Process 1, with a surplus of electricity, benefits from a high CO_2 emitting electricity production technology, while Process 2, with a deficit of electricity, benefits from a low CO_2 emitting electricity production technology. Both processes benefit from a high CO_2 emitting transportation technology, however Process 2 are benefited to a larger extent. As can be seen in Figure 2, it is only for one of the probable reference systems, the one with oil in the transport sector and coal in the electricity sector that Process 1 leads to the largest reduction of CO_2 emissions. This reference system is representative for the current situation and therefore frequently used in these types of assessments. However, as for the example here, if it is future implementation of technologies that are currently under development, it is important to make some kind of sensitivity analysis or include a discussion regarding the influence of different assumptions regarding the future reference system. This is however not always done. Furthermore, the assumptions regarding the reference system, or other parameters that influence the results, can naturally be chosen in order to obtain specific results, for example in order to promote a certain technology or product. Thus, when interpreting results from WTW studies, or studies

23 Any larger real world system is likely to display a mix of technologies. This applies to the installed capacity as well as to annual additions to capacity. For example, in 2011 the additions to the European electricity supply comprised of a mix of solar PV, natural gas power, wind power, coal power and a range of minor sources including biomass power as well as a decrease of fuel oil and nuclear power (European Wind Energy Association, 2012. Wind in power: 2011 European statistics).

estimating the possibilities for GHG emission reduction from other biorefinery products, it is very important to be aware of the assumptions made in the study about the surrounding system and how they affect the potential to reduce GHG for different technologies.

The examples of results presented here show that substantial reductions of GHG emissions can be achieved by substituting fossil-based motor fuels with certain biofuels. However, biomass is a limited resource and it is not possible to solve the whole climate problem by substituting biomass for fossil fuels. Therefore, it is important to compare the usage of biomass for biofuels with other ways to use the limited biomass resource. In Figure 7., the CO_2 reduction potential of the biofuel processes is compared with using biomass in a coal power plant (co-firing biomass and coal). As can be seen in Figure 7., the reduction of CO_2 emissions are in most, but not all, more probable cases larger if biomass is used in the coal power plant than in the biofuel processes. However, it should here be emphasized that reduction of global CO_2 emissions is, as stated, not the only driving force for introducing biofuels. Reducing the dependency of crude oil is also a major driving force. In a larger perspective, since it might be land available that eventually limits the simultaneous use of biomass in a multitude of high volume applications, the land use efficiency of biomass for different applications can also be compared to other types of land-use such as electricity production in solar power plants (see Figure 1.2 and Chapter 4). [24]

CONCLUDING REMARKS

When evaluating the GHG emission balances or overall energy efficiency of introduction of new biomass-based technologies, it is important to adopt a life cycle perspective and consider the impact of all steps from feedstock to final product(s). There are a number of different approaches that can be used for this purpose, and different choices can be made for each step from feedstock to product. Thus, different studies can come to very different conclusions about, for example, the climate effect for a given product and feedstock. This chapter has presented and discussed different methodological approaches and choices for the different steps in the life cycle in order to give the reader an improved understanding of the complexity of evaluating GHG emission balances for biorefinery products, with biofuels used as an example.

The choice of for example allocation method, reference system and functional unit influence the potential to reduce GHG emissions. Therefore, it is very important that the calculations are transparent and the reader is able to understand the underlying assumptions. It is also important to make a sensitivity analysis and show how different assumptions regarding for example the reference system influence the results. This is especially important when evaluating technologies as part of future systems, since the actual conditions for such systems are highly uncertain (see also discussion in Chapter 1). However, it is important to be consistent and clearly distinguish between likely and unlikely combinations of different reference technologies. Using different assumptions will naturally influence the absolute potential for GHG emissions reductions from biofuels, and other biomass-based products, but it could also influence the ranking of different biofuels, and of biofuels in relation to other biomass-based products. However, some technology pathways can hopefully be identified as more robust than others, giving a guideline as how to use the limited biomass resource in order to maximize the climate benefit.

24 For a comparison of area efficiency of biofuels and solar-electric propulsion, see for example Kushnir, D. and B. A. Sandén (2011). "Multi-level energy analysis of emerging technologies: A case study in new materials for lithium ion batteries." Journal of Cleaner Production 19(13): 1405-1416.