Comparing new Swedish concepts for production of second generation biofuels – evaluating CO₂ emissions using a system approach

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1. Introduction

Biomass based automotive fuels are needed both to meet today’s climate-change mitigation goals and to lower dependency on fossil oil. As there are several alternative biofuels, the need to make comparisons in a well-to-wheels (WTW) perspective is obvious. Since biomass is a limited resource, figures of merit concerning energy efficiency and climate impact are of great importance. The results from these types of comparisons can for instance be used as a basis for decision-making for politicians. However, comparisons are generally hard to make with adequate transparency, since many assumptions are needed for the calculations, especially about future surrounding systems.

The aim of this study is to use a system approach to show how assumptions about systems surrounding the fuel production affect the calculations of climate impact for different biofuels. The focus is on second generation biofuels and the three technologies represented by pilot plants in Sweden, i.e. black liquor gasification (BLG), solid biomass gasification (BMG) and lignocellulosic ethanol (EtOH). For comparison, co-production of electricity and heat in a BIGCC (Biomass Integrated Gasification Combined Cycle) is considered.

2. Difficulties when comparing future biofuels

When calculating figures of merit such as total energy efficiency and climate impact for future biofuels, a number of assumptions have to be made. Since second generation biofuel technologies are still under development there are uncertainties about both process efficiencies and vehicle powertrains. Visions for the biofuel production concepts developed in Sweden often include integration, especially heat integration, of the production plants with other industrial or district heating systems, which further complicates assumptions regarding the production process. While this will not be an option at all potential production sites, it is nevertheless an aspect that needs to be considered. Evaluation of energy efficiency and climate consequences necessitates assumptions about surrounding systems, e.g. electricity generation, heating and transportation systems. Depending on the assumptions for the development of these systems, different results are obtained when comparing future biofuels with each other and with other biomass applications, e.g. production of heat and electricity. Larson [1] states that the wide range of reported greenhouse gas (GHG) emissions results from LCA studies evaluating liquid biofuel systems is due in part to the wide range of plausible values for key input parameters, and that one of the most significant parameters is the allocation method used for by-product credits. There are a number of ways to handle by-product credits, e.g. allocation based on energy, weight, product market value etc. It is also possible to expand the system to include the by-product systems and give the biofuel a credit corresponding to the energy use and emissions that would have been caused by producing the commodities that can be replaced by by-products, by conventional routes.

One of the most widely spread WTW-studies was made by the EU JRC [2]. While being very detailed, with a large number of different fuels, both of fossil and renewable origin (including the technologies considered here), it is not completely consistent in its system view. In the study, the biofuel production processes are made electricity neutral by recalculating electricity into biomass, using the nearest equivalent wood-to-electricity process. For production processes with a deficit of electricity the calculated amount of biomass is added to the amount of biomass feedstock, and vice versa for processes with a surplus of electricity. In spite of the importance of comparability being accentuated in the study, different electricity production processes are considered for different biofuel routes. It should also be noted that for all other instances of electricity use in the study, EU mix 2010 is used. Another interesting aspect of the EU JRC study is that although CO₂ capture and storage (CCS) is investigated for some routes, none of the routes considered are biofuel routes and it is never mentioned that CCS could be an option for those cases as well.
3. Method and assumptions

For the two gasification technologies considered in this study, only the case of DME production is considered. To compare the efficiency of making motor fuels with other biomass use, a BIGCC case is included in the study. The four cases (BLG, BMG, EtOH and BIGCC) are used to exemplify how different assumptions about the surrounding system influence the results when evaluating total CO₂ emissions consequences. Since the main raw material is assumed to be forest residuals no other GHG emissions than CO₂ are considered.

3.1. Method for evaluating CO₂ emissions

The four cases are evaluated on the basis of net CO₂ consequences, by assuming that the net flows of energy and material entering or leaving the plant cause a change in the surrounding system. This method is similar to the system expansion by-product allocation method mentioned in the previous section and used by e.g. [2]. The difference from [2] is that here the system expansion method is used to evaluate the CO₂ emissions of all flows, not only the by-product flows. For example, if the biofuel production plant has a surplus of electricity, this causes a decreased marginal electricity production. In case of an electricity deficit of the plant, marginal electricity production increases. To take future integration possibilities into account, waste heat is also considered, and is assumed to replace alternative district heating production. Since biomass is a limited resource, biomass used for biofuel production lessens the amount of biomass available for other applications in the system. This is accounted for by assuming a marginal biomass usage.

To assess net CO₂ emissions, four energy market scenarios for 2020 developed by Axelsson et al. [3] are used. The scenarios reflect different possible future energy market conditions and are based on assumptions on fossil fuel prices and policy instruments, such as CO₂ emissions charge. For electricity production, the marginal technology in each of the scenarios is assumed to be the technology with the lowest production cost. The marginal biomass usage is determined by the intersection of the demand and supply curves for biomass. No marginal transportation technology is included in the scenarios in [3]. Here, the proposed EU target for 2012 [4] for new cars is used as base value. To account for CO₂ emissions related to other steps of the WTW-chain, values from [2] for emissions from production and distribution of gasoline are added to the base value of 130 g CO₂/km. For district heating the alternative production is assumed to be a modern biomass boiler with a heat efficiency of 115 %LHV. This releases biomass for other uses, in this case the marginal biomass usage, as defined in the scenarios. Table 1 shows the CO₂ emission values used.

<table>
<thead>
<tr>
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<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
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<tr>
<td>Fossil fuel price level</td>
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<td>High</td>
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<tr>
<td>CO₂ emission charge*</td>
<td></td>
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<td>Electricity production</td>
<td>NGCC</td>
<td>Coal with CCS</td>
<td>Coal</td>
<td>Coal with CCS</td>
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<tr>
<td>[kg CO₂/MWh]</td>
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<td>136</td>
<td>723</td>
<td>136</td>
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<td>Biomass use</td>
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<td>Co-firing with coal</td>
<td>Co-firing with coal</td>
<td>DME production</td>
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<td>[kg CO₂/MWhbiomass]</td>
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<td>329</td>
<td>329</td>
<td>159</td>
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<tr>
<td>[g CO₂/km]</td>
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<td>District heating</td>
<td>Biomass boiler</td>
<td>Biomass boiler</td>
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<td>[kg CO₂/MWhheat]</td>
<td>286</td>
<td>286</td>
<td>286</td>
<td>138</td>
</tr>
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* Low level corresponds to a moderate ambition for reduction of CO₂ emissions, high level to high ambition.

In Scenario 4 policy instruments promoting production of green transportation fuels are assumed.

Well-to-gate from marginal use.

Table 1. CO₂ emissions used for calculations of external effects.

3.2. Input data

Input data used for the calculations are presented in Table 2. For black liquor gasification with DME production data from [5] are used. The data are based on calculations where the recovery boiler, used for combustion of the black liquor, at a pulp mill using best available technology is replaced by a gasification plant coupled to a product gas conversion plant for production of DME. Table 2 shows the incremental biomass and electricity use compared to the pulp mill reference case. For biomass gasification, data from [6] are used for the DME case, while data from [7] are used for the BIGCC case. For the ethanol case, data from [7], [8] and [9] are used. The data are based on a process with enzymatic hydrolysis where lignin and other solid by-products are used in a CHP-plant. Biogas, another by-product from the ethanol production, is used in a gas engine, also producing heat and electricity. To account for CO₂ emissions related to collection, chipping and transportation of biomass, as well as to distribution and dispensing of the produced biofuel, values from [2] are used. The produced biofuels are assumed to be used in hybrid vehicles. Vehicle efficiency data, as given in Table 3, are taken from [2].
4. Results

The results are illustrated in Figure 1 as net CO₂ emissions reduction per TJ of biomass used, compared to a reference system as defined in the scenarios. As can be seen, the results differ greatly between the scenarios. These differences reflect the influence on the results of assumptions about the surrounding system.

When assuming a high CO₂ emissions charge, as in scenarios 2 and 4, all three studied technologies show higher, or less negative, CO₂ reduction compared to electricity and heat production by the BIGCC-concept. In scenario 4, policy instruments promoting production of green transportation fuels are assumed and thereby marginal biomass usage changes from co-firing with coal, to DME production. In this scenario all three studied biofuel technologies achieve positive CO₂ reduction. In scenario 3, with a low CO₂ emissions charge, the marginal electricity production is a coal-fired power plant (without CCS) which means that the BIGCC concept is highly favoured compared to the biofuel technologies. It should be noted that it is also possible to produce electricity and heat in a combined cycle from the BLG concept.

5. Discussion and conclusions

The results show that when varying the assumptions on surrounding systems, e.g. electricity- and transportation systems as well as marginal usage of biomass, very different values regarding the potential to reduce CO₂ emissions using biofuels are obtained, both when comparing different technologies and when comparing biofuels to BIGCC CHP. This shows the importance of being aware of the assumptions used in different WTW-studies regarding the surrounding systems and how they affect relative figures-of-merit for different technologies. It also shows the importance of a sensitivity analysis where the assumptions on surrounding systems are varied. Since energy market parameters are not independent of each other, but rather strongly connected, a good way to make a sensitivity analysis is to use different scenarios reflecting different possible future energy market conditions.

By using a system-oriented approach when evaluating potential for CO₂ emissions reduction, the fact that biomass is a limited resource for which there is competition from a number of different applications, is reflected. The importance of taking this fact into consideration is stressed by presenting the potential to reduce CO₂ emissions per unit of biomass. Another way to make allowance for the scarcity of biomass would be to...
calculate CO₂ emissions reduction per land area, but since the feed in this study is assumed to be forest residuals, this would be a less suitable method. This consideration of the limited amount of biomass available is the reason for the relatively low (or negative) potential to reduce CO₂ emissions using biofuels shown in this study, compared to other similar studies, since here the biomass used for the studied technologies lessens the amount of biomass available for other applications, thereby increasing the emissions for those applications.

As has been shown, CO₂ emissions reduction depends strongly on assumptions about the surrounding systems. Therefore it is of course important to be consistent and use the same assumptions for all technologies compared in a study. This is however not always the case. As has been exemplified, studies can be inconsistent in the system view, e.g. by using different technologies in order to make the biofuel production processes electricity neutral, where the power production technologies used do not necessarily reflect a realistic surrounding system. One important factor that has not been considered here, that could improve the results for the biofuels studied, is CCS. In the gasification processes as well as in the ethanol process, considerable amounts of CO₂ could be separated rather easily, thereby increasing the CO₂ reduction potential significantly. It should be noted that there are of course other aspects besides climate impact to consider, within or outside a life cycle analysis, when comparing biofuels; e.g. other environmental aspects, the need for changes in infrastructure and of course economics.

In this study DME from BLG shows the highest CO₂ emission reduction potential in all scenarios except scenario 3. A big advantage with BLG is that excess process heat can be used at the pulp mill. The absolute potential for biofuels via BLG is however limited, since there is only a very limited amount of black liquor. Even in Sweden, a country with one of the largest pulp and paper industries in the world compared to population, biofuels based on BLG could only cover about 30% of the need for transportation fuels. Hence, there is a need to continue the development of other technologies as well. For the BMG and ethanol processes there is no direct user of the excess process heat, as in the case of BLG. It is therefore of great importance to investigate possibilities of integration, e.g. with a district heating system or with another industrial process, in order to increase the total energy efficiency. However, since the amounts of low grade heat from the processes can be considerable, it will probably be hard to find large enough heat demand. When integrating with other industries, the complexity of the comparisons increases.

A final conclusion is that a system approach, such as the one described in this study, should be used when analysing the CO₂ effectiveness of applications using the limited biomass resources. This is particularly important when evaluating technologies that are expected to use a substantial amount of the available biomass in the future, as in the case for the technologies evaluated in this study.

6. References

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