Improving the greenhouse gas balances of bioenergy systems: The cases of Brazilian ethanol production and combined biofuel/district heat production in Europe

ANDREA EGESKOG

Division of Physical Resource Theory

Department of Energy and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

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Andrea Egeskog

Physical Resource Theory

Department of Energy and Environment

Chalmers University of Technology

SE-412 96 Göteborg

Sweden

Telephone: +46 (0)31-772 10 00

Email: andrea.egeskog@chalmers.se

URL: www.frt.fy.chalmers.se

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Andrea Egeskog

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Abstract

According to the Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change, the largest source of increased atmospheric CO_2 concentration is fossil fuel use. The second largest is land-use change. Emissions from combustion of fossil fuels and land-use change will need to be reduced in order to reach ambitious climate targets. Biomass is one of the renewable energy sources that could be used to replace fossil fuels. While biomass is a renewable source, it is a limited and expected to become scarce compared to future demand; therefore, it is desirable to use it as efficiently as possible. Further, when biofuels expand into new areas resulting in land-use change, the total biospheric carbon stock (the sum of soil and above ground carbon) may increase or decrease, thereby influencing the net greenhouse gas savings achieved. The overall aim of this thesis is to investigate different options for improving greenhouse gas balances of different bioenergy systems.

The first paper studies second generation biofuels produced in Europe and integrated with district heating systems to improve the total efficiency of the biomass use. We find that each investigated country, except Italy, has a heat sink capacity in its district heating systems that is larger than the amount of heat that would be co-generated in plants producing biofuels volumes corresponding to national biofuel targets.

The second paper studies expansion of sugarcane ethanol production in Brazil. The expansion takes place in combination with improved milk production where sugarcane residues are used as animal feed. We find that the effects of sugarcane production on soil carbon content (which is different in, e.g., cropland and pasture) and the harvest practice for sugarcane both have a large influence on total GHG emissions from sugarcane-based ethanol production.

Keywords: bioenergy, biofuels for transport, sugarcane ethanol, district heating, Brazil, EU

List of papers

Paper I: Co-generation of biofuels for transportation and heat for district heating systems—an assessment of the national possibilities in the EU

A Egeskog, J. Hansson, G. Berndes, S. Werner

Energy Policy, 2009, Volume 37, pp 5260-5272

Paper II: Integrating bioenergy and food production -A case study of combined ethanol and dairy production in Pontal, Brazil

A Egeskog, G. Berndes, F. Freitas, S. Gustafsson, G. Sparovek

Submitted to Energy for Sustainable Development

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1. Introduction

Carbon dioxide (CO_2) is currently the primary anthropogenic greenhouse gas (GHG). The largest source of increased atmospheric CO_2 concentration is fossil fuel use; land-use change (LUC) is the second largest source (IPCC, 2007a). Use of fossil fuels currently leads to emissions of about 30 Gton CO_2eq. per year, and the annual emissions from LUC are about 8 Gton CO_2eq. (IPCC, 2007b). GHG emissions will need to be reduced in order to reach ambitious climate targets. There are three main ways to reduce fossil CO_2 emissions: (i) use less energy; (ii) substitute fossil fuels with non-fossil energy sources or shift to less CO_2 intensive fossil fuels (typically, shift from coal to natural gas); and/or (iii) employ CO_2 capture and storage technologies to prevent the CO_2 from entering the atmosphere. Fossil CO_2 emissions can also be compensated for by various activities that remove CO_2 from the atmosphere, for instance reforestation to sequester atmospheric CO_2 in soils and growing biomass.

If managed sustainably, biomass is a renewable energy source that can be used as a substitute for fossil fuels. Biomass can be used in the electricity, heating and transportation sectors. In practice, bioenergy is never fully climate neutral because (i) production, including, e.g., cultivation, harvesting and transportation, often uses fossil resources; and also causes emissions of non-CO_2 GHGs such as nitrous oxide; (ii) the use of biomass as feedstock for the production of solid/liquid/gaseous biofuels can influence the biospheric carbon stocks (the sum of organic carbon in soils and in above-ground biomass) – in both positive and negative direction. For example, if forests are converted to croplands large CO_2 emissions typically occur. Such emissions are commonly designated as direct land use change (dLUC) emissions. Conversely, if perennial plants are planted on marginal lands with carbon-poor soils atmospheric CO_2 may become assimilated in the soils and aboveground biomass. Bioenergy can also cause GHG emissions associated with indirect land use change (iLUC), such as when the agriculture area expands to compensate for the losses in food/fiber production caused by a biofuel project claiming food commodity crops as feedstock.

Nevertheless, as long as the total GHG emissions, including those associated with possible decreases in biospheric carbon stocks, are smaller than emissions reduction achieved from the fossil fuel displacement, the use of biomass leads to a net reduction of atmospheric CO_2

emissions. Biofuels are primarily used for their possible ability of displacing oil and gas. However, in addition to reducing GHG emissions, they can improve the security of energy supply.

The biomass resource base, originating from forest, forest residues, bioenergy plants, agricultural residues, and organic waste, is influenced by a range of factors that are uncertain—such as population growth, diet changes, and productivity development in agriculture and forestry. There are many different estimates of the global potential for biomass; these come to diverging conclusions due to the inherent uncertainty of important determining factors (see, e.g., Berndes et al., 2003 for a review). However, many studies conclude that it might be possible to produce several hundreds of EJ of bioenergy per year by 2050, if development is favorable. Today the annual global consumption of biomass for energy is about 50 EJ (Wirsenius, 2007), which is about 10 % of annual global primary energy consumption (BP, 2009). Most of the biomass is used for cooking and heating in developing countries (mainly wood from forests). Wirsenius (2007), reports that about 6% of global bioenergy usage consisted of biofuels in the transport sector. However, global consumption of biofuels has increased rapidly in the last years (see e.g. ELOBIO, 2010). About 45 EJ of today's annual consumption of biomass comes from residue streams (including organic waste), but this resource base is limited and is assumed to be between 50 and 250 EJ by 2050 (IEA Bioenergy, 2009). This means that an increasing demand for biomass will probably lead to expansion of dedicated biomass production systems on current agricultural land and/or on natural ecosystems, e.g., savannas and forests. Crops grown for biomass feedstock currently take up less than 2% of the world's arable land (GBEP, 2008). Still, it is reported that demand for biofuels has contributed to increased global prices on food and feed since it has represented a significant driver of demand growth (see e.g. OECD-FAO, 2008). Increased demand for food and feed, speculation on international food markets, as well as incidental poor harvests due to extreme weather events are examples of events that have likely also had an impact on global food and feed prices (ELOBIO, 2010).

The overall aim of this thesis is to investigate different options for improving GHG balances of different bioenergy systems. The focus is on options for producing biomass-based fuels for the transportation sector (biofuels). Two main areas are studied:

(i) Second generation biofuels, produced in Europe and integrated with district heating systems to improve total efficiency of the use of biomass (see *Section 3* and *Paper I*).

(ii) Expansion of first generation biofuels, i.e., sugarcane ethanol, produced in Brazil and integrated with small scale milk production (see *Section 4* and *Paper II*).

In this thesis, first generation biofuels are defined as biofuels produced from common agricultural food/feed crops such as sugar cane, sugar beet, wheat or corn fermented into bioethanol, and biofuels from e.g. oil palm, soy, and rape seed pressed to yield vegetable oil that can be used in biodiesel. Focus will be put on ethanol from sugarcane. Second generation biofuels are defined as biofuels produced from lignocellulosic feedstocks and this thesis focus on the gasification of biomass with subsequent synthesis to make liquid or gaseous biofuels. Examples of second generation biofuels are DME (Dimethyl ether), methanol, Fischer Tropsch diesel, and methane.

2. Options for improving greenhouse gas balances of bioenergy systems

Considering that biomass is a limited resource, the increased global demand for biofuels makes it important to find efficient solutions for biomass and biofuels production. Within the EU, an increase in the use of bioenergy is promoted for heat and electricity production, as well as for transportation (EC, 2005). For example, each member state is supposed to achieve a minimum share of 10% renewable energy, primarily biofuels, in the transportation sector by 2020 (EC, 2008). Second generation biofuels are a widely discussed option (see, e.g., Naik et al., 2010; Sims et al., 2010). These fuels can be produced from residues and waste products from, e.g., the food and forest industries. Since the potential for biomass is limited, increased demand for bioenergy is expected to lead to that efficient biomass use for energy will be a high priority. Co-generation, i.e., the production of several products from the same biomass feedstock, is an attractive option. Co-generation of heat and power (CPH) is promoted in the EU (EP&C, 2004), but heat can also be co-generated with biofuels for transportation.

Biomass gasification with subsequent synthesis to make liquid or gaseous biofuels is under development. A number of development and demonstration projects are in progress (see, e.g., Babu, 2006; Renew, 2008; Thunman et al., 2008; Gode et al., 2008; Goldschmidt, 2005). In order to improve the overall energy efficiency (and economic viability) of the process, biofuel plants employing the gasification process can be designed and located so that part of the surplus heat can be used in district heating (DH) systems. These types of biofuel plants are designated CBH (Combined Biofuel and Heat) plants in this thesis. There are other heat sinks than DH systems where excess heat from CBH plants could be used, e.g. the fermentation process when producing ethanol. These heat sinks are however not treated in this thesis.

In Sweden, the opportunity for introducing biomass gasification applications in DH systems has been studied at the local and regional level. Fahlén and Ahlgren (2009) show that – given certain levels of policy support for biofuels for transportation and renewable electricity, and for certain prices for fuels, electricity, and CO_2 emissions – CBH would be a profitable option for the DH system in Gothenburg, Sweden. Difs et al. (2008) report that biomass gasification applications are interesting investment options for the local DH supplier in Linköping, Sweden. Both from a cost-competitive perspective and regarding global greenhouse gas emission reductions. Börjesson and Ahlgren (2008) discuss the potential competition between biomass gasification based CHP and CBH and estimate the subsidy level for biofuels for transportation needed for CBH to be a competitive option in the DH systems in the Västra Götaland region, Sweden. Wetterlund et al. (2008) evaluates policy instruments affecting the profitability of biomass gasification applications integrated in a Swedish DH system. Looking beyond Sweden, Renew (2008) indicates suitable locations for the production of liquid biofuels produced via biomass gasification from a biomass supply perspective (France, East Germany/West Poland, and Sweden). None of these studies analyze the national (or European) potential for CBH based on assessing the availability of specific heat sinks. There is a need for EU-level studies investigating possibilities for second generation biofuel plants to sell their excess heat.

The aim of the study presented in *Paper I* is to identify the potential for CBH production in the EU, based on the assumption that excess heat needs to be absorbed by DH systems. It is found that the heat sinks represented by the existing national aggregated DH systems in the

EU20 countries are in general large compared to the amount of surplus heat that would be generated from CBH plants having a combined biofuel production capacity corresponding to the 2020 renewable transportation target. The feedstock resource base for second generation biofuels may consist of a range of biomass sources including dedicated bioenergy plants as well as agricultural and forest residues (Sims et al., 2010). If alternative usages of the residues for climate mitigation are limited, their use as biofuel feedstock will not imply any significant direct or indirect LUC. The study did not include any analysis of feedstock availability and consequently did not investigate the possible land use effects of biofuels production at the level corresponding to the EU 2020 biofuels target (10% blending).

Second generation biofuels are not yet commercially available, so near-term biofuels use will have to rely on the availability of first generation biofuels. Ethanol currently dominates the commercial biofuels market (UNEP, 2009). Many studies show that sugarcane-based ethanol (mainly from Brazil) has low production cost, high land-use efficiency, and high GHG savings compared to corn (mainly from the U.S.) and wheat-based ethanol (mainly from Europe) (Börjesson et al., 2009). However, high net GHG savings requires that LUC emissions are kept low; strategies to maximize the GHG savings from replacing gasoline with sugarcane ethanol need to consider both GHG emissions from sugarcane cultivation and conversion to ethanol, and the (direct and indirect) LUC emissions that may arise when new sugarcane plantations are established (see, e.g., Fargione et al., 2008; Gibbs et al., 2008; Lapola et al., 2010). The dLUC associated with sugarcane plantation establishments leads to relatively small GHG emissions (since expansion typically takes place on pastures and cropland (Walter et al., 2010)). Going from pasture to sugarcane may lead to changes in soil carbon content (Galdos et al., 2009). Depending on the soil carbon content of the pastures and the harvesting management of the sugarcane, the change from pasture to sugarcane can lead to either increased or decreased soil carbon levels (Galdos et al., 2009).

The iLUC associated with sugarcane ethanol can arise in different ways. When sugarcane expansion takes place on pastures used for meat production the grazing land area becomes reduced. Unless meat demand is reduced proportionally, one of two iLUC events (or a mix of these) will happen: (i) meat production on the remaining pastures will intensify or (ii) new pasture areas will become established. Depending on where the new pastures are established, iLUC emissions can vary a lot. If, e.g., dense forests with high carbon content are replaced, this will lead to high iLUC emissions, and replacing gasoline with ethanol may not lead to net GHG savings for many years. Similarly, sugarcane expansion on cropland can result in iLUC due to cropland expansion to compensate for lost food crop production.

It is however difficult to quantify the iLUC associated with a given biofuel project and also debated whether biofuel production should be made responsible for effects that are directly caused by other activities, with only an indirect link to a certain biofuel project (see, e.g., Lapola et al., 2010; Nassar et al., 2008 for a discussion on iLUC emissions from sugarcane-based ethanol).

Brazil is the world’s largest exporter (second largest producer after the U.S.) of ethanol (Dossa, 2009) and is expected to increase its production as domestic and international demand grows. Increased ethanol production will mainly be accomplished based on establishment of new mills and plantations, and to a lesser extent through increased output from existing ethanol mills and fields. Sugarcane expansion for production of ethanol does not only lead to changes in GHG emissions. Focusing only on avoiding expansion over ecosystems storing large amounts of carbon (e.g., forests) may lead to other negative effects, e.g., expansion may take place in areas with low soil and above-ground carbon content but with high biodiversity value. Expansion will also likely affect the rural population living in the expansion areas.

Paper II presents results from a study that examines possibilities for small scale farmers to integrate their milk production with expanding sugarcane ethanol production in São Paulo state, Brazil. The study had several aims: (i) to investigate how the integration of milk and ethanol production would affect the small-scale farmers’ profits; (ii) to identify prerequisites necessary for increased farmer profits from the integration; and (iii) to investigate whether the integrated milk/ethanol system is attractive from a climate change mitigation perspective.

3. Paper I: Co-generation of biofuels for transportation and heat for district heating systems – an assessment of the national possibilities in the EU

In the EU25 there are more than 5,000 district heating (DH) systems. Together they provide about 15% of the total annual heat demand (not including electricity for heating, due to lack of statistics). The importance of DH varies among member states, reaching at most about 30-40% in the Baltic States and Denmark (estimates for 2003 based on IEA, 2005 and Werner, 2006). In 2003, about 80% of the DH in the EU25 was generated with fossil fuels either in combined heat and power (CHP) plants (about 75%) or heat-only boilers (HOB) (about 25%) (Werner, 2006).

The EU promotes an increased use of bioenergy for heat and electricity production as well as for the production of biofuels for transportation (EC, 2005). For example, each member state is supposed to achieve a minimum share of 10% renewable energy, primarily biofuels, in the transportation sector by 2020 (EP&C, 2009). Since the potential for biomass is limited, high efficiencies in processes using it are desirable. In order to improve overall energy efficiency (and economic viability) of the biofuels for transportation, biofuel plants employing gasification processes can be designed and located so that part of the surplus heat can be used in DH systems.

The purpose of this study is to estimate the heat sink capacity[1] of DH systems in the EU member states and, based on that, assess the possibility for biomass-gasification-based co-generation of synthetic biofuels for transportation and heat for DH systems in the EU member states. That is, we assess the opportunity for DH systems to be a base for synthetic biofuels for transportation production. It is investigated weather DH systems in the EU are large enough to accommodate heat from CBH corresponding to EU’s 2020 target (10% renewable fuels in the transportation sector). The term *synthetic biofuels* is used as a generic term for any biofuels for transportation possible to produce based on CBH. This means that we do not consider a specific production process or specific type of biofuels for transportation.

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[1] In this paper, the *heat sink capacity* represents the amount of heat that the district heating systems demand.

3.1 Method

The techno-economical potential for CBH is assessed based on a model characterization of the existing and potential DH systems in Europe year 2020. An inventory and characterization of the existing (2003) DH systems in the EU25 is made. The existing DH systems are characterized at the national aggregated level and include size of the heat sink and relevant characteristics such as the present fuel use and heat supply option used to provide the DH. The CBH unit is here assumed to be second-generation biofuel production where 50% of the energy input (biomass) is converted to biofuel and 10% ends up as usable surplus heat, corresponding to performance of CBH plants based on (Thunman et al., 2008). This characterization, along with the estimate of the sizes of the DH systems in 2020, forms the basis for investigating the possibilities for CBH in the EU25 countries. The Euroheatspot model (based on the Heatspot model, see e.g. ÖPwC, 2005) is used to analyze changes in the DH systems when heat from CBH is introduced.

In the Euroheatspot model, the national DH systems are described by a heat load duration diagram, in which the heat supply options in the system are placed in the specified merit order and are ranked by size. The installed capacity (in MW) for each included heat supply option, corresponding to the compiled production levels in each country, is estimated by using an analytical expression representing the annual load curve. Based on the estimated installed capacity the annual DH production from the different heat supply options is recalculated after the CBH has been introduced in the DH systems (see Figure 1).

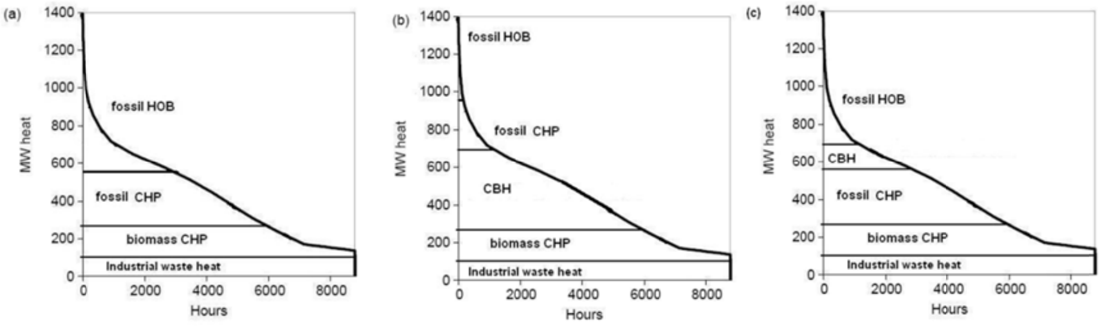

Figure 1. Description of the Euroheatspot model. Heat load charts for every European country's aggregate heating system and changes in heat source when CBH are introduced. (A) represent an existing DH system, (B) represents a system where heat from CBH is placed before fossil CHP, and (C) when the heat is placed after CHP.

3.2 Main findings and conclusions

Most countries DH systems can easily absorb the excess heat from the biofuel production (assuming that heat from CBH can successfully compete with fossil CHP as in Figure 1b). In Figure 2 the heat from CBH plants (producing biofuel to meet the EU's 2020 target) is presented in relation to heat production in different countries, assuming that CBH heat is cheaper than heat from fossil CHP (case B in Figure 1). Each investigated country, apart from Italy, has DH systems with capacity to absorb the heat from CBH production corresponding to more than the relevant national targets for biofuels.

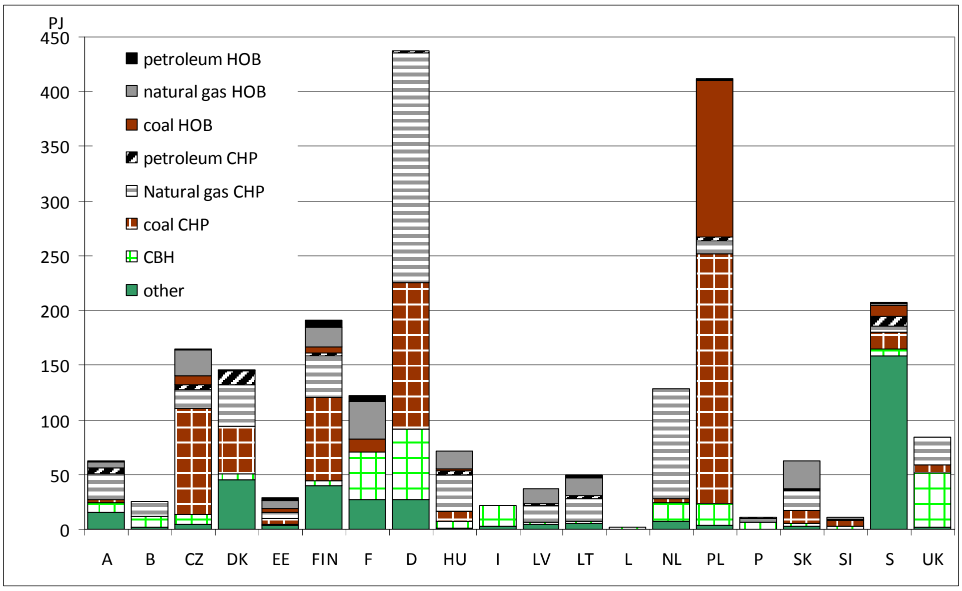

Figure 2. Distribution of heat sources in aggregated national DH where heat from CBH corresponds to the EU's biofuel target for 2020 (assuming that this heat is cheaper than heat from fossil CHP). The category "other" includes industrial waste heat, heat from waste incineration, waste heat from nuclear power plants, biomass CHP, geothermal heating, and solar energy.

Since there is a lack of information at the individual DH systems-level in the different countries, the overall potential is based on the aggregated national DH system. However, since the size of the individual DH system is crucial for the possibility for cost-effective biofuel (CBH) integration, assessments that take the sizes into account have been made for a selection of countries, including Finland, Lithuania, Sweden, and Germany (where information on systems-level is available). The assessments show that if the size of the CBH plants needs to be at least 1,000 MW (biomass input) to be profitable, about 20-30% of DH systems are large enough to absorb the surplus heat from CBH plants. If the minimum CBH plant size instead is 250 MW biomass input, 60-75% of the systems are sufficiently large.

The potential increase of use of industrial waste heat and waste incineration (potential low-cost options) in the DH systems was assessed. The assessment shows that in the majority of the member states, the calculated possible DH expansion is smaller than the estimated expansion potential for heat generation from these two options.

4. Paper II: Integrating bioenergy and food production - a case study of combined sugarcane ethanol and dairy production in Pontal, Brazil

Sugarcane is expanding rapidly in the state of São Paulo, Brazil. The region of Pontal do Paranapanema in the western parts of São Paulo is one possible region where sugarcane can expand (Freitas and Sparovek, 2008). At least six new ethanol plants have been built since 2006 (UDOP, 2010). This rapid expansion might negatively affect the relatively poor small scale family farmers living in the area. Freitas and Sparovek (2008) report that the small scale farmers who switch from existing milk production to sugarcane production experience economic stagnation. The farmers lack investment capital making it impossible for them to manage all stages of the sugarcane production. They have to buy services from the sugarcane industry and this leads to reduced net incomes from sugarcane production. Relatively small-sized farms also lead to restraints concerning possible size of net income (Egeskog and Gustafsson, 2007). There is a lack of studies investigating possible options for small scale farmers to increase their welfare from taking part in the sugarcane expansion.

One opportunity for the settlers in Pontal to benefit from the sugarcane expansion is to improve their milk production system in combination with planting sugarcane. If the settlers allow sugarcane on part of their property and in exchange for this are allowed to buy feed from sugarcane residues (which is readily produced in the ethanol plant), they can change to a more productive cattle breed, double the amount of milk producing animals and keep them on a smaller area than needed for their present cattle production.

This article presents results from a study of an integrated ethanol/dairy system. Small-scale settlers in Pontal include sugarcane production in their existing milk production. The study focuses on two main questions:

- What economic benefits may a combined ethanol/dairy system have for small-scale farmers, such as the settlers in Pontal?
- How may GHG emissions be affected if pastures in Pontal (within and outside the settlements) are converted to sugarcane plantations, milk production in the settlements is intensified, and the ethanol produced from the sugarcane replaces gasoline in the EU?

4.1 Method

Two different models were developed to analyze selected effects of implementing the integrated ethanol/dairy system in Pontal; one model for quantifying the net revenues from milk production in the settlements (the Change of Cattle (CoC) model) and one model for quantifying the associated GHG emissions (the BIOenergy net GreenHouse Gas emissions (BIOGHG) model). Emissions from production of sugarcane and ethanol are mainly based on Macedo et al. (2004) and Macedo et al. (2008).

The CoC model is constructed to represent the transition from low-productive to medium-productive dairy cattle; it describes the settlers' incomes and expenses connected to their dairy cattle production system. The annual net income for the settlers is quantified for the time period when they make the transition from the current milk production systems with low-productive dairy cattle to the integrated ethanol/dairy system with medium-productive dairy cattle. The model is developed using information from a questionnaire survey conducted in Pontal in 2006 (Egeskog and Gustafsson, 2007).

The BIOGHG model is constructed to quantify emissions connected to a scenario for sugarcane expansion in Pontal where the settlers shift to the combined ethanol/dairy system. The BIOGHG model considers GHG emissions and avoided GHG emissions associated with three different activities; 1) the use of fossil-based inputs in sugarcane and ethanol production; 2) the conversion of pastures to sugarcane plantations leading to changes in soil carbon; and 3) the replacement of gasoline with ethanol in the EU transportation sector and provision of electricity generated from bagasse. The annual as well as cumulative net GHG emissions are calculated for the studied period.

4.2 Main findings and conclusions

As can be seen in Figure 3, including all farmers (settlers and large-scale land owners), a sugarcane expansion for ethanol in Pontal will, based on our assumptions, lead to reduced GHG emissions from the transport sector when ethanol is used to replace gasoline in Europe.

Including settlers in the sugarcane expansion will help them increase their net annual income but will not improve the direct GHG savings. This is due to that bagasse use for producing animal feed results in reduced electricity production from bagasse (or reduced replacement of fuel oil in other industries). However, the medium-productive dairy cattle need a smaller area per liter produced milk and this can be important with respect to reducing the risk that ethanol expansion on pastures leads to GHG emissions connected to iLUC. If demand for milk is constant, the increased milk production in Pontal, rising from an average of 7,000 to 80,000 liters/settler annually, could displace other milk production and hence reduce total land requirements for milk production. This may reduce the pressure for expanding agriculture into forested areas and thereby indirectly reduce GHG emissions (positive iLUC effect).

Thus, while the transition to the integrated ethanol/dairy system does not obviously lead to reduced GHG emissions per liter milk produced, possible GHG emissions reduction from making the transition can follow from the improved land-use efficiency. The reduced land conversion pressure may be important for realizing the GHG savings potential of the system, since iLUC emissions can drastically reduce net GHG savings. Incentives may be needed to make settlers consider the transition an attractive option. Investigations of the feasibility of implementing integrated ethanol/dairy systems that also include land owners with large landholdings are warranted.

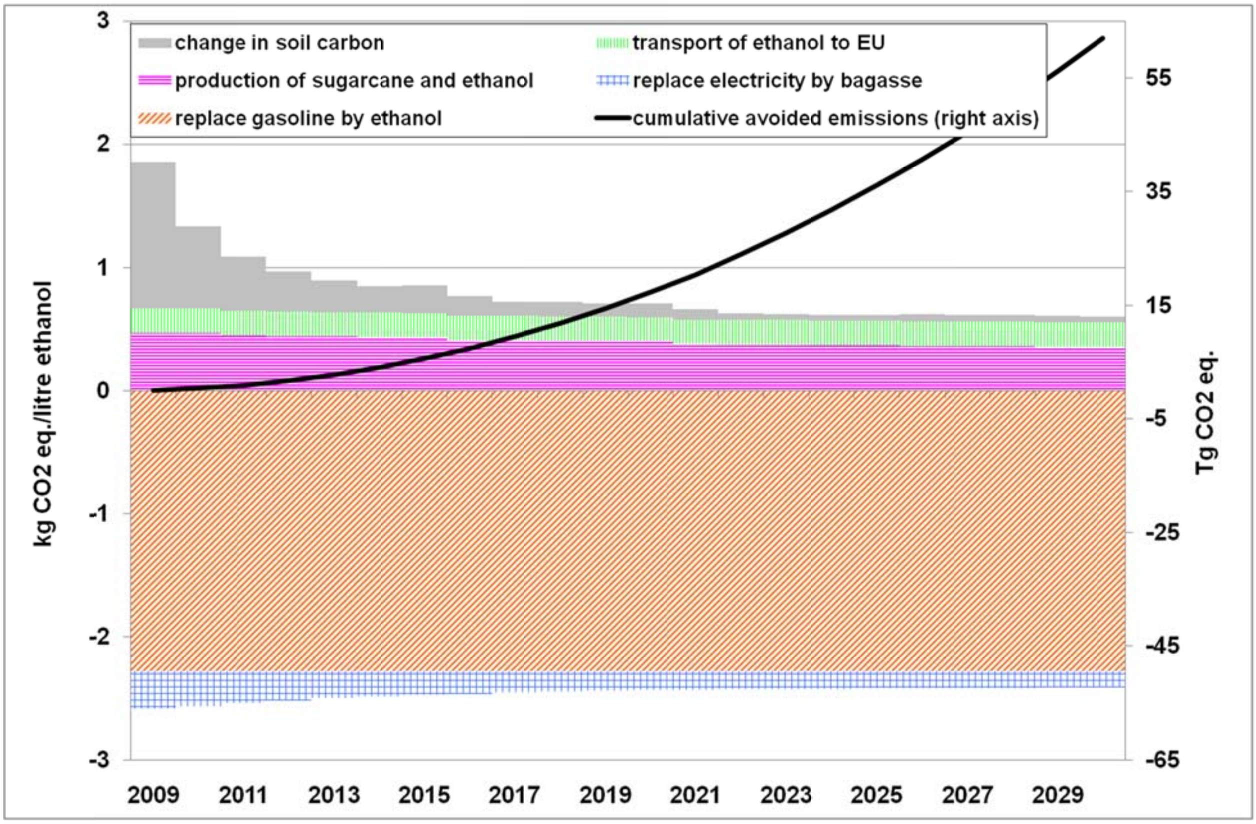

Figure 3. Emissions per liter ethanol and cumulative avoided emissions in conjunction with an expansion of sugarcane for ethanol in the Pontal region. Manual harvest is assumed to be phased out completely in 2017. Emissions increase in the first two years. Possible deforestation through iLUC is not included.

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Paper I

Paper II