Energy and Greenhouse Gas Balance of Decentralized Energy Supply Systems based on Organic Agricultural Biomass

A Life Cycle Perspective

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Abstract

More and more farms apply organic production methods to reduce their environmental impact, but currently even organic farms are mainly using fossil fuels. Technologies available today or in the near future make it possible to produce heat, electricity and fuels from agricultural residues or woody biomass. The agricultural sector can thereby contribute to the fulfillment of climate goals and energy security without reducing the output of food products.

The thesis describes and assesses possible energy supply systems based on biomass from an organic arable farm, using life cycle assessment (LCA) methodology. The impact categories used are energy balance, resource use and greenhouse gas (GHG) emissions. Technical systems are described for the supply of heat and power to a village near the farm, and for energy self-sufficiency at the farm. The systems utilize ley used as green manure, Salix and/or straw as the substrate for energy production, and are compared with a reference system based on fossil fuels. The emission calculations included field operations, processing and soil emissions, with a special model developed for estimating the impact on soil C concentration.

The results show that it is possible to supply the village or the farm with energy through the systems described without competing with food production. Ley-based scenarios require higher energy input than scenarios based on Salix, but lower than the scenario based on straw. In the self-sufficient farm system, ley-based scenarios give the highest reduction in GHG, 33% compared with the reference scenario whereas the corresponding reduction from a completely straw-based energy system is 9%. In the village energy supply system, the ley-based system give the highest reduction in GHG with a total of -19 Mg CO_2-eq./FU compared with 351 Mg CO_2-eq./FU in the reference system. The Salix-based systems give 42 and 60 Mg CO_2-eq./FU respectively.

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If we knew what it was we were doing, it wouldn't be research, would it?
Albert Einstein

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I   M. Kimming, C. Sundberg, Å. Nordberg, A. Baky, S. Bernesson, O. Norén, P.-A. Hansson (2011). Biomass from Agriculture in Small-Scale Combined Heat and Power Plants – a Comparative Life Cycle Assessment. Biomass and Bioenergy DOI:10.1016/j.biombioe.2010.12.027

II M. Kimming, C. Sundberg, Å. Nordberg, A. Baky, S. Bernesson, O. Norén, P.-A. Hansson (2011). Life Cycle Assessment of Energy Self-Sufficiency Systems Based on Agricultural Residues. Bioresource Technology 102(2), 1425–1432.

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The contribution of Marie Kimming to the papers included in this thesis was as follows:

I   Carried out data collection and calculations, and wrote the paper with input from the co-authors. Planned and structured the paper together with the co-authors.

II Carried out data collection and calculations, and wrote the paper with input from the co-authors. Planned and structured the paper together with the co-authors.

Abbreviations

AP – Acidification potential

CHP – Combined heat and power

DH – District heating

DME – Dimetyl Ester

FTD – Fischer-Tropsch Diesel

GWP – Global warming potential

FU – Functional unit

ILUC – Indirect land use changes

ISO – International Standardization Organisation

MC – Moisture content

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LHV – Lower heating value

PSA – Pressure swing absorption

RED – Renewable Energy Directive (Directive 2009/28/EC on the promotion of the use of energy from renewable sources)

RME – Rape Methyl Ester

TS – total solids

VS – volatile solids

1 Background

1.1 Introduction

In 2009, the European Parliament adopted the Directive on the promotion of the use of energy from renewable sources (abbreviated to Renewable Energy Directive or RED), according to which the EU-27 must increase the aggregated supply of renewable energy sources to 20% of total supply by 2020. Although this push for renewable energy is mainly driven by concerns over global warming, there are other important aspects of a higher proportion of renewable energy sources in the energy mix, such as securing the future energy supply and creating jobs.

Bioenergy is expected to play an important role in the fulfillment of the RED, including bioenergy from forestry, agriculture and the organic fraction of municipal waste. However, due to the relatively unexploited potential of the agricultural sector the European Environment Agency has concluded that in the long run, most of the additional biomass used for bioenergy will have to come from agricultural resources (EEA, 2006). This conclusion was supported by the European Commission's Impact Assessment of the Renewable Energy Roadmap (EC, 2007b).

At the same time, the agricultural sector as such is a major contributor to greenhouse gas (GHG) emissions in Europe, producing 14% of total emissions in 2008 (UNFCCC, 2010). As expectations on the agricultural sector to contribute to renewable energy supply increase, consumers' demands on the environmental performance of food and energy production are also increasing. An increasing proportion of the agricultural sector in

Europe is certified for organic cultivation, and is thus committed to excluding the use of artificial fertilizers and chemical pesticides, and to using local and renewable production factors to the greatest extent possible as stated in the European Council regulation on organic farming (EC, 2007a). This refers to, e.g., the recirculation of nutrients within the cultivation system, but could also be applied to energy consumption although no specific demands on the use of renewable energy sources are currently stated in the regulation. None-the-less, the use of renewable energy on organic farms would not only be a way to strengthen the competitiveness of European organic farmers as a sustainable option to conventional agriculture, but would also secure an energy supply to the agricultural production when fossil fuels become increasingly scarce. Moreover, local energy supply systems would create local jobs, which is the third objective of the EU biofuel policy after GHG savings and security of supply (JRC, 2008).

With the current pace of development and commercialization of conversion technologies for production of heat, electricity and fuel from agricultural biomass, it could be a real possibility within the near future to shift from use of fossil fuels to biomass-based fuels in the agricultural sector, or even for farms to become small-scale energy utilities supplying local villages (that are unable to connect to urban energy systems such as district heating) (Kjellström, 2007). This would also be a way to reduce the volume of transportation throughout the bioenergy supply chain.

However, the use of agricultural products for energy production is controversial, because there are emissions associated with the production itself, for example through tractor use and soil emissions. There is also the risk of food production being pushed aside or the profitability of energy crops providing incentives for deforestation or other indirect land use changes (ILUC). To avoid such issues, and due to the technical development in the area, more attention has recently been paid to the use of residues for energy carrier production. The advantage of using residues, e.g. lignocellulosic material such as wheat straw or maize stovers, is that it does not require additional land.

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This thesis assesses different technical energy supply systems based on agricultural residues or biomass grown on set-side land on an organic farm with life cycle assessment (LCA) methodology.

1.2 Life Cycle Assessment

There are several well-established environmental assessment tools, such as Strategic Environmental Assessment (SEA), Environmental Impact Assessment (EIA), Carbon Footprint and more. The methodology used in this thesis is Life Cycle Assessment (LCA), which is standardized in ISO 14044 (CEN, 2006) and is becoming an increasingly established and refined methodology for environmental assessment of products or services (Finnveden et al., 2009). It is also the methodology applied for calculation of emissions from renewable energy sources in the Renewable Energy Directive (2009/28/EC).

An LCA study consists of four stages;
1) Goal and scope definition
2) Life Cycle Inventory (LCI)
3) Life Cycle Impact Assessment (LCIA)
4) Interpretation of results

In stage 1, the systems are designed and system boundaries defined. In stage 2 data are collected, often from several different sources. In stage 3 the environmental impact from the systems, based on the data collected during stage 2, is quantified and categorized into different impact categories, for example land use or greenhouse gas (GHG) emissions. Finally, in stage 4 the results are analyzed via sensitivity analysis and conclusions are drawn.

1.3 Aims and objectives

The overall aim of this thesis was to study how organic arable farms can increase their competitiveness as sustainable food producers, while contributing to energy security and the achievement of climate goals in Europe, by producing energy from residues or biomass produced on set–aside land.

There were two main objectives:
1. To describe potential energy supply systems based on biomass from an organic arable farm and modern conversion technologies, for a nearby village or for self-sufficiency on the farm
2. To assess the impact of the systems described on resource use, energy balance and GHG emissions in a life cycle perspective

The conditions prevailing in south-western Sweden were assumed in these studies.

2 Technical and conceptual framework

2.1 Principles of organic farming and decentralized energy systems

European consumers have become increasingly aware of the impacts on the environment, the climate and their own health from the food they consume, and the demand for organically produced goods has undergone a steady increase in the last few years (EC, 2010). The European Council's regulations on organic production methods were first developed in 1991 but, as organic agriculture started to play a more prominent role in European agriculture, these were replaced with the current Council regulation No 834/2007 in 2007. The aim of the organic farming principles is to minimize the environmental impact and resource use. The use of artificial fertilizers, chemical pesticides and genetically modified organisms is prohibited and nutrients must be recycled within the production system to the maximum extent possible. For farms with livestock, the animal feed must be organically produced and should preferably come from within farm, and a longer grazing period than for conventional farming is stipulated. Only products for which all, or almost all, of the regulations are complied with can be marketed as organic. (EC, 2007a)

However, one aspect in which organic farming does not differ much from conventional farming is when it comes to the use of primary energy sources. The agricultural sector is a major consumer of fossil fuels, mainly diesel for tractors and fuel oil for heating and grain drying (Baky et al., 2002), and

organic farms are usually no exception. However, as stated in article 5b of Council regulation No 834/2007, the use of non-renewable and off-farm resources must be minimized on organic farms. One readily available source of renewable energy is biomass produced on the farm, for example residues from cash crop production (such as straw or manure). The conversion technologies for residual agricultural biomass are quickly developing and some are already established on the market, such as biogas production systems and straw boilers. More technically advanced technologies, such as lignocellulosic ethanol production, could become commercially available within the not too distant future as demonstration plants have been successful (Dwivedi et al., 2009). Moreover, it been shown by Ahlgren et al. (2008a) and Hansson et al. (2007) that it is possible for farms to supply themselves with fuel from their own biomass resources by using a certain fraction of the available area for production of biodiesel from rapeseed.

Raw biomass is bulky material with low energy density, and is usually not transported over long distances. For example, Swedish Salix chips are generally not transported further than 100 km (Kimming et al., 2008) and straw transported even shorter distances. Compacted products on the other hand, such as pellets, are transported internationally, but the compaction process requires energy and sometimes additives, thus making the material more expensive (Olsson et al., 2010). A way to avoid this would be if the energy produced on the farm were to be used in a self-sufficiency system, or for a local supply of energy to rural villages located close to the farm.

A potential problem with small energy supply systems is how to handle the fluctuations in supply and demand, which are not likely to coincide. Today, it is not possible to store electricity, heat or biogas in a cost-effective way, except in small quantities (van der Linden, 2006). Thus, a system in which a farm or a village becomes an isolated system would be inefficient. Therefore, electricity produced in each scenario in the present study is assumed to be fed into the national grid where supply and demand are balanced by the system operators. The output of electricity from the systems can thus be kept relatively constant over the year, and investment in over-capacity avoided, as long as the total annual production equal to the total annual consumption. Heat can be stored in accumulation tanks to some extent, but as it is produced as a by-product from electricity production, it is likely that a lot will be waste heat during the warm summer months. The

biogas can either be combusted immediately or distributed via pipelines to large-scale facilities.

For liquid fuels the storage possibilities are practically unlimited except for fuels that require extremely high pressures or a high level of insulation. In such systems, it is nearly impossible to avoid leakage over time (Astbury, 2008). Large-scale facilities are often required for the production of liquid fuels, but there are some exceptions such as small-scale units for the production of biodiesel from rapeseed (Bernesson et al., 2005).

2.2 Biomass resources

In Sweden, where 20% of total primary energy supply comes from biomass, about 87% of this from forestry and only 4% from agriculture (SEA, 2010). In Europe, slightly over 4% in total of aggregated primary energy supply is from biomass of which 80% is from forestry. However, it has been recognized by the European Environment Agency (2006) and the European Commission (2007b) that the largest potential for expansion of the use of biomass for energy generation exists in the agricultural sector.

The supply of forest residues to energy producers is a well-established business in the forestry sector. Furthermore, primary products from the forest are purchased by the timber industry and the pulp & paper industry, often using its own residual products for process energy (Anonymous, 2008). In the agricultural sector on the other hand, production of biomass to be used as fuel is not common practice and the infrastructure, supply chains and markets are far less developed and established. In an initial phase, this also means that there are institutional, technical and economic barriers to overcome before the agricultural sector can be a real player in the energy sector. The risk is higher for agricultural businesses who venture into the industry, for example by growing energy crops (Kimming et al., 2008). For example, the result of a push for producing Salix in Sweden, strongly promoted by Swedish policies in the 1990's, was a disappointment for many farmers as both yields and market prices for the Salix chips proved to be lower than expected (Helby et al., 2006).

In RED, biomass is defined as "the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal

and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste". Biofuels is defined as "liquid or gaseous fuel for transport produced from biomass". (EC, 2009). The following sections briefly describe the two groups of biomass resources, namely agricultural residues and short rotation coppice, that were studied as substrates for the energy supply systems in Paper I (Salix, straw and ley used as green manure) and Paper II (straw and ley used as green manure).

2.2.1 Agricultural residues

When producing cash crop such as grains and oilseeds, straw and other crop residues are by-products. In Europe, the straw is either left on the fields or collected and baled. The alternative chosen normally depends on the concentration of organic material in the soil (low levels of organic carbon in the soil would justify leaving the straw on the fields) and the economic value of the straw (for example as bedding material for cattle or horses). Straw can be also be used in straw furnaces to heat farm buildings, often on farms that produce a lot of straw themselves. Straw combustion was originally problematic due to the high ash and alkali content, which caused sintering and corrosion in combustion chambers (Bernesson&Nilsson, 2005). Today however, straw boilers are common in many European countries.

The Lower heating value (LHV) of straw is approximately 18 MJ/kg total solids (ts) and the moisture content (MC) 10-20% at harvest, depending on the weather conditions between harvest and collection (Lundin&Rönnbäck, 2010). Straw consists mainly of cellulose, hemicelluloses and lignin.

Nitrogen-fixating ley and clover species, ploughed down into the soil, can be included in crop rotations on organic farms as organic fertilizers. Such crops are in this function referred to as green manure. Although not a residue per se, an alternative option instead of ploughing down the ley fresh is to harvest and use it as a substrate for biogas production, in which case the digestion residues are spread on the fields – the nutrients end up here. Studies show that the fertilization effect in fact can be even higher in this form than in fresh ley (Marcato et al., 2009).

The LHV of ley is approximately 17 MJ/kg ts, and MC around 30% (Edström et al., 2008). There are few statistics available on ley yields, but trials in Sweden show approximately 8 Mg ts/ha in conventional farming after correction for higher yields in the trials (Halling, 2008).

2.2.2 Short rotation coppice - Salix

Salix is a short rotation coppice (SRC) planted on arable soil and harvested every 3-5 year. The lifetime of a plantation is 20-30 years (Agroenergi, 2010). The yield of Salix varies depending on soil quality and crop management, and yield data are not readily available. However, models have shown that maximum yields in Sweden can range between 8-15 Mg ts/ha yr (Lindroth&Båth, 1999) whereas estimations on actual yields in Sweden show a range of 4-7 Mg ts/ha yr (Mola-Yudego&Aronsson, 2008).

The harvested Salix stems and branches are normally chipped during harvest, and used in district heating (DH) or CHP plants in a co-firing process, for example with forest residues or coal. Many plants will only accept up to 10% Salix chips in the fuel mix, due to the low ash melting point and high alkali content of the Salix chips that might cause sintering and reduce the efficiency of the combustion chamber (Kimming et al., 2008).

The LHV of Salix is approximately 19 MJ/kg and MC normally around 50% at harvest (Agroenergi, 2010).

2.3 Biomass conversion technologies

There has been significant progress in the development of technologies for converting biomass to heat, electricity and liquid or gaseous fuels in the last few years, in particular for small-scale applications (Kjellström, 2007). Small-scale CHP applications were of interest here, as they are suitable for use on average sized farms (for Swedish conditions). However, fuel production is not always feasible other than in large-scale facilities due to the high investment costs and the complexity of the technologies.

2.3.1 Biogas production

There are many potential substrates for biogas production, of which the most common are stable manure, ley, straw, organic waste or a mix of these. In the process, substrates are fed to aerobic, hermetically sealed, heated chambers where microbes produce a gas consisting of 55–60% methane and 40–45% carbon dioxide. The systems can have different configurations with either one-stage or two-stage production (in the latter case, there is a secondary digestion chamber, and more of the methane can be extracted due to the prolonged total retention time) and with continuous or batch-wise feeding. The gas is collected at the top of the chamber and transferred to a sealed storage unit, and the residues are pumped to a storage site and commonly used as fertilizer. (Edström et al., 2008).

After reduction of the hydrogen sulphide content, the gas produced can be used in gas engines for production of electricity and/or heat, or for production of compressed or liquid biogas (CBG and LBG respectively). This requires that the gas is upgraded to 97% methane, i.e. that the CO_2 is removed. There are different separation technologies used today, such as water scrubbing, pressure swing adsorption (PSA) or cryogenic separation, in which the gases are cooled until separated at different condensing temperatures. In the latter case, the product obtained is liquid biogas (LBG) whereas the other technologies give compressed biogas (CBG). (Persson, 2003).

2.3.2 Lignocellulosic ethanol production

Lignocellulosic ethanol production is referred to as the second generation of ethanol production (the first generation is based on direct fermentation of starch or sugar crops) and is produced using any type of material consisting of celluloses and lignin, such as woody materials or straw. In the process, the material undergoes a pretreatment and then a hydrolysis (saccharification) process in which the enzymes break down the cellulose and hemicelluloses into shorter carbohydrates, i.e. pentoses (C5) and hexoses (C6). Hexoses are easily fermented to ethanol with the addition of yeasts, whereas pentoses are more difficult in this respect and can be used as cattle or pig feed or for biogas production (Dwivedi et al., 2009). The lignin content of the material is separated in the process and with its high LHV (approximately 27 MJ/kg ts) constitutes a good biofuel, which typically is used for process energy.

Although not yet in commercial production, according to official company data from DONG Energy, the yield of the production process is approximately 0.2 l ethanol/kg ts of straw (Inbicon, 2010). Research is however on-going at several locations in the world to increase production efficiency (Gnansounou&Dauriat, 2010).

For the ethanol to reach fuel quality, additives such as ignition improver (when used in diesel engines), denaturant, corrosion inhibitor and water must be added (Bernesson et al., 2005). Vehicles running only on ethanol fuel require a higher resistance to corrosion, and the alcohol can moreover be aggressive to rubber components. Ethanol fuel has a lower energy density than petrol, but also a higher octane number, which means higher engine efficiency (Hsieh et al., 2002).

2.3.3 Small-scale combined heat and power (CHP)

To date, the development of heating plants and combined heat and power (CHP) plants has been towards increasingly large-scale plants, due to scaling-up benefits such as higher electric efficiency. However, biofuels are also commonly used in small-scale heating systems, as for example pellets boilers for use in residential buildings. Using unprocessed biomass such as wood chips and straw or gasified biomass such as syngas or biogas, in decentralized systems could also prove preferable to large-scale systems, because transportation of non-compacted biomass and gases over long distances is not cost- or energy efficient due to the low energy density. Biogas can produce CHP in conventional internal combustion engines after cleaning of hydrogen sulfide (Bedoya et al., 2009). Microturbines for use with biomass with electric output of a few kW(e) are commercially available today and can be a viable technology for small-scale production of heat and power (Dong et al., 2009). The Stirling engine is manufactured in capacities down to a few kW(e) and produce heat and electricity via external combustion, which allows for fuel flexibility and the use of fuels with difficult combustion properties (Kjellström, 2007).

2.4 Energy balance of biofuels

The fact that production of biofuels requires a substantial amount of energy, which is often of fossil origin, has made some experts question their use as a renewable fuel. It is therefore relevant to calculate the required input energy required in relation to the output energy obtained in the form of biofuels.

There are several studies in the literature on the energy balance of biofuels. According to a study by Börjesson (2004), primary energy required to produce biogas from ley or ethanol from wheat range between 42-76% of the energy content in the fuel, depending on the pathways assumed for the co-products. The corresponding figure for production of RME from rapeseed in an organic production system is reported to be in the range of 25–30%, depending on the scale of production (Bernesson et al., 2005). A study by Ahlgren et. al. (2008a), indicated that Fischer-Tropsch diesel (FTD) produced from straw or Salix contains 8.9 and 9.6 times more energy than the input of primary energy, while the corresponding figures for dimethylester (DME) from straw or Salix is 10.1 or 10 respectively.

2.5 Greenhouse gas emissions from biofuels

The potential for GHG emission reduction through the use of biofuels has been questioned. Although most studies conducted to date show that biofuels provide a reduction in GHG emissions compared to fossil fuels (Cherubini et al., 2009), the results can vary considerably. According to e.g. Börjesson (2009), Spatari et al. (2010) and (Whitaker et al., 2010), the main source of the variability is the different assumptions and methodological choices made. A synthesis study by (Gnansounou et al., 2009) comparing outcomes from assumptions on land use changes, allocation methods , fuel efficiency etc. reported that the results fall in the range of –24% to 383% emissions from biofuels compared with fossil fuels, depending on the choices made. According to that study, biofuels will only reduce GHG emissions compared with fossil fuels if there are no adverse indirect land use changes, such as deforestation. Cutting down forest stands releases carbon dioxide to the atmosphere (previously bound in the standing biomass) and creates a carbon debt. The payback time of this debt can be very long. According to a study by Fargione et. al. (2008), the payback time for cutting

down rainforests to establish palm oil plantations in Malaysia, or soybean plantations in Brazil (both for the production of biodiesel), is 423 years and 319 years respectively. The payback time for maize ethanol on agricultural land in the US is 48 years according to the same study.

In addition, such crops means more tillage of the soil than forests and the soil will parts of the year be uncovered, two factors that increases the rate of mineralization of carbon to carbon dioxide (Andrén&Kätterer, 2001). In early LCA studies of biofuels, such effects of soil carbon dynamics where omitted due to lack of scientific data and reliable models to estimate the effect on soil carbon of different land use. Lately this aspect has however gained attention and today there are a number of models used to simulate the carbon dynamics in agricultural soils.

Modern cultivation practices that apply nitrogen fertilization to maximize yields also result in cultivated soils becoming an important source of nitrous oxide (N_2O) emissions. N_2O is produced when nitrogen (N) mineralizes via the activity of microbes, and the production rate depends on soil climate parameters such as temperature and moisture content. The relationships are complex and contain threshold effects and feedback systems, and can therefore differ widely between geographical areas (Kasimir-Klemedtsson, 2009). N_2O has a very high global warming potential (approximately 300 CO_2-equivalents) which means that the calculation methodology and assumption made have a high impact on the final results.

3 Methodology

3.1 Consequential LCA

The consequential approach to LCA was used in this thesis. The principle of this approach is to calculate the *change* in emissions due to the introduction of a new product or service onto the market (Ekvall&Weidema, 2004). Use of material and energy has an impact on related markets, i.e. increasing demand will cause a marginal increase in production, and it is the emissions from this marginal increase that are attributed to the system. Hence, marginal data are always used, whereas in the attributional LCA average data are used and the emissions calculated stem from a snapshot of the product. This means that system expansion is used to handle by-products in consequential LCA whereas allocation (and sometimes system expansion) is commonly used in attributional LCA. (Finnveden et al., 2009)

3.2 Scope and limitations

In this thesis, energy systems based on biomass resources from the agricultural sector were analyzed. The demands on substrates studied for the energy supply systems were that they should be renewable and possible to harvest with typical farm machinery and to use in technical systems for energy generation. Moreover, the biomass had to not be in competition with food production but consist of residual products or products cultivated on land that would otherwise lay fallow. For the technologies studied, the preconditions were that they had been demonstrated successfully and that they could be considered feasible based on information from producers, scientists or other relevant actors that they become commercially available

within the next five years. However, the current investment and operation costs of the systems were not considered. Technical data were chosen so as to represent the current state of the systems, for example conversion efficiency and process energy requirement.

The location of the farm was chosen in order to be representative for Swedish climate and production conditions, and hence it was placed in the County of Västra Götaland in south-western Sweden. The farm applies organic production methods in accordance with the European regulations (EC, 2007a) in a 7-year crop rotation shown in Table 1. The suggested infrastructure and distance between farm and external facilities used in the systems were developed based on the conditions of this region.

3.3 Energy and material flows

The basic concepts of the material and energy flows in the two studies are shown in Figure 1. Production at the farm has two main outcomes; commodities such as cash crops, residues such as straw, and ley used as green manure. These are converted into useful high value energy carriers, and where the residues contains nutrients (nitrogen and phosphorous) these are returned to the production system (the soil) in the form of digestion residues and ashes. Any by-products or co-products are sold on the market where they substitute other, potentially more emission-intense products.
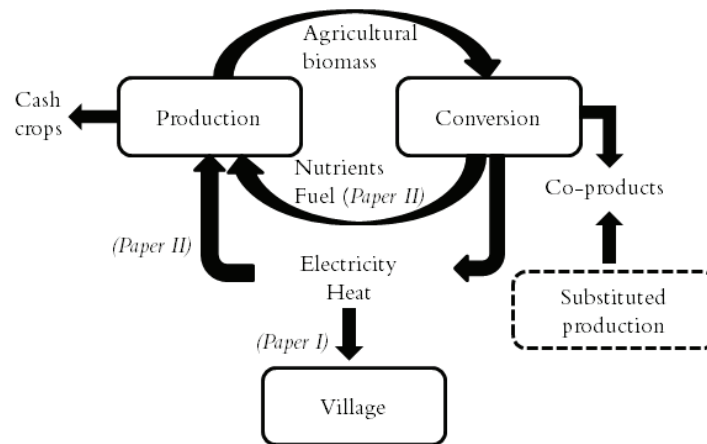

Figure 1. Schematic description of the energy and material flows in LCA systems. Where specified, the flows take different routes in paper I and II.

3.4 Calculation of emissions

Greenhouse gas emissions (Papers I and II) and acidifying emissions (Paper I) are formed during production activities such as tractor use and crop drying, transportation, in the soil, process energy for conversion of biomass to useful energy carriers, during combustion of the fuel (Paper I only) and from production of infrastructure (included to a very limited extent).

3.4.1 Machinery

Emissions from tractor use, crop drying and transports in the reference scenarios were calculated by applying emission factors for the fossil fuels used in the respective machinery, taken from Uppenberg et al. (2001) multiplied by the fuel consumption for each activity using factors taken from Lindgren et al. (2002). Combustion of the biomass-based energy carriers in the respective machines or technical systems was assumed to be a carbon neutral process (as is common practice in LCA). However, in Paper I formation of methane and N_2O in engines was included.

Manufacturing of machinery, plants and equipment was excluded, based on an assumption that this constitute a small proportion of the total emissions (Bernesson et al., 2005).

3.4.2 Process energy

Process energy for conversion of biomass to the respective energy carriers was based on the actual fuel produced in all scenarios, since the aim of each technical system in both papers was to create circular (self-sufficient) systems, in Paper I an "isolated" energy supply system with system boundaries drawn around the farm and the village (although an exchange takes place with the national electricity grid), while in the Paper II there was a self-sufficient system for the farm only (also with an exchange to the national grid). This means in fact that all energy use is carbon neutral in the biomass-based scenarios.

Emissions from the digging of trenches for a pipeline system for heat supply to the village in Paper I, and for biogas pipelines in Paper II, was included because it was considered to have a potentially large impact.

3.4.3 Soil emissions – nitrous oxide

Calculating emissions of N_2O from the soil is a less straight-forward task due to lack of reliable models and data on the oxidation of N_2 to N_2O, in particular with high geographical resolution. The most established methodology today for calculation of N_2O from agricultural soils is that suggested by IPCC (2006), in which it is assumed that a certain fraction of applied N_2 will be reduced to N_2O via microbes in the soil and volatize. N_2O emitted (in kg/ha) from the application of fertilizer is calculated according to equation 1:

Equation 1. $N_2O_{emitted} = D_{ts} \times Frac_{N-tot} \times (44/28) \times EF$ *(kg/ha)*

where *D(ts)* is the amount of fertilizer, in kg ts (total solids), *Frac (N-tot)* is the fraction of N-tot in *D(ts)* and *EF* the emission factor, i.e. the percentage which is assumed to be volatized as N_2O. The factor 44/28 is a conversion factor from N_2 to N_2O.

In the same way, emissions from crop residues left on the fields are calculated. The emission factor for crop residues is 1% of N contained in the biomass (IPCC, 2006). Data on crop residues left on the fields were taken from the Swedish National Inventory Report to the UNFCCC (S.E.P.A, 2008) and the ratio of biomass above and below ground in Salix plantations (van Bussel et al., 2005). Data on N content in the respective type of biomass were taken from IPCC Guidelines (2006).

Indirect emissions in the form of leached N that volatizes downstream were set to 0.75% of leakage (IPCC, 2006) and the amount leached was assumed to be 11 kg N/ha (Wivstad et al., 2009). The amount of applied N that volatizes as ammonia and is later redeposited was assumed to be 1.2% of applied fertilizer based on common Swedish fertilization practices (Ahlgren et al., 2009) and the emissions factor of the re-deposited N was set to 1% (IPCC, 2006).

3.4.4 Soil emissions – carbon dioxide

The carbon (C) dynamics of agricultural soils is commonly estimated by the use of models that simulate the rate of carbon dioxide formation given relevant parameters. A special methodology was developed for the specific crop rotations used in this thesis. The methodology is based on the ICBM model developed at the Soil Science Department at SLU (Andrén&Kätterer, 2001). The model assumes two carbon pools ("young" and "old") of which only C entering the old pool is considered bound in the soil. This is because the decomposability is 100 times higher in the young pool (Andrén et al., 2004), meaning that the C quickly mineralizes and is emitted as CO_2. The most important parameters are C input (from crop residues such as straw, rhizodeposition and manure), humification rate and soil climate. The humification rate depends on the ratio of the C sources, with a lower rate for ploughed-down crop residues than for manure (Andrén and Kätterer, 2004). The mineralization rate of C increases with increasing frequency of soil tillage, and will consequently be higher for the annual crops in the crop rotation than for perennial crops, which is accounted for in the soil climate parameter that is based on climate parameters for the region (air temperature, precipitation and potential evapotranspiration).

The C input is calculated according to equation 5.

Equation 5. $(((Y_c \times Frac_{ssrr}) - Frac_s) \times Frac_C) + (DR \times Frac_C)$

where Y is the crop yield in dry matter, $Frac(ssrr)$ is the fraction of the yield left on the field or in the soil after harvest, for example straw, stubble, roots and rhizodeposition and $Frac(s)$ is the fraction of the total straw production that is removed (only wheat straw is collected). DR is the amount of fertilizer spread per hectare. $Frac(c)$ is the fraction of C of the biomass on dry matter basis.

In the adapted model used here, the carbon content of the soil was simulated during three crop rotations (21 years) given an assumed initial carbon content year 1. Each year and for each field, the C content will increase or decrease based on the amount of C input to the soil in the form of crop residues and fertilizers and parameters set in the ICBM model. The resulting C content after each year's cultivation is the input data for the next

year. The simulation was also applied to the Salix plantation in paper I, which was assumed to have a lifetime of 21 years (also the timeframe for the simulation of the crop rotation).

Table 1. *Yields of cash crops and associated crop residues*

	Field beans	Oats	Ley	Rapeseed	Winter wheat	Ley	Rye
Crop yield (kg DM/ha yr)★	2400	3200	6000	2000	3500	6000	3200
Straw yield★★ (kg DM/ha yr)★	–	2756	–	1818	2846	–	4571
Total plowed down biomass★★★ (kg DM/ha yr)	3600	4800	1500	6000	7000	1500	4800

★(Ahlgren et al., 2008b)
★★(Berglund et al., 2002)
★★★(Sundberg et al., 1997)

Total C concentration in the cultivated soil was assumed to be 2.4% based on weighted means of C content in the sandy loam and loam of the South Central Plains but excluding high C soils (Andrén et al., 2008). The mean was based on nationwide samplings of soil (Eriksson et al., 1997). Soil mass was assumed to be 3 million kg soil/ha.

The C content of all growing biomass was assumed to be 46% on dry matter basis, and the C in the digestion residues from biogas production was calculated to 48% based on an initial C content of the silage of 45.8% (Nordberg&Edström, 1997) and a reduction in total solids and C reduction in the digestion process of 38% and 35% respectively.

4 Paper I and II – systems descriptions and results

4.1 Basic farm description

The farms in paper I and paper II are identical with respect geographical location (i.e. weather conditions) and the applied crop rotation (Table 1). In both studies, the farm was assumed to apply organic production methods according to the criteria stipulated in Council Regulation (EC) No 834/2007. As a substitute for commercial fertilizer, which is not permitted in organic farming, the crop rotation included an N-fixing ley crop twice in the 7-year rotation, also referred to as green manure (Table 1). In the reference scenarios, the green manure is ploughed back into the soil, and in two of the scenarios harvested and used as substrate for biogas production.

The area of the farm was not defined in Paper I, where minimum land area required for the energy supply system was calculated as a result of the biomass demand from the energy supply system. This area is not necessarily limited to one farm, but could be a farm cluster. It was moreover assumed that the farm has set-aside land available which in the reference system is unmanaged (not fertilized or harvested) grassland. This land is used for Salix production in two of the scenarios.

In Paper II, the area of the farm with a self-sufficiency system was set to 200 ha. For this study, the dimensions and materials of the farm buildings were specified in order to calculate energy demand. Buildings consuming energy are the residential house (150 m^2) and a workshop (40m^2).

4.2 Paper I - CHP supply for a rural village

4.2.1 System descriptions

Four different scenarios for supply of heat and electricity to a village were described and assessed. The impact categories were Energy use, Global Warming Potential (GWP) and Acidifying Potential (AP), and the functional unit (FU) is one year supply of heat (including hot water) and electricity to the village consisting of 150 modern houses.

Three of the scenarios utilized the organic biomass produced at the farm for production of heat and power in small-scale CHP plants. The system were based on biogas produced with ley as substrate, used in a microturbine (Bio1), gasification of Salix chips with gas combusted in an IC-engine (Bio2) an use of Salix chips in a Stirling engine (Bio3). The two first scenarios also required a straw boiler for extra heat supply in the winter whereas the system in the third scenario has a high heat output which covers the demand in the winter (with high losses in the summer).

In the fourth scenario, heat was produced in electricity-driven heat pumps, and all electricity consumed in the village (including household electricity) was assumed to be produced in a natural gas-fired large-scale power plant (the scenario is referred to as NG and is the reference scenario).

The systems are described schematically in Figure 2. The upper box represents external production of input factors. The middle boxes represent the field activities related to Bio1 (to the left) and Bio2 and Bio3 (to the right), and the box at the bottom represent the technical systems used for the systems.
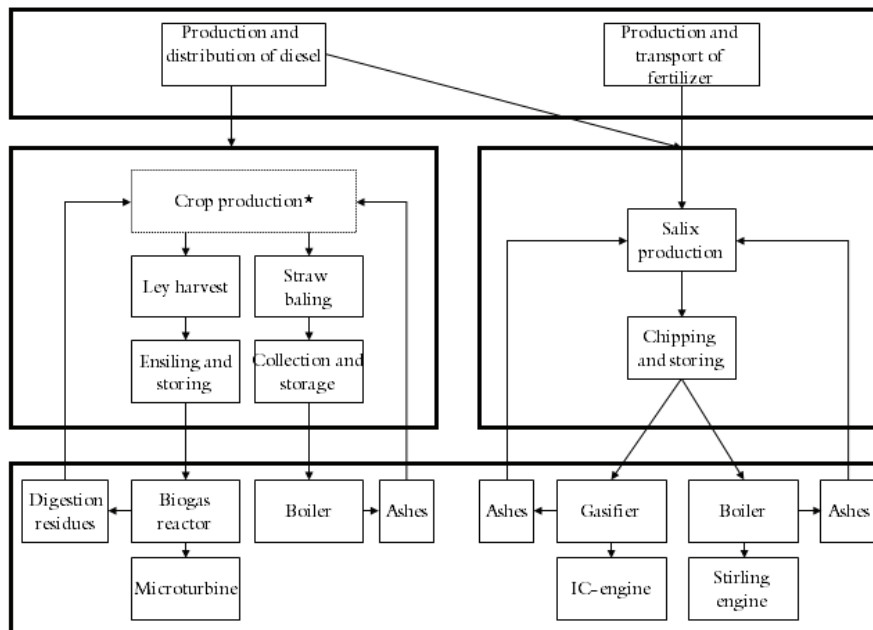
The crop production constitutes the reference system from which changes induced by biomass production for energy generation are calculated.

Figure 2. The different pathways represent the different biomass-based scenarios. Left middle box shows activities in Bio1, right middle box activities in Bio2 and Bio3. The ends of the figure also represent the system boundaries.

4.2.2 Results

The farm can supply the village with heat and power in either of the three scenarios. The land requirement is shown in Table 3; this land area does not correspond to extra land taken into production, but is an indication of the land area that residues will have to be collected from, or how much set-aside land that will have to be taken into production.

Table 3. *Area from which biomass is collected in each scenario (ha)*

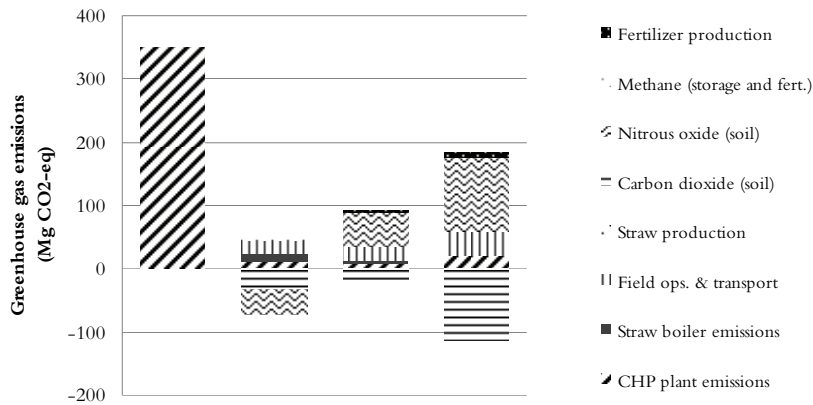|	Bio1	Bio2	Bio3
Farmland			
Ley	303	0	0
Straw	99	40	0
Set-aside land			
Salix	0	81	169
Total	402	121	169

Figure 4. Relative GHG emissions of the respective scenarios

The results with respect to GHG emissions are given as total emissions from activities related to energy production; field operations beyond what would otherwise take place in the reference system (for example straw baling), emissions during conversion, etc. For soil emissions, the *change* in emissions compared to the reference crop production system were calculated. This means that the results can turn out negative, if the emissions are lower in the respective biomass-based scenarios compared to the reference scenario. In the NG scenario, net emissions are 351 Mg CO_2-equivalents/FU which hence stem from the fossil fuel consumption, and the cultivation system in this scenario is set 0 (baseline).

For Bio1 the net GWP is negative (-19 MgCO_2-equivalents/FU) compared with the reference scenario due to a cultivation system where ley is anaerobically digested instead of ploughed down fresh. This is both increasing the soil C content and reduces the emissions of N_2O from the soil, the latter due to the possibility of a more strategic distribution of the organic material and nutrients from spreading the storable digestion residue compared with ploughed-down ley, which results in a large amount of organic material and N in two of the seven fields in the crop rotation.

In Bio2 and Bio3, a C sink is created with the establishment of Salix on set-aside land. The effect is larger in Bio3 because the area planted is about

twice as large as in Bio2. On the other hand, emissions of N_2O increased compared with the reference case, due to fertilization of set-aside land (unfertilized in the reference scenario) and the higher quantities of crop residues on the fields. Net GWP for Bio2 and Bio3 is 60 and 42 Mg CO_2-equivalents/FU, respectively.

4.3   Paper II - Energy self-sufficiency systems

4.3.1 System descriptions

Paper II of this thesis describes and assesses two different scenarios for an energy self-sufficiency system for the farm. The impact categories were Energy use and GWP and FU was the supply of heat, electricity and fuel for the entire farm for one year.

The first scenario, ESS I, was based on biogas production from the ley used as green manure. The biogas produced was used in a CHP system, i.e. an IC engine, in the grain dryer and in an external upgrading plant. Heat from the CHP system was distributed between the farm buildings and the biogas plant, and the produced electricity covers the requirement of the buildings, biogas plant and upgrading facility on an annual basis, even though an exchange with the national grid takes place. Digestion residues from the biogas production were returned to the fields. The biogas upgrading plant produces liquefied biogas (LBG) with 99% methane content at an external, large-scale upgrading plant for field operations on the farm. Liquid CO_2 (LCO_2) is a co-product from the upgrading and was used in the upgrading process as cooling agent (99%) and sold on the market for refrigerants (1%).

The second scenario, ESS II, was based on production of ethanol fuel from wheat straw produced at the farm at a large-scale lignocellulosic ethanol production facility. Electricity is produced as a co-product from lignin separated in the process, and covers the farm and process requirement. However, the electricity was fed to and retrieved from the national grid. Heat was supplied to the farm via a straw furnace.

In the reference scenario, the farm used diesel for field operations, oil for grain drying and electricity consumed was assumed to be produced from natural gas.

For calculation of energy balance, the energy consumption was divided into three categories: Cash Crop Production (CCP), which includes field operations and grain drying; Farm (F), which includes heat and electricity for the residential building and the workshop; and Energy Carrier Production (ECP), which includes harvest and storage of straw and ley, ley digestion, transport to and from external fuel production facilities and process energy for fuel production. TEC is the total consumption of energy in each scenario, i.e. the three categories mentioned above combined.
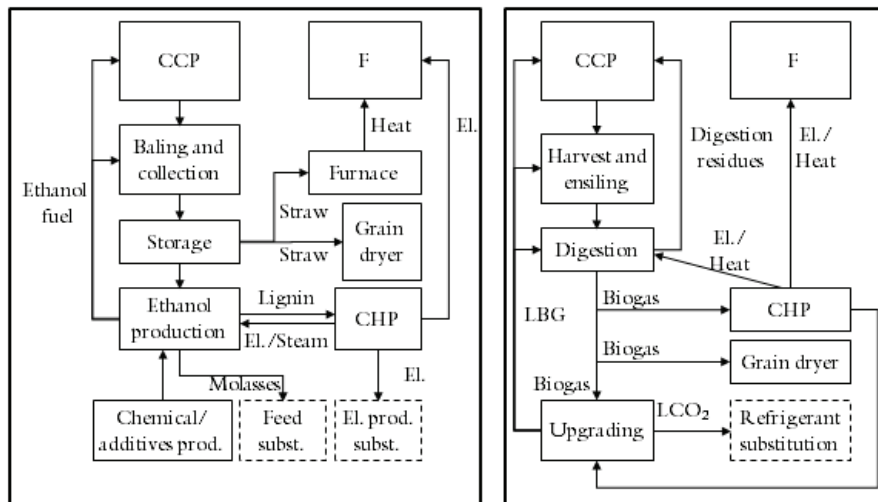

Figure 4. Energy and material flows in the self-sufficiency scenarios. Cash crop production is referred to as CCP, the farm (including residential house and workshop) as F and energy carrier production as ECP. Dotted boxes represent processes avoided in the self-sufficiency scenarios.

4.3.2 Results

The farm can become self-sufficient in energy in both of the two described systems. ESS I requires that ley is harvested from 25 ha, which is 13% of the

total farm area. ESS II requires 49 ha of straw, which is 25% of the total farm area. This biomass is available, since ley is planted on 29% of the farm area and cereals on 44% in the given crop rotation (Table 4).

Energy balance is shown in Table 4. The system in ESS II requires more energy, but also utilizes a larger fraction of the energy content of the biomass. A considerably larger fraction of the energy used is process energy for the conversion to energy carriers in this scenario compared with ESS I.

Table 4. *Energy requirement as Total Energy Consumption (TEC), Energy Carrier Production (ECP) as fraction of TEC, ECP as fraction of energy consumption for cash crop production (CCP) and farm buildings (F) and utilization of primary energy in biomass*

	TEC (GJ)	ECP/TEC	ECP/ (CCP+F)	Fraction of energy in biomass utilized			
				El.	Heat	Fuel	Tot
ESS I	1020	24%	31%	4%	16%	20%	40%
ESS II	1416	45%	83%	7%	23%	27%	57%
Ref.	755	24%	24%	n/a	n/a	n/a	n/a

The GHG emission calculations show that the reduction in emissions is 35% in ESS I and 9% in ESS II. Figure 5 shows the GHG relative to the reference scenario, which constituted the baseline.
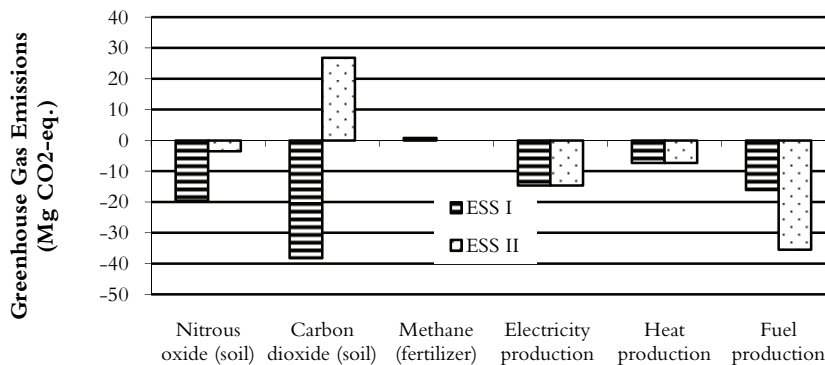

Figure 5. Relative GHG emissions from the systems in study 2, disaggregated

Nitrous oxide emissions from the soil are lower in both self-sufficiency scenarios compared with the reference scenario, but the impact on the C

content of the soil differs significantly. Methane released from digestion residues produced in ESS I only has a minor impact on the results, while production of all energy carriers, in particular fuel production that convey useful co-products, gives considerably lower GHG emissions than energy carrier production in the reference scenario.

5 Discussion

5.1 Potential barriers to farm-based energy supply systems

An important finding both in Paper I and in Paper II is that the energy supply systems in the respective papers are indeed possible with the chosen technologies. The systems could be implemented as a means to make the organic farm more competitive against the conventional farm based on the high sustainability of the production methods, and also securing energy supply for the future.

There are however other barriers than the physical/technical barriers to the actual implementation of the systems. Investments are always associated with risks, such as falling electricity prices that result in lower revenues for the producer. The farmer must be willing to accept certain risk, or be relieved fully or partially of the risk by polices measures such as feed-in tariffs (Germany), or green certificates and investment supports (Sweden). For the farmer, the implementation of an energy supply system will also consume time and personnel for operation and maintenance, in particular during the initial phase of installation and learning.

5.2 Implications of straw removal

Agricultural soils is an important global C sink (Batjes, 1996). Measures that increase the soil C include adding crop residues and other organic matter to

the soil, reduce tillage, improve soil texture and soil fauna activity etc (Sainju et al., 2008). Trials are currently on-going in different parts of the world on the impact of adding charred residues from biomass gasification (biochar) to the soil, with early results showing that this could both increase the soil C content and the productivity, and with a long-term effect (Downie et al., 2010). Growing perennial crops such as Salix is a way to stock C in the soil, as the Salix trees continuously add organic matter via leaf deposition and through roots and rhizodeposition. In addition, they cover the soil a large proportion of the year which reduces the rate of C oxidation. Another important parameter is the frequency of tillage, since perennial crops require less tillage than annual crops. According to research at the U.S. Department of Agriculture, CO_2 is emitted from the soil in proportion to the volume of soil loosened (Sundermeier et al., 2004). This has however been contested by a study by for example Baker et al. (2007), indicating that no-till agriculture merely results in a redistribution of soil organic matter to a deeper level in the soil.

Hence, removing straw from the soil as in scenario ESS II in Paper II is perhaps counter-productive when it comes to lowering GHG emissions from agriculture, as it means not utilizing the soil's natural ability for carbon sequestration. The lignocellulosic ethanol production technology in this scenario is considerably more complex, expensive and immature than the biogas production and upgrading technologies used in the biogas-based system. Research efforts are underway in for example the USA, Canada and Denmark to increase the efficiency and cost-efficiency of this technology – however, this study indicate that it is relevant to ask whether the climate benefit is really there, and consequentially whether all this effort should be devoted to this technology.

5.3 Implications of the use of marginal land

In Paper I, it was assumed that there is available set-aside land for the farmer, which means that ILUC effects can be excluded. According to estimations from the Swedish Board of Agriculture (2008), there are approximately 300 000 ha of set-aside land available in Sweden – marginal land that is not cultivated due to a lower soil quality, inconvenient shape or location or slack of profitability. However, on a global scale such land

cannot be expected to be available. A study conducted by the Stockholm Environmental Institute (Johnson et al., 2010) indicated that the potential for future biofuel production on available agricultural land is unevenly distributed over the world, with the largest potential found in Latin America and sub-Saharan Africa where there is still uncultivated agricultural land available. Asia, although it contains available land areas, was considered to have less potential due to an expected faster increase in population and wealth, and consequentially higher pressure on food production. Moreover, in Central and Eastern Europe substantial land areas could be freed with an increase in yields, which on average are only half of yields in Western Europe (Fischer et al., 2009).

An on-going discussion for policymakers in EU is how to account for ILUC effects under the RED. One solution is to include a quantified ILUC factor, added to the calculated emissions from production and processing etc. However, studies conducted up to date on potential ILUC factors have reported very diverging results, indicating the methods to estimate the ILUC effect from biofuel production need to be further developed and refined. A method for calculating an ILUC factor would include both actual analyses of how the global land use changes over time (for example with Geographical Information Systems, GIS), economic models that can track the trade of agricultural commodities (such as the Global Trade Analysis Project model, GTAP) and a number of experts from several disciplines.

5.4   Implications of methodological choice

Methodological differences in LCA studies were reported by Whitaker et. al. (2010) to be the main reasons behind the highly variable or even completely opposing results from LCA studies on biofuels. Two main approaches to LCA have been identified; the consequential and the attributional approach. These differ in that the consequential LCA describes the impact of a change to a system, and uses marginal data, whereas the attributional LCA describes the system in a "snapshot" and average data are used (Finnveden et al., 2009), (Ekvall&Weidema, 2004).

Which of the two approaches that should be used, and when, has been debated amongst LCA practicioners. Some argue that the attributional type

is best suited e.g. for labeling schemes, because it is a simple and transparent approach that gives an indication of the present impact of a certain product/service. The consequential approach would be appropriate for assessing the expected impact of a new product/service, or different policies to promote for example renewable energy systems, as it gives an indication of how a change of the system would affect the environmental impact (Lundie et al., 2007a).

The consequential approach was chosen for both studies in this thesis. However, when choosing consequential LCA the challenge is to find relevant and accurate marginal data, as such data often are associated with having to make projections of the future and consequentially high uncertainty. Situations in which a projection of the future is necessary are usually handled with models and simulations, or by making educated assumptions based on currently available information. It should however be kept in mind that the uncertainty of data can be high in consequential LCA.

5.5   Estimating soil emissions rates

5.5.1 Nitrous oxide

There are currently insufficient field trials conducted or accurate models available to statistically verify the relationship between different parameters affecting the volatilization of N_2O from agricultural soils (Berglund et al., 2009). A few methodologies for emission estimations have been suggested. The IPCC (2006) method used here assumes a linear relationship between N_2O emissions and the amount of N added to the soil in the form of commercial fertilizers, farmyard manure, N-fixating crops and crop residues, and gives emission factors based on conducted field measurements. The methodology was developed to fit data collection for the national inventor reports on GHG emissions to the UNFCCC.

Other studies indicate that the emission rates with the IPCC methodology are underestimated. Based on synthetization of international data, Kasimir–Klemedtsson (2008) suggested emissions to be 4,1±2,5 and 5,0±7,2 kg N_2O/ha and year, for fertilization with less and more than 100 kgN/ha and year respectively. Crutzen et. al. (2008) estimated the emissions to 3-5% of added nitrogen by studying the pre-industrial level of N_2O in the

atmosphere and comparing to the current level, with the difference assumed to be anthropogenic emissions. When the emissions from industrial activities were deducted from the total, the remainders were assumed to be from global soils. A study from the EU:s Joint Researach Center (JRC) based on a soil model by Edwards et al. (2007), assuming a linear relationship between the soil organic C concentration and N_2O emissions, gives 2,23 kg N_2O per hectare and year of grains on average for all EU member states.

N_2O is a greenhouse gas with almost 300 times the global warming potential (GWP) of CO_2, which means that they potentially have a very large impact on the LCA results. The sensitivity analyses conducted in Paper I and Paper II suggests that the emission factor chosen for N_2O will play a large role for the results – as shown in Paper II, altering the emission factor +/-20% changes the total GHG emissions +/-5%. Hence, the methodology chosen to calculate N_2O is important.

This is a major uncertainty contained in this study (as well as in all LCA study on agricultural products). However, it should be kept in mind that the IPCC methodology is based on a large number of studies and data from international science groups whereas the other studies rely on the work of individual groups or researchers. Therefore, it is currently considered the best method available, but better models based on validated data are urgently needed, and these require large numbers of field trials to be conducted.

5.5.2 Soil carbon

The carbon sequestration function of agricultural soils has been brought to attention by researchers in relation to the global warming issue. Carbon pools currently hold about 1500 Pg of C (Batjes, 1996), the equivalent to C storage in 7500 billion ha of tropical forest (Gibbs et al., 2007). Applying cultivation systems that causes superficial C to oxidize at an increased rate would mean an addition of CO_2 to the atmosphere and that this soil C sequestration potential is not utilized.

The ability of a Salix plantation to function as a C sink below ground is well–documented. Previous modelling studies have concluded that a Salix plantation annually sequesters 410 or 76 kgC/ha and year

(Grogan&Matthews, 2002); (van Bussel et al., 2005), corresponding to 1500 and 279 kg CO_2/ha not added to atmospheric CO_2.

The soil C content will decrease when cereals are grown organically as opposed to conventionally, according to a modeling study by Andrén and Kätterer (2009). Those authors concluded that this is mainly due to the low yields in comparison with conventional cropping, i.e. the lower C input to the soil (Andrén et al., 2009). However, an additional C input, in particular in the form of manure, would balance out the loss of biomass input. Triberti et al (2008) showed that after 34 years of organic fertilization, the soil organic C concentration of soil fertilized with cattle manure, cattle slurry and crop (wheat or maize) residues had increased by 51%, 30% and 19% respectively, compared with the non-fertilized control fields (Triberti et al., 2008).

The humification rate of the ley digestates is here assumed to be of the same rate as for cattle manure. This is partly based on a study by Marcato et al (2009) indicating that pig slurry shows higher stability (lower carbon mineralization rate) if digested than when fresh, and thus higher potential for build-up of soil C. Moreover, a field experiment at the Swedish University of Agricultural Sciences between 2003 and 2005 showed that the yield of spring wheat and winter wheat were 24% and 23% higher respectively when fertilized with anaerobically digested ley than if fresh ley was ploughed down (SJV, 2006). The reason for this was assumed to be the better nutrient uptake from processed ley compared with the fresh product due to mineralization of organically bound N to ammonium (NH_4).

5.6 Implications of key assumptions - marginal electricity production

As a side-study to this thesis, the problem of making a valid assumption with regards to long-term marginal electricity production capacity for LCA applications was studied in-depth.

It is the long-term marginal electricity capacity that is of interest as we are looking at systems implemented on a long-term basis, replacing existing capacity. It is important to differentiate between short-term and long-term

marginal electricity production. Short-term marginal production is 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 operation costs. The long-term marginal production involves changes in capacity, i.e. installment of new plants as a response to a change in demand from consumers. Whereas short-term marginal electricity can be determined with quite high certainty through historical data and statistics, the long-term marginal electricity production is not a straight-forward issue to identify as the answer lies in the future. How to handle this in LCA has been discussed by many experts on both LCA and energy markets (e.g. Finnveden 2008 (Finnveden, 2008)).

LCA practitioners in particular in the field of waste management (often conveying an element of substitution of existing energy sources) have put quite some effort into analytically solving the question, for example with dynamic energy system models taking into account market parameters (Lund et al., 2010). Others make simple assumptions, often with coal or natural gas on the margin (Mathiesen et al., 2009). The reality is, of course, that it is impossible to determine the exact response to an increase somewhere, as market factors, related policies as well as site-specific conditions (such as available resources, climate conditions and political situation) will come into play. It would however make the LCA studies more transparent, comparable and reliable if a consensus on the issue could be reached, to the extent that this is relevant, i.e. within common or interconnected energy systems. The electricity market is complex and today increasingly international, although with constraints, but performing complex modeling of the energy market for each individual study produced is hardly feasible from a time and resource perspective for the researcher. . An opinion paper was submitted to the International Journal of LCA in July 2010 (Kimming&Sundberg, 2010), suggesting a simplified approach to determining long-term marginal electricity production.

Throughout Paper I and Paper II, it was assumed that natural gas would be the fuel used in the units decommissioned as a result of the implementation of the new systems for farm self-sufficiency. This argumentation was based mainly on two facts. Firstly, studies have shown that 75% of planned new thermal electricity production capacity in Europe in 2007 was natural gas-fired plants (Kjärstad&Johnsson, 2007). Secondly, natural gas-fired plants have emissions that lie just between those of renewable energy sources

(nearly CO_2-free) and coal-fired plants (the dirtiest technology) so this is a rather convenient approximation. This is explained at length in Kimming&Sundberg (2010).

6 Conclusions

Organic arable farms can indeed supply small rural village with heat and power, or create a self-sufficient energy system by using agricultural residues or biomass grown on set-aside land.

The scenarios based on anaerobic digestion of ley require a higher input of energy for the production of energy carriers (i.e. input of energy beyond what is required for production of cash crops) compared with Salix, but lower than the straw-based scenario.

The ley-based systems also achieve the highest reduction in GHG emissions. Salix-based systems reduce GHG emissions when set-aside land is available for the production, but straw-based energy systems reduce GHG emissions to a far lesser extent.

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7 Future work

The assessment of energy supply systems based on an organic arable farm will be followed up by a similar analysis of self-sufficient energy supply systems on organic dairy farms. Dairy farms have substrates available for energy production in the form of manure from cattle, and straw and other residues from feed production. Future study objects could also be meat farms or horse farms.

One important finding in this thesis is that the soil emissions constitute a very large share of the emissions from agricultural biomass-based systems, and hence so will any changes altering these emissions in either direction. The methodologies and models used in this thesis for estimation of emissions of N_2O and CO_2 are perhaps the best options available today, but better tools for accurate and preferably site-specific soil emission estimations should be developed as the importance of bioenergy from agriculture increases.

Acknowledgements

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