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Title

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Abstract

This study delineates promising, innovative and resource efficient biochemical production concepts for the integrated production of ethanol and biogas as vehicle fuels from lignocellulosic biomass feedstock. Four scenarios are studied, two based on straw as feedstock, including a small- and a large-scale biofuel plant, one based on hemp as feedstock, representing an energy crop, and large-scale plant, and one based on a forest residue-based, large-scale plant. The study is based on a literature review and previous and ongoing work performed by the project partners, where the efficiency in pre-treatment and bioconversion to fuels in integrated processes have been experimentally determined. The complementary assessments performed within the study include modelling of energy and cost performance, and life cycle assessment of greenhouse gas performance. In addition, suitable geographic locations are identified, based on the technical implementation potential in existing infrastructure in Swedish district heating systems and forest industries, and on the regional potential of sustainable lignocellulosic feedstock supply from agriculture and forestry. The overall conclusion is that integrated production of ethanol and biogas from lignocellulosic feedstock is promising from various aspects and has the potential to provide several benefits, compared with separate production systems.

Keywords

Ethanol, biogas, lignocellulose, co-production, biorefinery

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The f3 project partners included in this study are Lund University, the Swedish University of Agricultural Sciences, Lantmännen Energi and SEKAB E-technology. Economic support has also been received from the Swedish Energy Agency's research programme Ethanol Processes and Solid Biofuels.

Lund, August 2013

The authors

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SUMMARY

This study delineates promising biochemical production concepts for the integrated production of ethanol and biogas as vehicle fuels from lignocellulosic biomass feedstock. The focus is on innovative and resource efficient production routes promoting the co-production of high-value products (ethanol, upgraded biogas and electricity), prior to large amounts of excess heat. Four scenarios are studied, two based on straw as feedstock, including a small- and a large-scale biofuel plant, one based on hemp as feedstock, representing an energy crop, and large-scale plant, and one based on a forest residue-based, large-scale plant. The study is based on a literature review and previous and ongoing work performed by the project partners, where the efficiency in pretreatment and bioconversion to fuels in integrated processes have been experimentally determined. The complementary assessments performed within the study include modeling of energy and cost performance, and life cycle assessment of greenhouse gas (GHG) performance. In addition, suitable geographic locations are identified, based on the technical implementation potential in existing infrastructure in Swedish district heating systems (DHS) and forest industries, and on the regional potential of sustainable lignocellulosic feedstock supply from agriculture and forestry.

The overall conclusion of this study is that integrated production of ethanol and biogas from lignocellulosic feedstock is promising from various aspects and has the potential to provide several benefits, compared with separate production systems. One example is increased biofuel conversion efficiency where up to over 60% of the energy in the biomass feedstock can be transformed to ethanol and upgraded biogas. This biofuel conversion efficiency is similar to that in, for example, thermal gasification. The total energy conversion could be between 70-85%, also including excess electricity and heat.

The production costs are lowest for large-scale biofuel production based on straw and logging residues. These systems are estimated to be profitable under current conditions, with a calculated production cost between approximately 4.50 to 6.40 SEK per litre of ethanol. For comparison, the current ethanol sales price is approximately 6.50 SEK per litre. However, small-scale co-production of ethanol and biogas is not profitable today due to high investment costs per amount of biofuel produced. Thus, scale effects are of significant importance since the capital cost is the dominating cost in the economy of the biofuel plants studied. Another critical parameter for the economy is the cost of enzymes and the amount needed in the processes in future commercial plants. Hemp-based co-production of ethanol and biogas is also not profitable today due to a significantly higher feedstock cost compared with agriculture and forest residues.

The biofuel production systems based on straw and logging residues lead to GHG reductions of 80 to 85%, compared with petrol and diesel. This is well above the required reduction level of 60% in future biofuel systems, stated in the EU renewable energy directive (RED). The corresponding GHG reduction of the hemp-based biofuel system is lower and approximately 55%, due to higher GHG emissions in the feedstock production phase. Enzymes are shown to be the main contributor of the GHG emissions in systems based on straw and logging residues, thus future dosages and production systems of enzymes will significantly affect the GHG performance of integrated production systems of ethanol and biogas.

To maximize the profitability and the overall energy efficiency of future combined ethanol and biogas production systems, where also excess heat is produced, these systems should preferably be integrated with potential heat sinks. Regarding large-scale, straw-based biofuel plants, suitable locations are Skåne and Östergötland, where a sufficient amount of straw for energy purposes is available. In Skåne, the city of Lund could be an option for integration to the district heating system, and in Östergötland in the city of Norrköping, the plant could be integrated with the existing ethanol plant based on cereals. Regarding large-scale logging residue-based biofuel plants, suitable locations will be along the Norrland coast, and in inland counties such as Jämtland and Dalarna. In these regions, the amount of logging residues available for energy purposes is sufficient, and integration options exist in forest industries and, to some extent, in district heating systems in the larger cities. A preferable location from a business point-of-view is in connection to large-scale ports which would provide increased flexibility regarding the supply of biomass feedstock.

Lignocellulosic feedstock in the form of agriculture and forest residues normally fulfils existing sustainability criteria, as defined in the EU's RED, but there are some environmental risks linked to an extensive increase in recovery. Examples are the effects on biodiversity, soil carbon content, nutrient balances and long-term soil productivity. However, such risks could be minimized with appropriate measures, for example by avoiding or partly recovering residues on critical sites, nutrient compensation, etc, but also by cultivating dedicated energy crops on fallow and abandoned land. Energy crops normally have better environmental performance than traditional food crops, but cultivation of energy crops, such as hemp, may raise questions about land use competition. The process concepts included in this study assume incineration of the digestion residues (after dewatering) for generating process heat. However, from a sustainability point-of-view, it may be more attractive to apply the digestion residues as biofertilisers, especially if external nutrients are added to the process, leading to recirculation of nutrients and organic material back to arable and forest land.

Commercial investors in new, large-scale, integrated ethanol and biogas plants need to handle technological risks, financial risks and market risks. The technological risks will be reduced by more applied research together with the development of pilot and demonstration plants. Thus, there is motivation in the near future to increase the funding within this field of R&D. In the longer term, it is crucial that policy makers introduce investment subsidies for the first large-scale commercial plants being built, to reduce the inherent and great financial risk. Additional long-term, stable and efficient biofuel policies, including taxation of competing fossil vehicle fuels, are needed to reduce market risks for sustainable and resource-efficient biofuel production systems.

Lignocellulose-based, co-production systems, such as the ones analysed here, could also lead to decreased risks compared with separate biofuel production systems based on a specific feedstock. The flexibility in feedstock, for example, opens up for a large and diverse biomass raw material market. The diversification in products also leads to operation on different markets, leading to reduced commercial risks. Future lignocellulose-based, co-production systems could also produce additional, high-value chemicals, which opens up additional markets.

There are today three clear trends regarding the development of biofuel production systems;
- increased focus on sustainable production of biomass feedstock

- increased focus on the competition for arable land, which promotes low, indirect impact biofuel systems
- maximizing the output of high-value products from the biomass feedstock, which is driven both by increased feedstock costs and improved environmental performance.

All these three trends promote innovative biofuel production systems, such as integrated production of ethanol and biogas from lignocellulosic biomass.

SAMMANFATTNING

Denna studie beskriver och analyserar biokemiska produktionskoncept för att samproducera etanol och biogas som fordonsbränsle från lignocellulosa. Fokus är på innovativa och resurseffektiva produktionsvägar som premierar högvärdiga produkter (etanol, uppgraderad biogas och el), framför stora mängder av överskottsvärme. Fyra scenarier studeras, två baserade på halm inklusive en småskalig och en storskalig anläggning, en baserad på hampa som representerar energigrödor inklusive en storskalig anläggning samt en baserad på skogsbränsle inklusive en storskalig anläggning. Studien baseras på en kunskapssammanställning samt tidigare och pågående forskning av de partners som ingår i projektet kring effektivitet i biokemisk förbehandling och omvandling till biodrivmedel i integrerade processer via experimentella försök. Kompletterande analyser i studien är modellering av energibalans och kostnader samt livscykelanalys av växthusgasemissioner. Dessutom identifieras lämpliga geografiska lokaliseringsplatser i Sverige baserade på den tekniska implementeringspotentialen i existerande infrastruktur i form av fjärrvärmesystem och skogsindustri, samt den regionala potentialen av hållbar biomassetillförsel från jord- och skogsbruk.

En generell slutsats i denna studie är att integrerad produktion av etanol och biogas från lignocellulosa är lovande utifrån olika aspekter och har potential att ge många fördelar jämfört med separata produktionssystem. Ett exempel är en ökad energikonverteringsgrad från biomassa till biodrivmedel där över 60% av biomassans energiinnehåll kan omvandlas till etanol och uppgraderad biogas. Denna konverteringsgrad är jämförbar med de vid till exempel termisk förgasning av lignocellulosa till drivmedel. Den totala energikonverteringsgraden varierar mellan 70-85% när också överskott av el och värme inkluderas.

Produktionskostnaderna är lägst för storskalig biodrivmedelsproduktion baserade på halm och avverkningsrester. Dessa system uppskattas kunna bli lönsamma under dagens förutsättningar. Den beräknade produktionskostnaden ligger mellan 4,50 och 6,40 SEK per liter etanol vilket kan jämföras med dagens försäljningspris kring 6,50 SEK per liter etanol. Däremot är inte småskalig samproduktion av etanol och biogas från lignocellulosa lönsam idag p g a höga investeringskostnader i förhållande till den mängd biodrivmedel som produceras. Skaleffekter har således en stor betydelse för lönsamheten eftersom kapitalkostnader är den största kostnadsposten i de biodrivmedelsanläggningar som studeras här. En annan kritisk parameter för lönsamheten är kostnaden för enzymer samt volymen enzymer som krävs i omvandlingsprocesserna i framtida kommersiella anläggningar. Hampa-baserad samproduktion av etanol och biogas är inte heller lönsam idag p g a höga råvarupriser jämfört med skörderester som halm och avverkningsrester.

De produktionssystem för biodrivmedel som baseras på halm och avverkningsrester ger en reduktion av växthusgaser kring 80-85% jämfört med bensin och diesel. Denna reduktion är betydligt över den gräns om 60% som krävs för framtida biodrivmedelssystem enligt EU's direktiv om förnybar energi. Motsvarande reduktion av växthusgaser för hampa-baserade biodrivmedelssystem är cirka 55% p g a högre utsläpp vid produktion av råvara. I system baserade på halm och avverkningsrester är enzymer som används i omvandlingsprocesserna den största källan till växthusgaser. Framtida produktionstekniker för enzym samt de mängder som krävs i omvandlingsprocesserna har således stor påverkan på klimatprestanda för integrerad etanol- och biogasproduktion.

För att maximera lönsamheten och den totala energieffektiviteten i framtida system för samproduktion av etanol och biogas där också överskottsvärme produceras krävs att dessa system integreras med potentiella värmesänkor. När det gäller storskaliga anläggningar baserat på halm är lämpliga lokaliseringsplatser Skåne och Östergötland där det finns överskott av halm tillgängligt för energiändamål. I Skåne är Lund en lämplig lokalisering tack vare en möjlig integrering med det befintliga fjärrvärmesystemet och i Östergötland är Norrköping en lämplig lokalisering. Här kan t ex en integrering med den befintliga etanolanläggningen baserad på spannmål vara möjlig. När det gäller storskaliga anläggningar baserat på avverkningsrester är lämpliga lokaliseringsplatser längs Norrlandskusten och i inlandslän som Jämtland och Dalarna. I dessa regioner är tillgången av avverkningsrester för energiändamål tillräcklig och integreringsmöjligheter finns med befintlig skogsindustri samt till viss del fjärrvärmesystem i större städer. En fördelaktig lokalisering ur ett företagsperspektiv är i anslutning till en större hamn vilket medför en större flexibilitet vid tillförsel av biomassaråvara.

Biomassa i form av skörderester som halm från jordbruk och avverkningsrester från skogsbruk uppfyller normalt de hållbarhetskriterier som finns idag, t ex inom EU's RED, men det finns också miljömässiga risker med ett ökat uttag. Exempel är effekter på biodiversitet, markkolshalter, näringsbalans och långsiktig bördighet. Dessa risker kan dock minimeras genom att lämpliga åtgärder vidtas och uttagsmetoder används, t ex undvika eller delvis uttag av skörderesterna på känsliga platser, näringskompensera mm, men också genom att nya dedikerade energigrödor börjar odlas på trädesmark eller annan mark som inte används idag. Odling av energigrödor som hampa kan innebära frågeställningar kring ökad konkurrens om jordbruksmark även om energigrödor normalt har bättre miljöprestanda än traditionella ettåriga livsmedelsgrödor. De processkoncept som inkluderas i denna studie bygger på att rötresterna efter biogasproduktion förbränns (efter avvattning) för att generera processvärme. Utifrån ett hållbarhetsperspektiv kan det dock vara mera attraktivt att raffinera rötresten till biogödsel, speciellt när kompletterande näringsämnen tillförs till omvandlingsprocesserna, eftersom detta innebär att näringsämnen och organiskt material återförs tillbaks till åkermark och skogsmark.

Kommersiella investerare i nya storskaliga anläggningar för samproduktion av etanol och biogas från lignocellulosa måste hantera teknologiska, finansiella och marknadsmässiga risker. De teknologiska riskerna kan reduceras genom mer tillämpad forskning samt utveckling av pilot- och demonstrationsanläggningar. Det är därför motiverat att i dagsläget öka finansieringen inom dessa områden. I ett något längre tidsperspektiv är det också viktigt att politiska verktyg som investeringsstöd införs för de första kommersiella anläggningar som byggs eftersom detta reducerar den finansiella risken. Dessutom krävs långsiktiga och stabila politiska styrmedel för biodrivmedel, inklusive beskattning av fossila drivmedel, för att minska de marknadsmässiga riskerna för hållbara och resurseffektiva biodrivmedelsproduktionssystem.

Samproduktionssystem baserade på lignocellulosa likt de som analyseras här kan också innebära minskade affärsmässiga risker jämfört med separata produktionssystem för biodrivmedel baserat på en specifik råvara. En orsak är flexibiliteten i val av råvara då marknaden för olika typer av lignocellulosa är stor och diversifierad. En diversifierad produktmix innebär också att man opererar på olika marknader vilket minskar de marknadsmässiga riskerna. Framtida lignocellulosa-baserade samproduktionsanläggningar kan också komma att producera högvärdiga kemikalier vilket öppnar upp för ytterligare marknader.

Det finns idag tre tydliga trender inom utvecklingen av produktionssystem för biodrivmedel;
- ökat fokus på hållbar produktion av biomassaråvara,
- ökat fokus på konkurrens om jordbruksmark vilket driver utvecklingen av så kallade ”low indirect impact biofuel systems”, samt
- maximerad omvandling av biomassan till högvärdiga produkter drivet av ökat pris på biomassaråvara och förbättrad miljöprestanda.

Alla dessa tre trender understödjer utvecklingen av innovativa produktionssystem för biodrivmedel, t ex integrerad produktion av etanol och biogas från lignocellulosa.

1. BACKGROUND

The current trend in biomass conversion technologies and production systems is towards a more efficient utilization of the biomass feedstock by co-production of high-value energy carriers, at times also including platform chemicals. Drivers behind this include expected increases in biomass costs related to higher oil prices, carbon dioxide taxes and so forth, these, in turn, leading to an anticipated future increase in competition for biomass feedstock and productive land. Another trend is the increased focus on the sustainability performance of the biomass feedstock utilized, and how the various sustainability criteria that are currently under development and roll-out are fulfilled. The development of more cost-, energy- and resource-efficient biomass conversion systems and verified sustainable biomass feedstock production systems is a prerequisite for continued or improved international competitiveness of Swedish energy, forest, agriculture and chemical industries. This future development is also in line with the EU strategy plan “A Bioeconomy for Europe” and the OECD strategy report “The Bioeconomy to 2030”.

Lignocellulose-rich biomass such as agricultural residues (e.g. straw), cellulosic crops on surplus land and forest biomass have been identified as a biomass resource with potential to fulfill various sustainability criteria while also reducing the risk of increased agricultural land-use competition (IEA Bioenergy, 2010). Energy crops such as hemp, ley crops and grasses etc on arable land may also lead to a more sustainable biomass production from existing agriculture, when these crops are included in the traditional crop rotations (EEA, 2006). For example, hemp and ley crops could lead to an increased content of soil carbon, reduced weed problems, a better soil structure and improved soil fertility, and thereby higher yields on existing arable land. Thus, an efficient conversion of these various lignocellulosic feedstocks into high-value energy carriers and products can be seen as a potential biomass conversion system that could reduce the risk of negative environmental impacts and be competitive. Such strategies are encompassed within biorefinery concepts. These innovative biorefinery systems can be implemented via an integration and development of current, first generation biofuel production systems, e.g. cereal-based ethanol production plants that can also start to use straw as feedstock for ethanol production in combination with biogas production. Other important examples of system integration include links with district heating systems (DHS) where the current production of heat and electricity is expanded to also include ethanol, biogas, lignin etc. or with pulp mills where waste streams (e.g. fiber sludge etc.) could be refined into ethanol and biogas.

The objectives of this project are to:

(i) delineate and summarize promising biochemical production routes for the integrated production of ethanol and biogas (together with electricity, heat, lignin etc.) from lignocellulosic biomass in innovative concepts when analysed from a resource-, energy-, environmental- and cost-efficiency point of view, based on previous and on-going research and development activities at Lund University (LU), the Swedish University of Agricultural Sciences (SLU), SEKAB E-Technology and Lantmännen Energi, and select four scenarios for further assessment (see Section 2 and 3);

(ii) assess the energy and cost performance of the selected scenarios, based on modeling in Aspen plus (see Section 4);

(iii) discuss the technical implementation potential of the selected process design and scale concepts in existing infrastructure in Swedish DHS’s, forest industries and ethanol plants, and as stand-alone co-production plants (see Section 5);

(iv) discuss the corresponding regional potential of lignocellulosic feedstock supply from agriculture and forestry (see Section 6);

(v) describe the performance of the various biomass feedstocks in relation to relevant sustainability criteria developed in international standardisation systems (see Section 7);

(vi) analyse the new, innovative systems of ethanol and biogas production systems in Sweden from a life-cycle perspective with focus on greenhouse gas performance (see Section 8); and

(vii) synthesize and outline recommendations regarding the future potential of realizing sustainable, integrated production of ethanol and biogas in Sweden from biochemical conversion of lignocellulosic feedstock (see Section 9).

2. PROMISING ETHANOL AND BIOGAS PRODUCTION SYSTEMS

2.1 State-of-the-art

The development of biofuel production from lignocellulosic material through biochemical conversion has over the past decades been focusied primarily on ethanol production. The vast amount of knowledge gained from this research is, however, also most useful in the development of new systems where ethanol and biogas are co-produced, thereby increasing the output of transport biofuels. The current knowledge generated from previous and on-going research is summarised below.

2.1.1 Lignocellulosic feedstock

The composition of lignocellulosic materials (i.e lignin containing cellulose-rich plant material) differs from one source to another. However, the main constituents are of the same type: about 50–60% carbohydrates in the form of cellulose (made up of glucose) and hemicellulose (mainly pentose and hexose sugars), which can also be fermented to ethanol, and some 10–35% lignin (see Table 2.1). Agricultural crops and hardwood contain more pentose sugars than does softwood. There are also valuable components such as extractives and fatty acids, which should preferably be separated prior to ethanol production. Lignin has a high heating value and is thereby a valuable co-product which can be used to generate heat or a solid fuel, thus helping to improve the overall energy efficiency and process economics. Lignin, which contains aromatic compounds of a complex structure, can also be used for the production of chemicals. Some are already produced today, for example Vanillin, and the potential products from lignin are vast.

Table 2.1.*Composition of some lignocellulosic raw materials (% of dry matter) (from Olofsson et al, 2008a)*

Raw material	Glucan	Mannan	Galactan	Xylan	Arabinan	Lignin
Agricultural residues						
Corn stover	36.4	0.6	1.0	18.0	3.0	16.6
Rice straw	34.2	-	-	24.5	-	11.9
Sugar cane bagasse	40.2	0.5	1.4	22.5	2.0	25.2
Wheat straw	38.2	0.3	0.7	21.2	2.5	23.4
Switch grass	31.0	0.3	0.9	20.4	2.8	17.6
Hardwood						
Salix	41.5	3.0	2.1	15.0	1.8	25.2
Softwood						
Pine	46.4	11.7	-	8.8	2.4	29.4
Spruce	49.9	12.3	2.3	5.3	1.7	28.7

The challenges for biomass-based ethanol production are mainly related to the conversion steps, as cellulosic materials are much more difficult to break down to monomer sugars than is starch. One of the major challenges is to improve the yield of sugars from hemicelluloses and cellulose in a cost-effective way (Hahn-Hägerdal et al., 2006). This requires improved pre-treatment methods, cheaper and more efficient cellulose degrading enzymes and novel technology to do this at high solids concentration. Another challenge is to develop robust fermenting organisms, which are more tolerant to inhibitors and which ferment all sugars in the raw material, i.e. both hexoses and pentoses in concentrated hydrolysates at high productivity and at high ethanol concentration. Increased process integration, in order to reduce the number of process steps, decreases the energy demand and reduces the amount of fresh water and waste streams by re-using process streams, is also a challenge that has high research priority today (Wingren et al, 2008).

Softwoods, e.g. pine and spruce, are more difficult to hydrolyse due to their higher lignin content than hardwood and agricultural residues but also due to the structure of the material. However, the advantage of these species is that the sugars are mainly hexoses, which can be fermented by normal baker’s yeast with a theoretical yield of ethanol higher than 400 litre per tonne dry matter. The small amount of pentoses present can then be converted to biogas in an anaerobic digestion (AD) step, which is used to convert the remaining organic substances present in the stillage stream from the ethanol production.

Agricultural residues like corn stover, wheat straw and sugar cane bagasse as well as hardwoods like aspen and salix, are easier to hydrolyse to monomer sugars, but on the other hand the hemicelluloses consist mainly of pentoses (xylose and arabinose), which are more difficult to ferment to ethanol and require either genetically modified baker’s yeast or a different type of microorganism (Öhgren et al, 2006; Sassner et al, 2008). When combining ethanol production with subsequent biogas production it is possible to convert the pentose sugars to biogas instead (Kreuger et al., 2011).

2.1.2 Improved pre-treatment

The choice of catalyst in the pre-treatment step is dependent on how the various parts of the biomass are intended to be used (Figure 2.1) (Galbe and Zacchi 2007).

One option is low pH methods, i.e. addition of acids, e.g. dilute acid hydrolysis or steam treatment with addition of acids. Most of the hemicellulose is usually hydrolysed to monomer sugars and to some extent oligomer sugars available in the liquid fraction after pre-treatment. Depending on the severity, i.e. temperature, acid concentration and residence time, also a part of the cellulose will be hydrolysed. Also, a minor part of the lignin is solubilised as phenolic compounds, but the major part remains in the solid fraction albeit redistributed. These pre-treatment methods also result in production of sugar degradation products, like the furans 2-furaldehyde (commonly called furfural) and 5-hydroxymethyl 2-furaldehyde (abbreviated HMF). A low pH method prior ethanol production has the advantage that hemicellulose is autohydrolysed during pretreatment and no hemicellulolytic enzymes need to be added subsequently.

A second option is high pH methods, e.g. alkaline pre-treatment and wet oxidation with addition of alkali. These methods result in partial solubilisation of hemicellulose and solubilisation of the major fraction of the lignin. The hemicellulose sugars that are solubilised are, however, mainly oligomer sugars. This makes it possible to utilize a part of the hemicelluloses with high molecular weight as starting materials for polymers, e.g. for barrier materials in food packaging. The liquid could also be used for biogas production as this can be performed without hydrolysing the oligomers to monomer sugars. In the case that the hemicellulose sugars are to be converted to ethanol, hemicellulases acting both on solid and dissolved hemicelluloses are required.

A third option covers methods working close to neutral conditions at the start of the pre-treatment e.g. steam pre-treatment and hydrothermolysis. Most of the hemicellulose is solubilised due to the acids released from the hemicellulose, e.g. acetic acid. However, the sugars are obtained as a mixture of monomer and oligomer sugars. Also in this case hemicellulases are required to act on soluble oligomer fractions of the hemicelluloses if ethanol is to be produced. However, this is not needed if the hemicellulose sugars are used for biogas production.

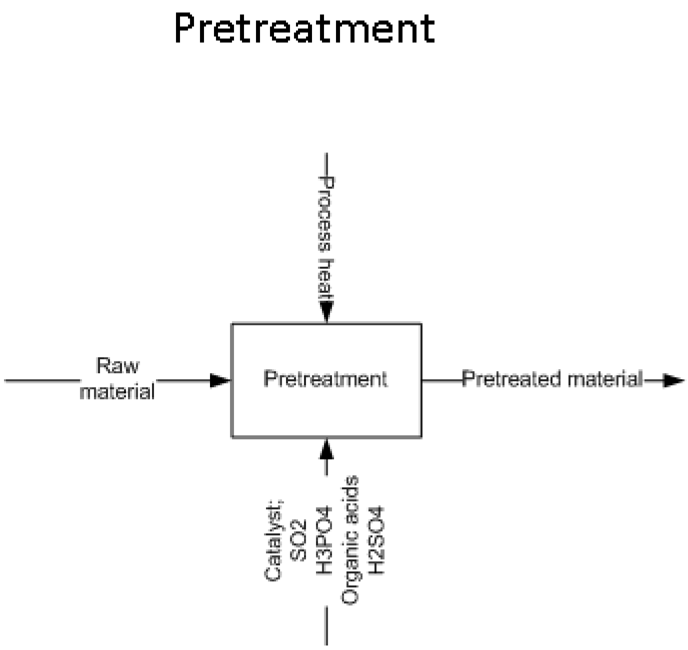


Figure 2.1. *Pre-treatment in ethanol production.*

The catalyst can be chosen to be useful in the downstream processing. If biogas is to be produced from either the hemicellulose sugars and/or the stillage stream, an organic acid can be used in the acid-catalysed pre-treatment. This acid can then be converted to biogas in the anaerobic digestion (AD). However, the liquid after pre-treatment should in this case go directly to biogas production and not ethanol fermentation as this could be inhibited by the organic acid. The organic acid can be produced from the biomass in a separate fermentation step. Another acid that could be used is phosphoric acid which could then be neutralised with ammonia before fermentation, resulting in ammonium phosphate which provides the anaerobic digestion with both nitrogen and phosphorus. It would also be beneficial when the sludge from the anaerobic digestion is used as fertiliser, for example, in the cultivation of energy or food crops.

2.1.3 Expanded fermentation

The pre-treatment provides a slurry in which the liquid fraction will contain solubilised hemicellulose – either in the form of oligomers or simple sugars depending on the catalyst used in the pre-treatment – and in the case of alkaline pre-treatment/wet oxidation solubilised lignin. The solid fraction will in all cases contain most of the cellulose present in the original raw material, some hemicellulose and – for the case of acid pre-treatment – also most of the lignin.

The solid and liquid fractions can be separated – in which case the liquid fraction can be used directly in fermentation, whereas the solid part will have to be enzymatically hydrolysed before fermentation. This process option is called SHF, Separate Hydrolysis and Fermentation. The cellulolytic enzymes to be used will consist of a mixture comprising of several endoglucanases (endo-1,4- β-glucanases, EGs), cellobiohydrolases (1,4-β-D-glucan cellobiohydrolases, CBH) and β-glucosidase. The former two act on the polymeric substrate and usually have discreet cellulose-binding modules that are essential for optimal hydrolysis of the insoluble substrate, whereas the β-glucosidase further cleaves the soluble saccharides (e.g. cellobiose) produced into glucose units. Early strain development of the industrially important filamentous fungus *Trichoderma reesei* indicated that strains that secrete high levels of efficient cellulase mixtures. However, the cost of the enzymes in the hydrolysis has been identified as a major bottleneck in the process. For this reason the US Department of Energy (DOE) has been supporting industrial programmes for several years, for instance, through grants to Novozymes A/S and Genencor (Danisco), aimed to decrease the cost of cellulases (reviewed by Wilson 2009). The approach taken was, for example, to decrease the production cost of enzymes by simplifying the medium and also try to increase the enzyme titer in the production e.g. by strain improvements. On a molecular level the issue of end-product inhibition has also been a target. The basic problem here is in particular cellobiose which inhibits some cellulases. For this reason it is difficult to obtain a full conversion of the cellulose, but at least the hydrolysis process slows down. Approaches to optimise individual enzymes are, among other things, rational engineering and directed evolution (Zhang et al, 2006) – or a combination of these strategies.

A different problem concerns optimising the enzyme mixture to be used. The synergistic action of cellulases has been extensively studied and it is also clear that other proteins can enhance the hydrolysis (Wilson, 2009). Although further strain improvements have been made, the enzyme mixture produced of some of the most widely used strains of *T. reesei,* is typically deficient in β-glucosidase activity. This enzyme therefore has to be added to the mixture. However, depending on the substrate used, also other enzyme components, in particular hemicellulases but also various ligninases may give improved hydrolysis. The remaining hemicellulose after pre-treatment may block the cellulose, potentially possible to circumvent by the addition of hemicellulases such as xylanse or mannanase which are the main endo-acting hemicellulases (Gilbert et al 2008). A support for this strategy is the synergy indicated between xylanases and cellulases (Öhgren et al 2007). The development of strategies where “helper” enzymes, such as hemicellulases and ligninases, are added can be expected to be relatively tailored and directed towards specific feedstock, whereas improvement of cellulase mixtures will be more generic. It will be important to use realistic, complex substrates to identify limiting factors. Discovery of new enzymes or proteins and optimal mixtures will be an important task. Here, post-genomic strategies as well as metagenomic strategies may prove to be important. An advantage of metagenomic approaches is that they allow cloning of genes from organisms that can not be cultivated *in vitro*.

An alternative to treating the solid and liquid fractions together, is to use both fractions simultaneously in a SSF process (simultaneous saccharification and fermentation – see Fig 2.2). In this case, both enzymes and yeast are added and the enzymatic hydrolysis takes place together with the fermentation. This gives several advantages; the end-product inhibition caused by hydrolysis products is avoided, one separation step is removed, and the hydrolysis reactor is no longer needed (for a review see e.g. Olofsson et al, 2008b).

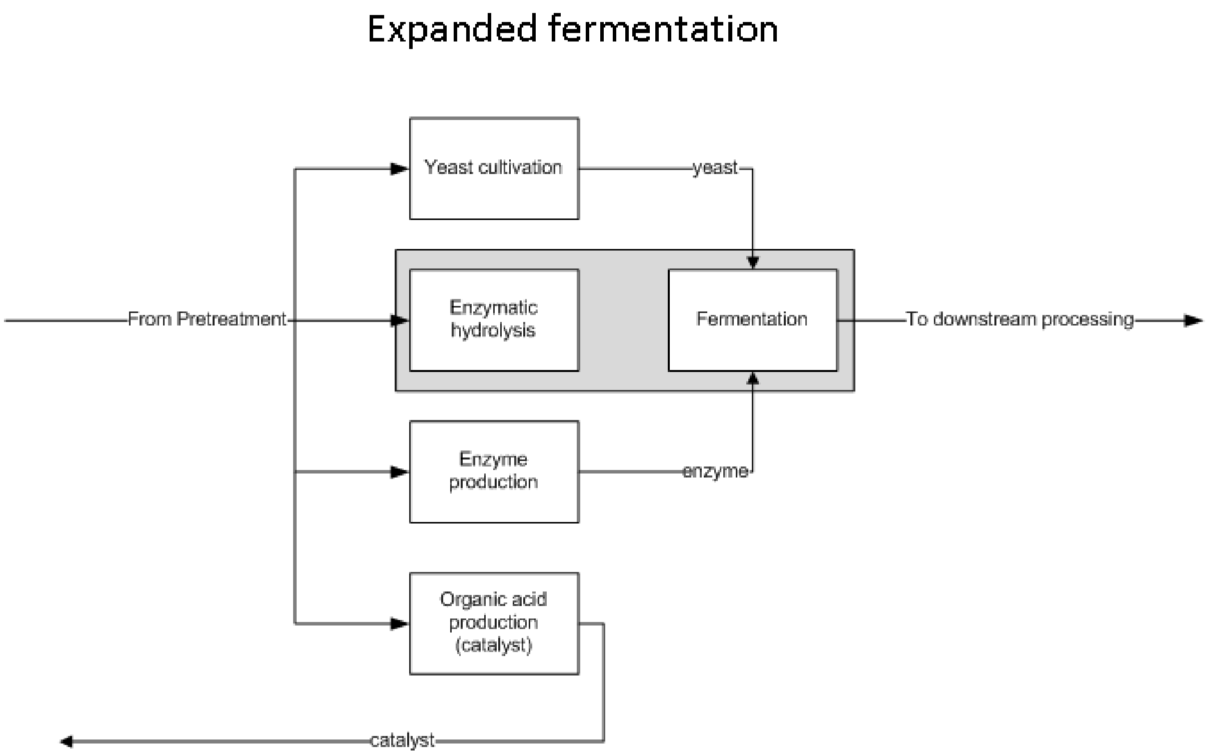


Figure 2.2. *Expanded fermentation in ethanol production. The enzymatic hydrolysis can take place before the fermentation in a separate process step, or together with the fermentation, called SSF (simultaneous saccharification and fermentation)*

However, the drawbacks are that the flexibility of the process is decreased in the sense that the conditions (temperature, pH) for the enzymatic hydrolysis have to be the same as those for the fermentation. The upper temperature limit for the fermentation is typically around 36-38^{o} C, depending on the yeast strain used, whereas the optimum temperature for enzymatic hydrolysis is usually about 40 – 50^{o} C. A lower temperature for hydrolysis also increases the risk of contamination and potentially putting additional demands on the enzyme preparation.

Another drawback relates to the great difficulties in separating the yeast after the SSF process. Currently, reuse of the yeast is not possible in an SSF process. This necessitates the use of a low yeast loading in the fermentation, which in turn requires very tolerant yeast (reviewed by Almedia et al, 2007a,b).

Yeast tolerance is increased substantially by producing the yeast on the actual hydrolysate to be fermented, and one can therefore predict advantages of process integration by on-site production of the yeast (as shown in Fig 4.4). Thereby, the necessary yeast concentration can be decreased by approximately 20-30%, which in turn may increase the overall ethanol yield by 3-5%. On-site production also of enzymes, allows flexibility with respect to the use of specific carbohydrate fractions from the pre-treatment.

The pre-treatment liquid in particular, consists of a mixture of different sugars. This relates to the fact that the hemicellulose composition – in obvious contrast to the cellulose – is strongly dependent on the raw material. From a fermentation point-of-view, there is an important difference between pentose-rich materials, which include grasses, straw, hardwoods, and materials which do not contain large amounts of pentoses, such as softwood (see Table 2.1). In the pentose-rich materials, such as wheat straw or sugar cane bagasse, clearly the pentoses need to be utilized efficiently. The pentoses are typically – to a large extent – hydrolysed already in the pre-treatment and will be found in the liquid fractions. Options for use of the hemicellulose-derived, sugar-rich liquid stream include; production of enzymes; production of yeast, production of co-products, biogas production and/or fermentation. For the latter option, efficient xylose fermenting organisms – preferably yeasts – will be needed (reviewed by, among others, Hahn-Hägerdal et al, 2007). Typically, the xylose conversion, in fermention at relatively high solid concentrations, is still below 50% (Olofsson et al., 2008b). A complete conversion of pentoses, may therefore improve the overall ethanol yield by another 20% in pentose-rich materials.

The SSF step as such can also be improved in terms of fermentation control, in which enzyme and substrate feed to the process are optimised. In this way, a substantial increase in the conversion of xylose can be obtained (Olofsson et al, 2008a).

2.1.4 Co-production of ethanol and biogas

Both in first-generation ethanol production, based on sugar and starch crops, and second-generation ethanol production, based on lignocellulose, hexose fermentation to ethanol is the main production pathway. In agricultural residues, crops and hardwood, much of the organic carbon is bound in pentoses. Efforts are made to identify/develop organisms that can convert also these sugars to ethanol with high productivity, and yet another challenge is to make these organisms tolerant to the inhibitors that can occur in the fermentation broth (see Sections above).

An alternative is to use the residues after ethanol production for biogas production. In anaerobic digestion (AD) not only hexose and pentose sugars can be converted to biogas, but also proteins, organic acids, lipids, nucleic acids and some secondary metabolites. The development of integrated processes for ethanol production and AD is part of the ongoing research at Lund University and the Swedish Agricultural University (Barta et al., 2010; Kreuger et al., 2011; Linde et al., 2008; Sipos et al., 2010; Deriere et al., 2011). It has also been explored by other research groups, e.g. Fan et al., 2006; Petersson et al., 2007. The co-production can be designed in many different ways. To maximise the total ethanol yield both pentoses and hexoses should be used for ethanol production. However, lignocellulose pre-treatment offers a possibility to explore the benefits of biomass fractionation, and separation and use of the liquid fraction after steam pretreatment for AD, and results in a higher conversion of hexoses to ethanol (Kreuger et al., 2011; Sipos et al., 2010), potentially since also a large part of fermentation inhibitors are removed with the liquid fraction. The removal of the liquid fraction before further enzymatic hydrolysis and conversion and fermentation of the solid fraction has been shown to increase the fermentation yield of hexose-based ethanol (Sipos et al., 2010). The concentrations of furfural and hydroxy methyl furfural (HMF) that can be found after pretreatment of lignicellulosic materials have been shown not to affect methane yields or degradation rates in the anaerobic digestion process (Badshah et al., 2012). Thus, apart from yielding biogas, AD of this liquid fraction can remove potential inhibitors such as HMF, furfural, acetic acid, lactic acid and products derived from lignin. This liquid detoxification opens up for recirculation of process liquid, potentially reducing both environmental impact and costs (Torry-Smith et al, 2003).

The stillage can also be used for AD, either directly in a stirred tank reactor or after separation into a solid and liquid fraction. AD of this process stream (Fig. 2.3) can further increase the yield of biogas from the process. Residual sugars and also proteins, fats, nucleic acids and some secondary metabolites can be converted into biogas. Therefore, the combined ethanol and biogas yield can exceed the theoretical yield from hexose and pentose sugars. An additional advantage of combined production is that the enzymes and yeast added in ethanol production can also be converted to biogas (Kreuger et al., 2011).The solid fraction can then be used for incineration and the liquid fraction can be treated in an AD reactor with higher efficiency (an upflow anaerobic sludge blanket or an expanded granular sludge blanket or internal circulation reactor). If using the entire stillage for AD, separation can be done after AD and the lignin-rich solid fraction can still be used for heat and power production. Using the entire stillage for AD should give a higher methane yield. However, further experimental work and techno-economic analyses are needed to determine which is the economically most interesting alternative.

Kreuger et al. (2011) have shown that it is advantageous for the hexose fermentation to use the liquid hemicellulose-rich fraction after pretreatment directly for AD instead of using it to explore the possibility of biomass fractionation that lignocellulose pre-treatment gives. Removal of the liquid after acid-catalysed steam pre-treatment leaves a solid residue which retains the majority of the hexoses and much of the lignin, while pentoses and other carbon sources, including potential fermentation inhibitors, can be transferred to the anaerobic digestion (AD) with biogas production (Kreuger et al., 2011).

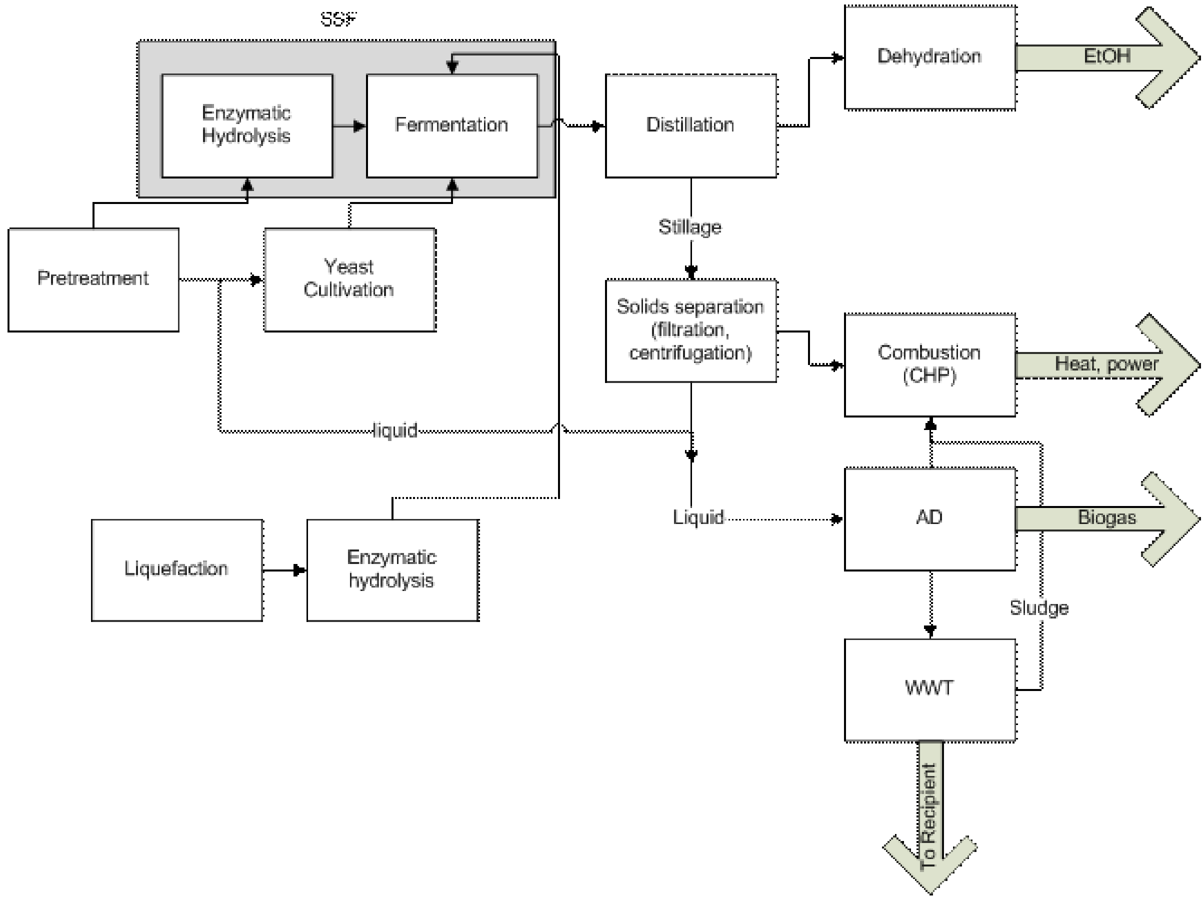


Figure 2.3. *Overview of the combined biogas and ethanol production system. Liquid from pre-treatment, containing pentose sugars, is withdrawn and treated in the anaerobic digester instead of passing as dead load through the fermentation.*

The concept of ethanol and biogas co-production has been investigated for several types of lignocellulosic biomass, such as wheat straw, winter rye and hemp (Linde et al., 2008; Fan et al., 2006; Petersson et al., 2007; Kreuger et al., 2011). In Figure 2.4, an example of the outcome of combined ethanol/biogas production from hemp is shown. In alternative F, the pre-treated biomass goes to ethanol production, and the stillage goes to AD. In alternative G, only the solid fraction after pre-treatment goes to ethanol production which increases the ethanol yield. In alternative H, both the liquid after pre-treatment and the stillage goes to AD, as shown in Figure 2.3. The latter increases both the ethanol and the biogas yield from the hemp. In addition, biogas is produced from the added enzymes and yeast.

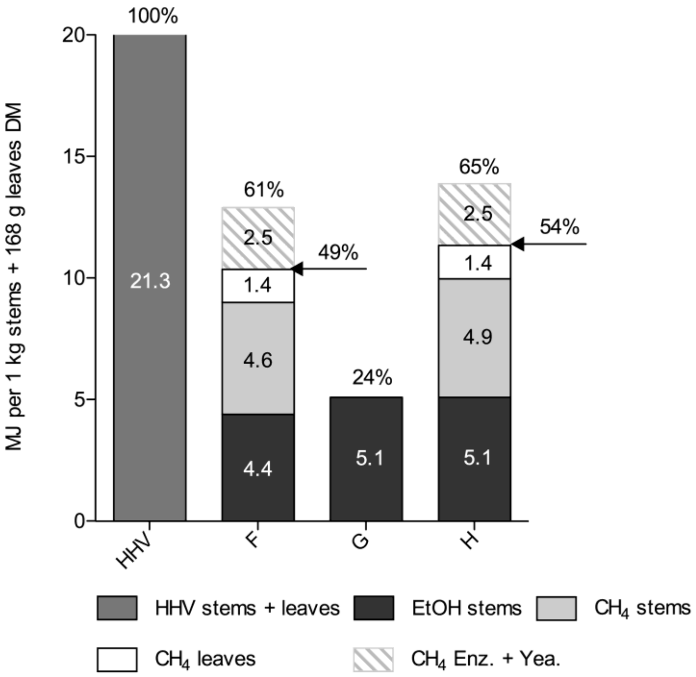


***Figure 2.4**. Energy yield for 1 kg hemp stems plus 168 g hemp leaves dry matter (DM) expressed as higher heating value (HHV) of ethanol and methane and compared to the HHV of hemp biomass. 'CH_4 Enz. + Yea.' designates biogas production from the degradation of the enzymes and yeast added during SSF. Modified from Kreuger et al. (2011).*

Integrated production of ethanol and biogas gives high output of these fuels. The experimentally determined values of the combined production of ethanol and biogas from hemp, shown as the "H" bar in Figure 2.4, gives totally 11.7 MJ fuel (HHV) per kg DM of feedstock. Of this, 2 MJ per kg DM was biogas produced from the degradation of the other carbon sources added to the system (yeast, enzymes) (Kreuger et al., 2011). In comparing integrated ethanol and biogas production with sugar-based ethanol production from lignocellulosic feedstocks, Kreuger et al. (2011) show that 90% of the theoretical ethanol yield from combined hexose and pentose fermentation of hemp stems would give 9.9 MJ per kg DM. . The corresponding value for corn stover would be 7.6 MJ per kg DM (calculated based on practical sugar yield after steam pre-treatment and enzymatic hydrolysis, Öhgren et al., 2005) or 7.8 MJ per kg DM for Salix (practical yield from fermentation of hexoses plus and estimated yield from pentoses, Sassner et al., 2006). Thus, the output of biofuel for vehicles per amount of lignocellulosic biomass could increase significantly if ethanol and biogas are co-produced, compared with solely ethanol production.

2.1.5 Limitations in the co-production of ethanol and biogas

The physical, chemical and biological properties of the stillage produced at different ethanol plants will vary depending on the initial feed stock (Sánchez & Cardona, 2008) and this will consequently also have an impact on the methane yield and performance of the anaerobic digestion process. Factors that need to be considered when stillage is used as substrate for biogas production include: i) low C/N ratio (<15), as the high protein content of distiller's waste poses a risk of process disturbance due to ammonia inhibition (Chen et al., 2008; Weiland, 2010, Westerholm et al., 2012a); ii) high levels of sulphate, as sulphuric acid is often added for pH control and pre-treatment during ethanol fermentation. Sulphate in distiller's waste can activate sulphate-reducing bacteria, which compete with methanogens for substrate, resulting in gas production with comparably lower levels of methane and higher levels of hydrogen sulphide (summarised in Moestedt et al., 2013). Moreover, the hydrogen sulphide produced inhibits various bacterial groups, as well as methanogens in the anaerobic process (Chen et al., 2008); and iii) low buffering capacity and low content of trace elements, as nutrient and trace element limitations have been reported to cause poor process efficiency when using materials such as energy crops, crop residues and distiller's waste as sole substrate for biogas production (Demirel & Scherer, 2011, Gutsavsson et al 2011).

There are different options available to meet the requirements of nutrients, trace metals and buffering capacity in the anaerobic digestion of distiller's waste. One possibility is to add mineral nutrients, shown to significantly improve anaerobic degradation and biogas production from stillage (Gustavsson et al., 2011). An alternative option is to ensure the availability of trace elements and buffering components by co-digestion with complementary substrates, such as, for example, manure (Westerholm et al. 2012b). To improve gas quality, sulphides can be precipitated with ferric or ferrous iron inside the digester (Ek et al. 2011). Alternative methods are aeration of the gas to obtain elemental sulphur, and biological treatment with, for example, *Thiobacillus* strains etc. (Ramirez et al. 2011; van der Zee et al. 2007). Independent of technique, removing sulphides requires either expensive, extensive use of chemicals or large investments in new equipment.

In conclusion, when considering combined ethanol-biogas production it is important to take into consideration that stillage is an energy-rich but somewhat nutrient-limited material. For successful biogas production, co-digestion with complementary materials or nutrient additions is required. To improve gas quality and secure the stability of the biogas process it is also advisable to avoid sulphur-containing acids during pre-treatment and ethanol production.

2.2. Design of scenarios

The design and selection of scenarios analysed in this study are based on the following parameters:

1) Type of feedstock
2) Process technology
3) Size of conversion plant
4) Geographic location

The choice of feedstock in the various scenarios is based on the diversity of potential biomass sources in agriculture and forestry available for biofuel production. The feedstocks included are a) straw, representing crop residues from agriculture, a source which is available for energy purposes today, b) hemp, representing a dedicated energy crop which can be cultivated on excess arable land or be included in conventional food crop rotations, and c) residues from forestry (e.g. tops and branches, thin stem wood etc), representing a commercial bioenergy feedstock which can be expanded further.

The design of the conversion technologies is based on previous modelling of process configurations using the flow sheet program Aspen Plus, and experimental data. The parameters assessed are energy efficiency and economic performance. The findings of these studies show that the production of several products (ethanol, biogas, electricity, lignin pellets, heat etc) make it is easier to utilise all parts of the lignocellulosic material, which gives both higher energy efficiency and a lower production cost (see e.g. Sassner and Zacchi, 2008). Many different process configurations are possible, utilising more or less of a fraction for a specific product. This can also influence the rest of the process in a beneficial way. As described in Section 2.1.4, biogas can be produced from the stillage, which can replace evaporation as waste water treatment and reduce the energy demand in the process. Biogas can also be produced from the whole liquid stream after pre-treatment, including the hemicelluloses sugars. This facilitates the ethanol fermentation, as most of the inhibitors are removed, which makes it possible to perform the SSF at higher consistency and thereby decrease the energy demand for distillation and the capital cost for SSF and distillation. Other examples are the utilisation of the solid fraction for the production of heat and power and in the future to utilise, for instance, lignin and hemicelluloses in the production of chemicals/materials. Thus, the scenarios include different process configurations to illustrate the differences between these in relation to energy efficiency and cost reductions.

The size of the conversion plant will affect the economy, where large-scale plants normally show higher profitability than small-scale plants, due to lower investment costs per amount of biofuel produced. However, since large-scale plants require a much larger amount of feedstock, this may imply an expanded biomass recovery area and increased transportation costs, compared with small-scale plants. The location of a large-scale plant may also be more dependent on the transport infrastructure in the vicinity, such as accessibility to a suitable harbour, making biomass transport by boat possible. Furthermore, the integration potential with, for example, district heating systems (DHS's) through which excess heat can be sold and distributed, primarily as base-load heat, will decrease in parallel with increased plant size and excess heat production. In an effort to illustrate the pros and cons of different scale of plant, two sizes (small- and large-scale) are included in the scenarios.

The geographic location will obviously influence the type of feedstock available for biofuel production. In agricultural regions, dedicated energy crops and crop residues, such as straw, are often suitable feedstock, whereas logging residues from forestry are a suitable feedstock in forested regions. The availability of straw for energy purposes may be limited in regions with intense animal production, where the straw is utilised as feed and bedding material. Cultivation of specific energy crops may be limited by climate, soil conditions etc, and the crop yields will also differ between regions. Concerning the integration between biofuel plants and DHS's, forest industries etc, to utilise excess heat, the geographic location will also be of importance. Large-scale biofuel plants producing sizeable amounts of excess heat will require large-scale DHS's, which are normally located in densely populated areas, that is, in large cities. Alternatively, large-scale industries with high heat demands, such as specific forest industries, may determine potential geographic location. Therefore, the scenarios include different geographic locations in Sweden to cover the various specific local and regional conditions discussed above.

Based on the description above of the different criteria in the design of scenarios, the following four scenarios have been selected for the assessment in this study:

- *Scenario 1*: Large-scale biofuel plant with a maximised production of ethanol, and minor biogas production, using straw (120,000 tonnes biomass/yr), located in Skåne and Östergötland where a sufficient amount of excess straw for energy purposes is available, as well as an adequate technical potential for integration with large-scale DHS's (in Lund) and with the existing 1st generation ethanol plant (in Norrköping).

- *Scenario 2*: Large-scale biofuel plant with production of only biogas, or hexose-based ethanol production combined with production of biogas, using cultivated energy crops in the form of hemp (234,000 t biomass DM/yr), located in Skåne with average biomass yields for the region, and integrated with adequate by large-scale DHS's to distribute the excess heat.

- *Scenario 3*: Large-scale biofuel plant with a maximised production of ethanol, and some biogas production, using forest-based feedstock in the form of forest logging residues including thin stem wood (200,000 tonnes biomass/yr), located in the northern coastal area of Sweden where a sufficient amount of excess forest residues for energy purposes is available, and where the plant can be integrated with adequate forest industries (alt. large-scale DHS's) for the distribution of excess heat.

- *Scenario 4*: Small-scale biofuel plant with maximised production of biogas, and some ethanol production, using straw (20,000 tonnes biomass/yr), located in Mälardalen where a sufficient amount of excess straw for energy purposes is available, as well as an adequate technical potential for integration with medium-scale DHS's (in medium-sized cities).

3. TECHNICAL DESCRIPTIONS OF SELECTED BIOREFINERY SYSTEMS

3.1. Scenario 1

In Scenario 1, a plant that utilises straw for the production of ethanol, biogas, electricity and heat is considered. The raw material loading in Scenario 1 is 15 tonnes dry matter (DM) of wheat straw per hour, which results in a yearly demand of 120,000 tonnes DM of straw if the plant is in operation for 8000 h/year. The modelling process of all steps included is described in more detail in Ekman et al. (2012). A schematic diagram of the process is shown in Figure 3.1.

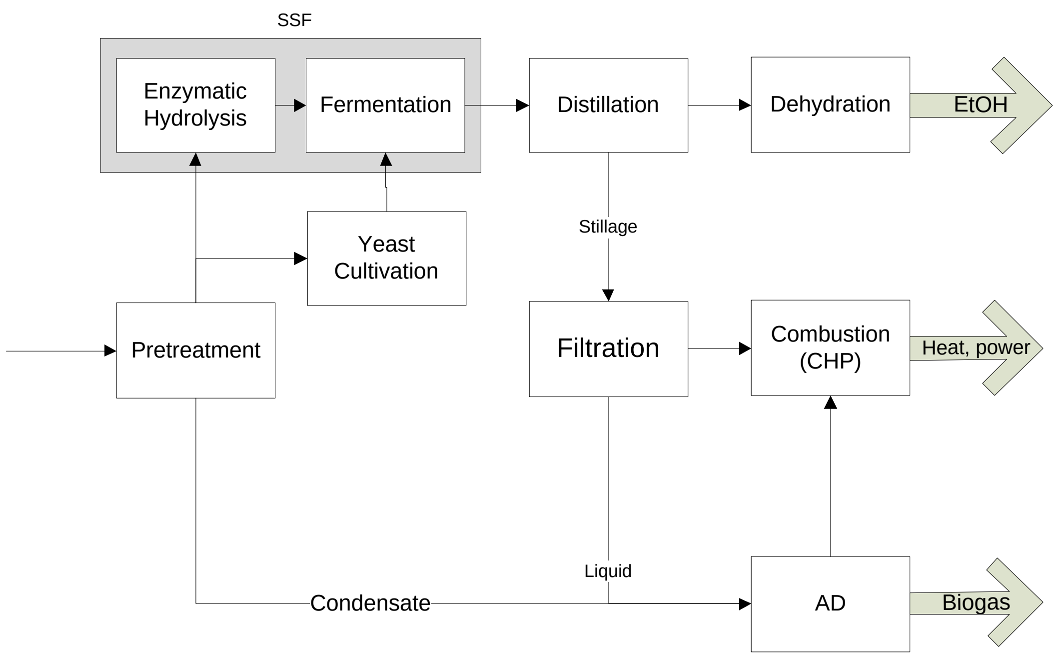


Figure 3.1. *Schematic diagram of Scenario 1*

In Scenario 1, diluted acid pre-treatment was applied and modelled to be carried out in a continuous reactor working at 190°C. The material going in to the reactor contained 10% water insoluble solids (WIS). After pre-treatment, the material was cooled in two steps by flashing the material at 4 bar and 1 bar and the heat formed in condensation was utilised in other processes. Yeast was cultivated in a separate fermentor and fed into the ethanol fermentation. In conventional ethanol production only hexoses (C6 sugars) are fermented to ethanol (SB1A) but Scenario 1 includes cases in which also pentoses (C5 sugars) are fermented to ethanol (S1B and S1C), thus representing future technology. The products produced in the three cases are shown in Table 3.1. The WIS content in fermentation was 10% as described by Erdei et al. (2010) and Linde et al. (2008). The yeast concentration is 2 kg/m3 and the enzyme load is 23.1% of the WIS. Distillation and molecular sieves are used to concentrate the ethanol from 3-4%, depending on configuration, up to 100%.

The ingoing SSF stream was preheated by heat exchange before going into the distillation unit. This consists of two parallel, 25-stage stripper columns with a Murphree efficiency of 50% and a maximum pressure of 3 and 1.25 bar followed by a 35-stage rectification column with a 75% efficiency and a maximum pressure of 0.3 bar. To improve the energy efficiency in the distillation, heat integration between the different steps was applied.

After filtration to remove solids, the liquid part of the stillage from the stripper columns, together with the flash steam from the pre-treatment is sent to an anaerobic digestion facility where biogas is produced. The stillage contains mainly water and lignin but also unfermented carbohydrates, unhydrolysed cellulose and inorganic substances. It was assumed that 90% of the easily digested compounds, 50% of the moderately difficult substances and 0% of the inert substances were converted in the biogas plant. The amount of biogas was calculated to be 0.35m³ per kg Chemical Oxygen Demand (COD) digested.

The solid residue, mainly lignin, is combusted in a boiler-turbine system producing superheated steam (90 bar, 470 °C) to cover the steam demand of the processes. Steam that is not used in the process is used for the production of electricity and/or heat sold outside the plant. In Scenario 1 biogas is not upgraded but sold as “raw biogas”.

Table 3.1. *Products produced in the different cases of Scenario 1*

	S1A	S1B	S1C
Ethanol	X[1]	X[2]	X[2]
Biogas	X	X	X
Electricity	X	X	X
District heat	X	-	X

[1]Only hexoses fermented to ethanol
[2]Hexoses and pentoses fermented to ethanol

3.2. Scenario 2

In Scenario 2, biorefinery systems based on industrial hemp (*Cannabis Sativa* L.) are studied. In these systems, a load of 234 000 tonnes DM hemp enters the biorefinery annually. Within Scenario 2, six cases have been studied. In cases S2A, S2B, S2C and S2D, only biogas, electricity and district heat are produced but in the cases S2E and S2F, ethanol is also produced. The products produced in the biorefinery are shown in Table 3.2. Pentose fermentation to ethanol is not included in any of the cases. Process schemes are given is Figures 3.2 and 3.3 (Barta et al., 2013).

***Table 3.2.** Products produced in the biorefinery cases of Scenario 2.*

	S2A	S2B	S2C	S2D	S2E	S2F
Ethanol	-	-	-	-	X	X
Biogas	X	X	X	X	X	X
Electricity	X	X	X	X	-[1]	X
District heat	X	X	X	X	X	X

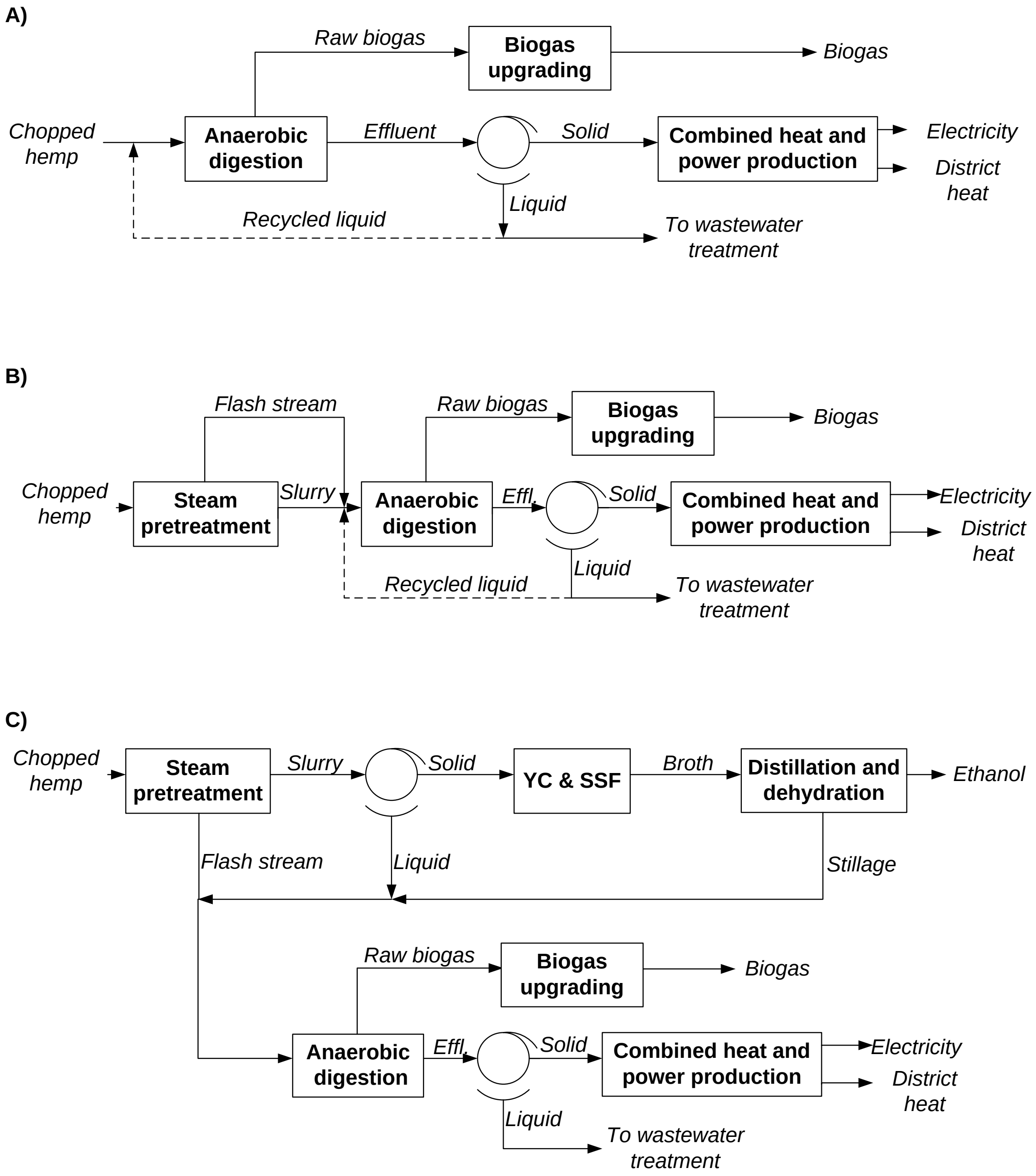


***Figure 3.2**. Process schemes of the cases of Scenario 2. A) Case S2A and S2B B) Case S2C and S2D and C) Case S2E and S2F*

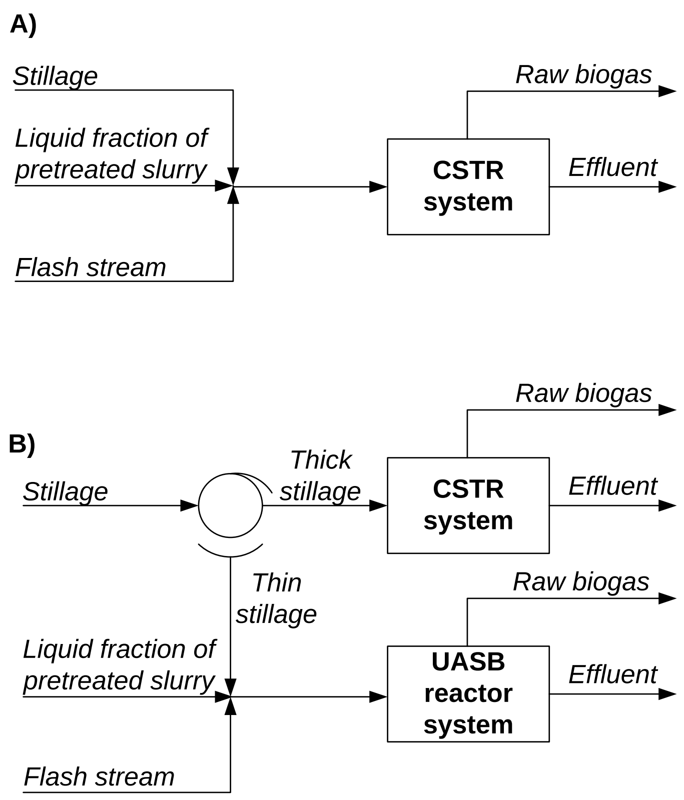


Figure 3.3. *Process schemes for variations in AD between Case S2E (A) and S2F (B).*

Cases S2A and S2B differ from cases S2C and S2D in the choice of pre-treatment method. In case S2A and S2B, chopped hemp is diluted with water before entering the anaerobic digester but in cases S2C, S2D, S2E and S2F, the chopped hemp undergoes steam pre-treatment with SO_2 as catalyst. In cases S2B and S2D, part of the liquid fraction from the AD is recycled and used to dilute the ingoing biomass and thus replaces some of the water that would otherwise be needed. The liquid fraction after AD is treated in a waste water treatment plant.

Steam pre-treatment takes place at 210^{o}C for 5 min with 2% SO_2 as catalyst. After the pre-treatment, the biomass enters the fermentation at a WIS concentration of 7.5%. SSF is applied and the fermentation takes place at 37^{o}C with 3 g yeast/L and an enzyme dosage of 20 FPU/g glucan. The resulting ethanol concentration is 2.1 %wt and distillation and adsorption with molecular sieves are used for the production of pure ethanol (99.8%wt). The stillage, the liquid fraction and the condensed flash vapours are fed into the anaerobic digestion in S2E and S2F. The DM content in the stream fed into the AD has a DM content of 5.9% in S2E and S2F. In S2E, this stream enters a continuously stirred tank reactor AD system directly, but in the case of S2F, the stillage is separated in a filter press. The thick part and the hemp leaves are fed into CSTR as in S2E but the liquid part is digested in UASB reactors. For a more detailed description, see Barta et al. (2013). The biogas is upgraded by amine absorption technology, the methane recovery is >99.9% and the methane purity is 99.3%.

3.3. Scenario 3

Scenario 3 is a biorefinery system in which ethanol, biogas, pellets, electricity and heat are produced from spruce. The scenario is based on the study presented by Barta et al. (2010), but with costs and prices updated as presented in Tables 3.4 and 3.5. The load of raw material is 25 tonnes DM of spruce per hour, the plant operates 8000 h/year and thus the total raw material intake is 200 000 tonnes DM spruce chips/year. In the reference scenario, part of the evaporation condensate, together with the condensed flash streams originating from pre-treatment and drying, is anaerobically digested followed by an aerobic treatment step. In alternative stillage treatment scenarios, either the liquid fraction of the stillage is anaerobically digested, or the whole stillage is fed directly to the anaerobic digestion. The waste-water streams, such as the condensed flash streams from pre-treatment and drying, are also fed to the anaerobic digestion (Barta et al., 2010).

The process is based on SO_2-catalysed steam pre-treatment (210^oC and 2.5% SO_2) followed by simultaneous saccharification and fermentation (SSF). SSF takes place under neutral conditions, 37^oC and 10% WIS. In all cases of Scenario 3 only hexoses are fermented to ethanol. After fermentation the 3.5%w ethanol solution is concentrated up to 99.8 %w by distillation and absorption with molecular sieves. The distillation step consists of two stripper columns and one rectifier which are heat integrated and operate at different pressures. After distillation the stillage from the stripper columns enters a filter press in which it is separated into a liquid stream and a solid fraction with a WIS content of 40%. Within Scenario 3 a number of cases are studied that are different concerning the design of the anaerobic digestion of stillage and wastewater and thereby also the combination of products produced. Anaerobic digestion takes place under mesophilic conditions (37^oC) and the inlet flows need to be cooled before they enter the AD unit. In some cases, pellets are produced from the solid residues. An overview of the products produced in the cases of Scenario 3 is shown in Table 3.3. The case called S3R is the reference case, cases S3A-S3D include anaerobic digestion only of the liquid fraction of the stillage whereas case S3E includes anaerobic digestion of the whole stillage. In cases S3A and S3B the amount of electricity needed by the plant exceeds the amount of electricity produced. The electricity required is taken from the national power grid.

Table 3.3. *Products produced in the biorefinery cases of Scenario 3.*

	S3R	S3A	S3B	S3C	S3D	S3E
Ethanol	X	X	X	X	X	X
Biogas[1]	-	X	-	X	-	X
Electricity	X	-[2]	-[2]	X	X	X
District heat	-	-	X	X	X	X
Pellets	X	X	X	-	-	-

[1]Upgraded biogas, sold as a product
[2]Electricity is produced but some electricity must be taken from an external source to cover process demand

3.4. Scenario 4

In Scenario 4 the pre-treatment is modelled to be performed using only 212°C saturated steam (20 bar) in a Steam Explosion reactor (Cambi A/S, Norway). The process is illustrated in Figure 3.4.

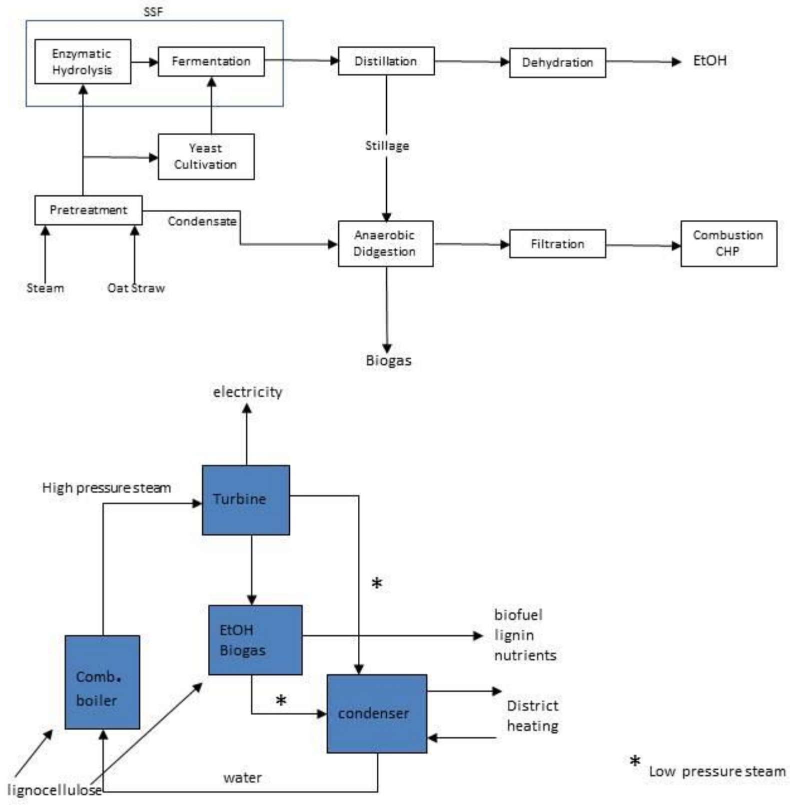


Figure 3.4. *Top; process schematic diagram for the biofuel production in Scenario 4. Bottom; schematic diagram of the integration with an existing Combined Heat and Power Plant.*

Cooling and condensation after pre-treatment, yeast cultivation and fermentation of C6 sugars were modelled in the same way as in Scenario 1. The difference is that in Scenario 4 oat straw is used as substrate and that filtration of the lignin residue occurs after anaerobic digestion. The substrate loading rate is 2623 kg dry weight (DM) oat straw/hour corresponding to 20 000 tonnes DM oat straw/year and the WIS content in the fermentation is less than in Scenario 1 due to the lack of liquid stillage recirculation. Distillation and absorption of water in molecular sieves is modelled as in Scenario 1.

The stillage and condensate from the pre-treatment is subjected to anaerobic digestion to produce biogas. The biogas process is modelled using the same parameters and assumptions as in Scenario 1. The solid AD residue, mainly containing lignin, is combusted in a boiler-turbine system producing superheated steam to cover part of the the steam demand of the processes. As in Scenario 1 biogas is not upgraded but sold as "raw biogas".

The pre-treatment steam and the steam required for distillation is supplied from a biomass-fuelled Combined Heat and Power (CHP) plant in which the biofuel production is integrated (Figure 3.6). Excess, residual, low-temperature steam is recycled back to the distict heating system via heat-exchangers. Steam produced when burning the lignin-rich AD residue partly offsets the electricity and steam consumption for the process delivered from the CHP.

3.5. Summary of key parameters for the biorefinery systems

In Table 3.4., the key parameters for the different processes and systems applied in the different scenarios are summarised, to make easier a comparison and overview. The current prices used in the economic assessments of the different products sold are summarised in Table 3.5.

Table 3.4. *Summary of the most important parameters for the processes applied in the four scenarios.*

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Raw material	Straw	Hemp	Spruce chips	Oat straw
Amount/year	120000 tonnes DM	234000 tonnes DM	200000 tonnes DM	20000 ton DM/year
Raw material LHV	4.62 kWh/kg DM	4.34 kWh/kg DM	4.79 kWh/kg DM	4.7 kWh/kg DM
Raw material cost	78-156 SEK/MWh	355-380 SEK/MWh	200 SEK/MWh	69 SEK /MWh
Ethanol production/year	28300-44400 m^3	0-273 GWh	49416 m^3	3981-4081 m^3
Biogas production	17-65 GWh	273-401 GWh	148-223[1] GWh	12.5-35 GWh
Upgrading technology	-	Amine adsorption	Pressure Swing Adsorption	-
Electricity production	27-43 GWh	0-87 GWh	0-105 GWh	-1.4-12 GWh
District heat	0-139 GWh	143-455 GWh	0-399 GWh	4-26 GWh
Pre-treatment	Dilute Acid (H_2SO_4)	Mechanical pre-treatment Steam and SO_2	Steam and SO_2	Steam Explosion
Ethanol production	Enzymatic hydrolysis and SSF	Enzymatic hydrolysis and SSF	Enzymatic hydrolysis and SSF	Enzymatic hydrolysis and SSF
Separation	Distillation and molecular sieves	Distillation and molecular sieves	Distillation and molecular sieves	Distillation and molecular sieves
Additional input energy	No	Electricity (S2E)	Electricity (S3A1 and S2A2)	Electricity and Steam
Stand-alone or integrated facility	Stand-alone and integrated with DHS	Integrated with DHS	Stand-alone and integrated with DHS	Integrated with CHP and DHS

[1]Upgraded biogas

Table 3.5. *Current prices of the different products sold in the scenarios*

Products	**Selling price**
Ethanol	6. 52 SEK/L
Electricity	350 SEK/MWh
Electricity certificate	200 SEK/MWh
Biogas (crude gas)	300 SEK/MWh
Biogas (upgraded gas)[1]	600 SEK/MWh
District heat	280 SEK/MWh
Pellets	190 SEK/MWh

[1]Large-scale upgrading of biogas is assumed to cost 100 SEK/MWh upgraded gas.

4. ENERGY AND COST PERFORMANCE

In the following chapter, the results of the energy and cost assessment by Aspen Plus modelling are presented for the four scenarios, including the different cases within each scenario.

4.1. Scenario 1

4.1.1. Energy performance

In Scenario 1, the energy needed in the production process is supplied by utilising production residues, mainly lignin, originating from the straw. The total energy performance of the cases S1A, S1B and S1C are presented in Table 4.1. As was calculated by Börjesson and Tufvesson (2011) primary energy for harvest, collection and 50 km transport of straw is approximately 2.5% of the energy content of the biomass and this amount is added to the input energy in Table 4.1. Energy content of input straw is 600 GWh/year.

Table 4.1. *Energy performance of the production of 1 MWh ethanol*

	S1A	**S1B**	**S1C**
Straw (MWh)	3.3	2.1	2.1
Ethanol (MWh)	**1**	**1**	**1**
Biogas (MWh)	0.35	0.06	0.06
Electricity (MWh)	0.24	0.12	0.10
Heat (MWh)	0.75	0	0.32
Total energy efficiency	70%	56%	70%

4.1.2. Cost performance

Straw is a residue from the cultivation of grains and oilseed and the production cost is allocated to those products. The production costs for straw thus refers to costs for its collection, transportation and storage. The price of straw used in the calculations was 0.36 SEK/kg DM which is equal to 71 SEK/MWh (Ekman et al., 2012). To account for increases in raw material price, a sensitivity analysis in which the price of straw was increased by 100 % to 0.72 SEK/kg DM or 142 SEK/MWh, was also performed (see Table 3.4). Using the model by Berglund and Börjesson (2003) the transport distance necessary to cover the straw demand of the plant is 45 km in Skåne and 67 km in Östergötland (Ekman et al., 2012).

The major costs in the production of ethanol and biogas are, apart from the raw material as was discussed above, capital costs, chemicals and enzymes for the process, and labour costs. The total costs for ethanol production in the three cases used in Scenario 1 are shown in Table 4.2. The sale price of ethanol is assumed to be 6.52 SEK/L, based on present conditions (Ekman et al., 2012). Production cost of ethanol after subtracting the earning from by-products such as biogas, electricity and heat are also presented in Table 4.2. The higher numbers represent the production costs at the higher raw material prices.

Table 4.2. *Production costs of ethanol in the three cases of Scenario 1, data adapted from Ekman et al. (2012).*

	S1A	**S1B**	**S1C**
Gross ethanol production (m3/year)	28300	44400	44400
Gross ethanol production costs (SEK/L)	6.70-8.20	4.20-5.20	4.20-5.20
Net ethanol production costs (SEK/L)	3.60-5.10	3.50-4.50	3.10-4.50

As is seen in Table 4.2, increasing the ethanol output by realising fermentation also of pentoses will make the production profitable also when by-products are not sold. In a concept in which only hexoses are fermented to ethanol, selling by-products is necessary to make the ethanol production profitable. Compared to the current ethanol price (6.25 SEK/L, see Table 3.5), all cases can be profitable if all products can be sold on the market.

4.2. Scenario 2

4.2.1. Energy performance

The overall energy efficiency here refers to the total energy (LHV) in the products compared to the input energy in raw material and not a complete energy balance in which also energy for transportation and production of input chemicals and enzymes are included. For the analysis of energy performance in Scenario 2, the energy in enzymes and molasses for pre-cultivation of yeast are also included in the total input energy. The total energy efficiency varies between 80% (S2F) and 94% (S2B). However, district heat makes up a significant share of the energy output and if district heat cannot be recovered, the relative energy performance is reduced. The energy performance based on LHV of the different cases is shown in Table 4.3. The total energy in the input biomass is 1020 GWh/year. Scenarios S2B and S2D are based on modelling recycling of liquid over AD and not on experimental yields.

Table 4.3. *Energy performance of the production of 1 MWh biogas or 1 MWh ethanol with 100% utilisation of district heat*

	S2A	**S2B**	**S2C**	**S2D**	**S2E**	**S2F**
Hemp (MWh)	2.4	2.1	1.9	1.8	3.8	3.8
Biogas (MWh)	**1**	**1**	**1**	**1**	1.5	1.5
Ethanol (MWh)	0	0	0	0	**1**	**1**
Electricity (MWh)	0.21	0.17	0.07	0.14	-0.04	0.01
Heat (MWh)	1	0.90	0.6	0.58	0.67	0.52
Total energy efficiency	92%	94%	88%	82%	82%	80%
Energy efficiency[1]	73%	83%	72%	72%	75%	74%

[1]When 56% of the heat is utilised. This corresponds to selling heat for 4500 h/year if the biorefinery operates for 8000 h/year.

4.2.2. Cost performance

At present, hemp is not cultivated on a large scale but it has been shown to be promising as an energy crop. The benefits of hemp are that the input of pesticides and fertilisers needed in cultivation is relatively small and that its deep roots can potentially improve soil structure and fertility (Barta et al., 2013).

There are no exact numbers on the cost of hemp as raw material in biorefinery systems since this is not yet cultivated as an energy crop on a large scale. Estimates of the cost of hemp are presented by Barta et al. (2013) and rely on the work by Prade (2011). The production costs of hemp are assumed to be the same as the costs for maize of the same yield/ha, but an additional 10% is added to the price to account for unexpected costs in the handling of the hemp. The resulting production cost for ensiled hemp is 1.35 SEK/kg DM. The cultivation of hemp is assumed to take place in Skåne, with an average yield of 9.7 tonnes DM/ha after losses in harvest, handling and ensiling. 24,000 ha will be needed to supply the biorefinery with feedstock. To make storage of hemp possible, the hemp is ensiled. Assuming that hemp can be cultivated on a maximum of 5% of the agricultural land in the vicinity, assuming a circular geometry, and a tortuosity factor of 1.3, the average transport distance to the biorefinery was calculated to be 53 km. This gave a transport cost of 0.27 SEK/ kg DM ensiled hemp (Barta et al., 2012). The total biomass cost is 1.62 SEK/kg DM. This can be compared to the outcome of a parallel study on production cost calculated for ensiled and chopped hemp of 1.62 SEK/t DM (Gissén et al., 2012). This latter study, however, assumes a transport distance of only 8 km and is based on a slightly different yield of 9.1 tonnes DM/ha after losses.

The major costs in the production of ethanol and biogas in the biorefinery is feedstock followed by capital costs. The production cost for cases S2C and S2D compared to S2A and S2B is due to the cost of SO_2. The case with the highest production cost is case S2E since the separate AD reactors imply an increase in the consumption of chemicals (to supply the process with macronutrients) by 21%. In the cases with ethanol, the price of enzymes makes up about 6-7% of the total costs. Cases with recycling of the liquid fraction of AD effluent (S2B and S2D) have increased the investment costs and expenditures for chemicals but have lower costs for WWT and an assumed higher methane yield. The impacts of costs on the minimum selling prices of ethanol (MESP) and biogas (MBSP) are shown in Table 4.4. The numbers in Table 4.4 include the intervals of the sensitivity analyses in which the prices of feedstock and products are varied by +/- 50%, one parameter at a time. Both the highest and lowest MBSP are due to changes in the price of feedstock. Changing prices of other co-products all result in MBSP within this interval. All numbers are adapted from Barta et al. (2012). It is clearly seen that the MBSPs and MESPs obtained are almost twice that of current selling prices for both biogas and ethanol (Table 4.4). The feedstock cost would need to be reduced to about half to reach the current MBSP. This means that substrates with similar product yields and a lower cost than 0.8 SEK/kg DM are interesting from an economic point-of-view for the analysed process combinations.

Table 4.4. *Minimum biogas and ethanol selling prices incl. the intervals of sensitivity analyses (the prices of feedstock and products are varied by +/- 50%, one parameter at a time)*[1]

	S2A	S2B	S2C	S2D	S2E	S2F
Annual biogas production (GWh/year)	425	509	527	558	401	401
Annual ethanol production (GWh/year)	-	-	-	-	273	273
MBSP, base case (SEK/MWh)	1092	920	962	921	1140	1077
MBSP, sensititvity (SEK/MWh)	635-1549	538-1301	594-1330	574-1269	656-1624	593-1560
MESP, base case (SEK/L)	-	-	-	-	10.17	9.62

[1] MBSP = Minimum Biogas Selling Price, MESP = Minimum Ethanol Selling Price

4.3. Scenario 3

4.3.1. Energy performance

In Scenario 3, the energy needed for the process is supplied by burning the concentrated liquid and/or part of the solid fraction of stillage, biogas or sludge to produce steam and electricity. In cases S3R, S3A1 and S3A2 excess solids are dried and pelletised and sold as a solid fuel. If sold as a product, biogas is upgraded but if used internally the biogas is not upgraded. The total energy efficiency varies between 83% and 96%, when the excess heat is utilised (Table 4.5).

Table 4.5. *Energy performance of Scenario 3*

	S3R	S3A	S3B	S3C	S3D	S3E
Wood chips (MWh)	2.9	2.9	2.9	2.9	2.9	2.9
Ethanol (MWh)	**1**	**1**	**1**	**1**	**1**	**1**
Biogas (MWh)	0	0.52	0	0.51	0	0.77
Electricity (MWh)	0.05	-0.04	-0.01	0.22	0.36	0.15
Heat (MWh)	0	0	0.13	0.94	1.34	0.85
Pellets (MWh)	1.3	1.1	1.6	0	0	0
Energy efficiency[1]	83%	89%	92%	92%	94%	96%

[1]100% utilisation of heat. Energy content of molasses and enzymes not included.

4.3.2. Cost performance

In Sweden, wood chips are frequently used by the energy industry for production of heat and power in combined heat and power plants (CHPs). Today wood chips that are used for energy purposes are produced from logging residues i.e. tops and branches (GROT, in Swedish). The price of wood chips in this report is set to 200 SEK/MWh (see Table 3.4).

The major costs in the production of ethanol from spruce are raw material, chemicals, enzymes, utilities, labour insurance and maintenance. The ethanol is an important income but the incomes from co-products, namely, electricity, biogas, district heat and pellets have a large effect on the profitability of the spruce-based biorefineries. Variations in prices of co-products were assessed by Barta et al. (2010), and in the present study, are updated to current costs.

The findings are summarised in Table 4.6. An increase in the price of upgraded biogas has the single highest impact when it comes to reducing the net production cost for cases S3A, S3C and S3E. In cases where upgraded biogas was not produced the most important factor affecting the net production cost of ethanol was the price of electricity and pellets, while the impact of the price of district heat was somewhat smaller. In the cases where the electricity demand is higher than the electricity produced, an increase in electricity price will increase the production cost of ethanol. If the cost of feedstock (wood chips) is reduced by one third, from the current price of 200 SEK per MWh wood chips to 133 SEK per MWh, the ethanol production cost is estimated to be reduced by approximately 20%. With the exeption of S3R and S3B, the net ethanol production cost will be below today's ethanol price 6.25 SEK/L (see Table 3.5).

Table 4.6. *Ethanol production costs of Scenario 3, including sensitivity analysis.*

	S3R	S3A	S3B	S3C	S3D	S3E
Annual ethanol production (m^3/year)	49416	49416	49416	49416	49416	49416
Net ethanol production cost[1] (SEK/L)	6.30	5.40	6.44	5.17	6.18	5.16
Changed electricity price, +/- 40%	*6.2-6.4*	-	-	*4.9-5.5*	*5.7-6.7*	*5.0-5.3*
Changed biogas price, +/- 40%	-	*4.8-6.1*	-	*4.5-5.8*	-	*4.3-6.0*
Changed pellet price, +/- 40%	*5.7-6.9*	*4.9-5.9*	*5.7-7.2*	-	-	-
Changed district heating price, +/- 40%	-	-	*6.4-6.5*	*4.8-5.5*	*5.7-6.7*	*4.8-5.5*
Reduced feedstock cost, -33%	*5.1*	*4.3*	*5.2*	*4.0*	*5.0*	*4.0*

[1]Base case

4.4. Scenario 4

4.4.1. Energy performance

In Scenario 4, the energy needed in the form of steam and electricity for the production of ethanol and biogas is purchased from the CHP into which the biofuel production is physically integrated, but from which it is economically independent. The transport distance was estimated based on Nilsson (1995) to be 31 km from the collection site to the biorefinery with an empty return. The energy performance of the two cases, without recirculation of liquid stillage (S4A) and with stillage recirculation (S4B), respectively, is presented in Table 4.7.

Table 4.7. *Energy performance for Scenario 4.*

	S4A	S4B
Wood chips (MWh)	3.92	3.82
Ethanol (MWh)	**1**	**1**
Biogas (MWh)	1.51	0.52
Electricity (MWh)	-0,06	0.27
Heat (MWh)	0.18	1.10
Pellets (MWh)	0	0
Energy efficiency[1]	63%	74%

[1]100% utilisation of heat. Energy content of molasses and enzymes is not included.

4.4.2. Cost performance

The cost of straw was estimated in a similar way as in Scenario 1 with 0.36 SEK/kg DM as base case, including transportation of the straw-based on data from Nilsson (1995) (see Section 6.4 for details). The net ethanol production cost is presented in Table 4.8 without, and with recirculation of liquid stillage (S4A and S4B, respectively).

Table 4.8. *Ethanol production costs of Scenario 4*

	S4A	S4B
Annual ethanol production (m^3/year)	3980	4080
Net ethanol production cost (SEK/L)	16.40	13.90

4.5. Summary of energy and cost performance of the scenarios

In Table 4.9., the overall energy efficiency and production costs for the various scenarios are summarised, to make easier a comparison and overview.

Table 4.9. *Summary of energy and cost performance of the four scenarios*

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Overall energy efficiency[1]	56-70%	60-84%	81-92%	63-74%
Total production cost (main product)	4.20–8.20 SEK/L ethanol	15.40-16.10 SEK/L ethanol 1040-1850 SEK/MWh biogas	Not available	Not available
Net production cost (main product)	3.10-5.10 SEK/L ethanol	10.40-11.00 SEK/L ethanol 920-1150 SEK/MWh biogas	5.20-6.40 SEK/L ethanol	13.90-16.40 SEK/L ethanol

[1]Energy efficiencies are expressed in per cent of energy in input biomass

As can be seen in Table 4.9, as the configurations are in the systems, the highest energy efficiencies can be reached in Scenario 3 but the lowest production costs can be achieved in Scenario 1. The low production costs in Scenario 1 are mainly due to the lower cost of feedstock as well as the possibility to ferment also pentoses to ethanol, which can be sold at a higher price than biogas also when the latter is upgraded. The lower feedstock price of straw represents areas and years in which straw is available in excess, but the higher feedstock price may be more relevant in the future when the competition for straw as energy feedstock will be greater. In Scenario 2, the high production costs in the biorefineries are due to the more expensive feedstock. However, hemp is currently not cultivated on a large scale for energy purposes and it is thus difficult to estimate a proper market price for hemp.

The ethanol production cost in Scenario 3, as well as in Scenario 1, are on average lower than the current selling price of ethanol (approximately 6.50 SEK/L, see Table 3.6), thus indicating a potential profitability in these production systems. However, the ethanol production cost in Scenario 4, representing a small-scale, straw-based biofuel plant, is more than three times as high as in the large-scale, straw-based biofuel plant, and thus far from profitability. This indicates the importance of scale in the production cost of ethanol from lignocellulosic biomass.

Due to the somewhat different assumptions in the four scenarios, these variations may be both smaller and larger than are shown in this report. Furthermore, since the cost calculations are based on modelling of future plants, and not real data, the results presented include a high degree of uncertainty. One example is the cost of enzymes which is here assumed to be equivalent to 0,50 SEK per litre of ethanol, independent of the feedstock in use, based on the estimated, long-term enzyme cost in commercial biofuel plants by, for example, Novozymes (Lindstedt, 2012). However, the cost of enzyme will be higher in the first production plants due to the limited market. Future and cost efficient ways to produce enzymes will probably be on-site in conjunction with large-scale biofuel plants.

5. TECHNICAL IMPLEMENTATION POTENTIAL

The technical implementation potential is assessed based on statistics regarding the base load heat production and current fuel use in existing district heating systems (DHS's) and the heat demand in existing pulp mills and forest industries (i.e. large saw mills). The excess heat generated in the various process designs and plant scales (Scenarios 1-4) is compared with the potential heat demand in DHS's and forest industries. In addition, the potential process integration in the existing grain-based ethanol plant is investigated.

The potential locations are identified on a regional basis and special focus will be on locations close to large harbours. Locations next to harbours will be the focus regarding stand-alone plants, due to the flexibility for the supply of feedstock.

5.1. Scenario 1

The availability of heat sinks in district heating systems (DHSs) is an important factor in choosing a location for a large-scale, straw-based biorefinery. According to Ekman et al. (2012), the heat produced in the biorefinery should be used as base load in the DHS and thus not be a greater proportion than 1/3 to 1/2 of the total heat supplied, depending on local conditions. The two most promising locations for biorefineries such as in Scenario 1 would be Lund in Skåne and Norrköping in Östergötland. This is also due to the rich supply of raw material in these regions as is discussed in Section 6 below. In Lund the district heating system is primarily based on fossil fuels (natural gas) and if this can be replaced the climate benefit would be significant. In Norrköping, integration with the DHS is also an option but the base load is incineration of waste with which competition should preferably be avoided. However, in Norrköping integration with the 1st generation ethanol plant of Agroetanol may be possible and that may be beneficial for both processes. Apart from the exchange of heat between the processes also process equipment and transport infrastructure can be shared.

As was also shown previously, if the production of ethanol can be increased i.e. by pentose fermentation, the integration with heat sinks is of less importance for making the biorefineries profitable and this gives a significant increase in the number of possible locations. In such cases, here referred to as stand-alone plants, the feedstock supply is of greater importance and thus availability of infrastructure (roads and railroads) and harbours. Norrköping has direct access to a harbour but Lund is dependent on harbours in Landskrona and Malmö, both at an approximate distance of 20 km.

District heating systems of sufficient size in regions where a biorefinery based on agricultural residues could be built were reviewed by Ekman et al. (2012), as shown in Table 5.1.

Table 5.1. *District heating systems in the regions under consideration (Ekman et al., 2012).*

		Output /year[1]	**Input /year**					
County	**Munici-pality**	**Total heat supply [GWh]**	**Waste [GWh]**	**Industrial heat [GWh]**	**Biomass [GWh]**[3]	**Peat [GWh]**	**Heat pumps [GWh]**	**Fossil fuels [GWh]**
Skåne	Helsingborg	844		339	1073			
	Kristianstad	277			363			
	Lund	763					111/345	330
	Malmö	2331	1178	138	241		30/104	689
Östergötland	Linköping	1220	1154					206
	Norrköping	1005	459		495			156
V. Götaland	Borås	573	303		473			
	Göteborg	3661	1226	1110	799		89/285	
	Skövde	295	143		145			
	Trollhättan	290			340			
Uppsala	Uppsala	1289	1100			781		
Västmanland	Västerås	1483			816	1431		
Södermanland	Eskilstuna	669			920			
Örebro	Örebro	1103	180		833	314		
	Karlskoga	332	108			54		84
Stockholm	Södertälje	725			405	110		27
	Stockholm[2]	11471	1382	26	4680	171	1107/3386	2172

[1]Electricity production from CHP plants is not included in the table
[2]Stockholm includes the entire region plus neighbouring municipalities
[3]Biomass includes both refined and unrefined biomass

5.2. Scenario 2

The hemp used as raw material for Scenario 2 is assumed to be produced in Skåne and this is also the selected location for the biorefinery. As in Scenario 1 it is desirable that the biorefinery produces approximately 1/3 to 1/2 of the total amount of heat delivered by the DHS. A biorefinery with a district heat production of 455 GWh/year could potentially be integrated in the DHS in Malmö that supplies 2331 GWh/year. Other systems that could be of interest would be Helsingborg that supplies 844 GWh/year and Lund that supplies 763 GWh/year. However, Helsingborg already utilises a considerable amount of waste heat in the district heating system and this competition should be avoided. Lund was identified as a suitable option in Scenario 1 and is suitable also for Scenario 2.

The DHS in Malmö has the possibility to utilise the heat produced in the biorefinery but then there will be competition with waste-heat from other industries and incineration of waste and this is not desirable. The biorefineries with lower heat production would, however, be easier to integrate and also the DHS in Kristianstad could be an alternative even if the biorefinery produced 52% of todays' heat supply. Another option is to sell heat during a limited time period. In the paper by Barta et al. (2013) it was assumed that heat was sold during 4500 of the 8000 h that the biorefinery is in operation, or that 56% of the total amount of district heat is sold. Reducing the amount of heat sold will increase the possibilities for integration with

DHS but will reduce the energy efficiency, see Table 5.1. From this perspective, cases S2E and S2F with ethanol production would more easily be integrated with the existing infrastructure than the concepts that produce only biogas but more district heat.

5.3. Scenario 3

A biorefinery based on forestry by-products (logging residues) as in Scenario 3 is most likely to find an appropiate location in the Northern and central parts of Sweden since these regions have the best potentials to supply forest raw materials (see Section 6). However, the number of DHS of sufficient size is limited in these regions since it is sparsely populated. The largest DHS in the areas are listed in Table 5.2. The effects of efficiency or combined heat and power production are not included in Table 5.2 and thus, the energy content of input fuels and output heat may differ considerably. Since the climate in Northern Sweden is colder than in the south some heating may be required also in the summer and the base load may thus be higher than in Scenarios 1 and 2.

In Table 5.2 it can be seen that biorefinery with the highest heat production (399 GWh/year) could be built in Umeå, Luleå, Gävle or Jönköping. In all these locations even the biorefinery with the highest heat production will supply less than 50% of the total annual heat supply. In Luleå and Jönköping, considerable shares of the district heat supplied come from incineration of waste and in Gävle industrial waste heat is already utilised, and competition with this should be avoided. Case S3B has a DH production of 37,6 GWh/year and could be integrated in all the DHSs listed. However, it is advantageous if the biorefinery is sited in close vicinity to a harbour and this makes Falun, Borlänge, Östersund and Växjö less favourable options. If heat cannot be recovered in DHS, it would also be possible to build a stand-alone facility not producing DH but with an increased production of biogas, electricity and pellets.

Table 5.2. *District heating systems in the forest rich areas (Svensk fjärrvärme, 2012)*

System	Fossil fuels	Waste and landfill gas	Biofuels	Industrial waste heat	Heat pumps	Total delivered heat
Jönköping	165	317	216	0	93	813
Kalmar	4.11	3.4	355	0	0	418
Växjö	24.5	0	422	0	0	567
Karlstad	102.4	150	411	16.5	0	729
Borlänge	17.1	182	148	115	34	438
Falun	32.3	2.6	292	0	0	340
Östersund	14.1	1	537	4.6	0	599
Gävle	70.5	0	424	178	0	814
Sandviken	17.3	0	281	0	0	264
Luleå	96.3	740	38	0	0	862
Piteå	7.85	0	0	319	0	254
Lycksele	0.472	0	135	0	0	117
Skellefteå	17	0	354	0	0	348
Sundsvall	199.2	266	33	93.2	0	645
Umeå	73.6	230	609	0	41	945
Örnsköldsvik	7.48	21.7	536	0	0	512

The forest industry is one of the largest energy consumers in Sweden and thus, integration between a biorefinery and a heat-demanding forest industry would be an option if a DHS of sufficient size is not available. Most pulp and paper mills produce significant amounts of the energy which they consume in-house, either from the by-product black liquor, biofuels or fossil fuels. In Table 5.3, the amount of fuels consumed in some major forest industries is shown. When the amount of fuels used for the production of electricity is subtracted, the resulting fuels are assumed to be used for heat production and these could thus be replaced by heat from a biorefinery as in Scenario 3. The fuels saved can then either be used as feedstock, in a biorefinery or in the pulp and paper factory. In Table 5.3 pulp and paper mills that consume less than 1000 GWh fuels/year are not included.

Table 5.3. *Fuel consumption in some forest industries (Skogsindustriernas miljödatabas, 2012).*

Municipality	Mill	Total fuels purchased (GWh)[1]	Fuels for electricity production (GWh)[2]	Excess fuels (GWh)[3]
Kalix	Billerud, Karlsborgs bruk	2038	687	1351
Örnsköldsvik	Domsjö Fabriker[4]	1074	0	1074
Gävle	Korsnäs AB, Korsnäsverken[4]	3206	0	3206
Väja (Kramfors)	Mondi Dynäs AB	1529	275	1254
Örnsköldsvik	M-real Sverige AB, Husums fabric[5]	4024	702	3322
Askersund	Munksjö AB, Aspa bruk	1237	221	1016
Kristinehamn	Nordic Paper, Bäckhammars bruk AB	1089	347	742
Söderhamn	Rottneros AB, Vallviks bruk	1487	342	1145
Norrköping	Billerud AB, Skärblacka[5]	2339	719	1620
Lindesberg	Korsnäs AB, Frövi[5]	1873	486	1387
Umeå	SCA, Obbola[5]	1289	329	960
Sundsvall	SCA, Östrands massafabrik[5]	3466	1309	2157
Piteå	Surfit Kappa, Piteå[5]	2872	783	2089
Bromölla	Stora Enso, Nymölla[5]	1970	697	1273
Hammarö	Stora Enso, Skoghalls bruk[5]	2685	978	1707
Älvkarleby/Gävle	Stora Enso, Skutskärs bruk[5]	3828	897	2931
Grums	Billerud AB, Gruvöns bruk[5]	3745	1020	2725
Hudiksvall	Holmen AB, Iggesunds bruk[5]	2350	628	1722
Piteå	SCA, Munksund[5]	1772	544	1228
Mönsterås	Södra Cell AB, Mönsterås bruk[5]	5415	2249	3166
Karlshamn	Södra Cell AB, Mörrums bruk[5]	3066	980	2086
Varberg	Södra Cell AB, Värö bruk[5]	2808	1033	1775

[1]Biofuels and fossil fuels
[2]The amount of fuels for electricity production is assumed to be three times the delivered amount of electricity
[3]These fuels are assumed to be used for heat production and the heat produced could be replaced by heat from a biorefinery
[4]These mills already purchase heat from an external source and can be considered particularly suitable for integration with biorefinery
[5]These mills sell excess heat as district heating, for example.

In terms of raw material supply and logistics, i.e. access to seaports, places along the Norrland coast-line are considered to be of particular interest. These options should be analysed more in detail in future assessments. As is seen in Table 5.3, there would be room for integrating a biorefinery with a forest industry, at least in theory. In practice other, economic and organisational issues within the forest industry must be considered.

5.4. Scenario 4

The excess heat produced in the small-scale, straw-based plant in Scenario 4 is approximately one fifth (maximum 26 GWh per year) of the excess heat produced in the large-scale plant (maximum 139 GWh per year, Scenario 1). According to the data presented in Table 5.1, there will be an extensive number of DHS's potentially available for the integration of a small-scale plant such as in Scenario 4. Table 5.1 includes only DHS's having a yearly heat supply of approximately 280 GWh, or more. The size of the DHS'S needed for potential integration in Scenario 4 is approximately 50 to 75 GWh per year, thus the number of additional locations in medium-sized towns is estimated to be significant.

5.5. Summary of the technical implementation potential

As was discussed in this section, the technical implementation potential refers to the possibilities of integration with district heating systems or industries such as forest industries or first-generation biofuel plants. The most critical factor is the availability of district heating systems of sufficient size in cities with the necessary infrastructure such as access to large ports. A high production of heat is important for the energy balance of the biorefineries, as was discussed in previous sections, but this may not be crucial from an economic point-of-view. If the heat cannot be utilised, biorefinery systems that optimise other products may be favourable in terms of their technical implementation potential. For a biorefinery system based on forest raw materials, integration with a forest industry could be one option to utilise the heat that is produced and then either save biomass resources to be used as feedstock for an extended production of bio-based chemicals and materials or fossil fuels of which the use will lead to increased emissions of GHGs. However, this is still a theoretical discussion and economic and business-related hurdles must be overcome for this to be realised.

6. REGIONAL BIOMASS SUPPLY POTENTIAL

The regional, potentially available feedstock for combined ethanol and biogas production has been assessed based on previous work on straw and forest biomass, and new assessments regarding hemp. The potential supply of suitable feedstock presented in this section should be seen as rough estimations and need to be assessed in more detail to attain more reliable results. Furthermore, the biomass potentials may be defined in several different ways and include different limiting factors. Examples of biomass potentials are theoretical-, social-, ecological-, technical-, economic- and market-potential, all changing over time (see Figure 6.1).

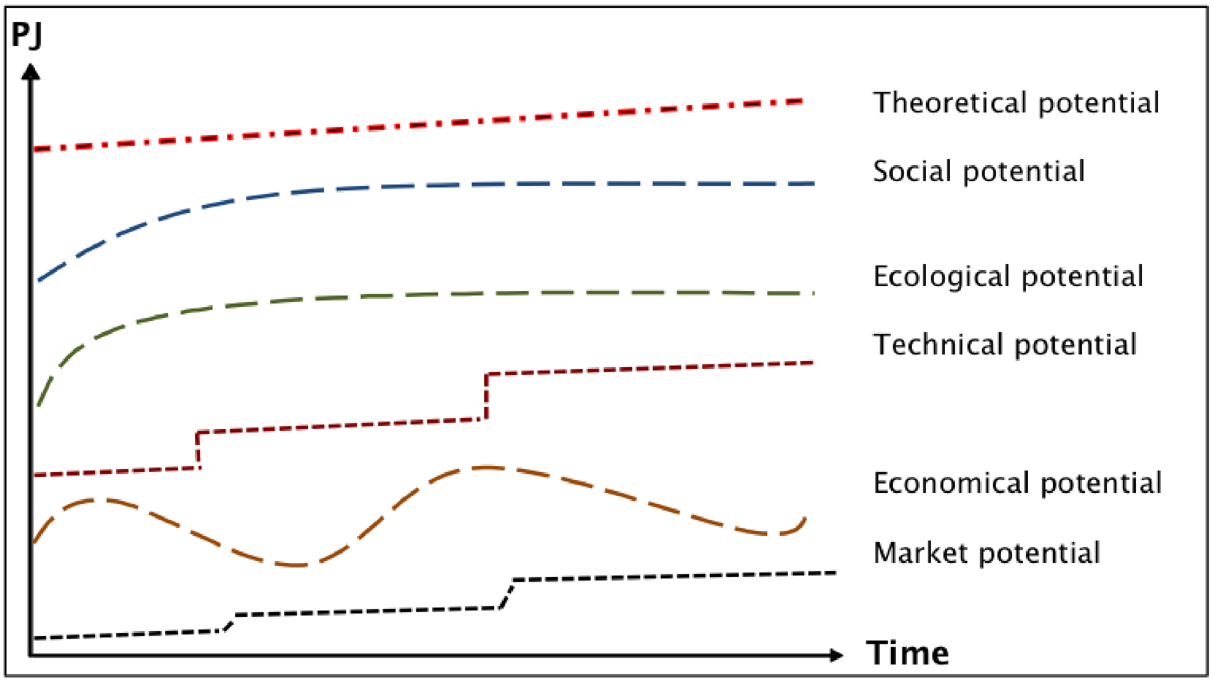


Figure 6.1. *Schematic figure illustrating that the potential biomass available on the market for energy due to social, ecological, technical, and economic limitations, is far below the theoretical potential (Egnell and Börjesson, 2012).*

6.1. Scenario 1

Straw resources available in Sweden have been assessed by Nilsson and Bernesson (2009). The availability of straw is obviously higher in agricultural areas and the major alternative uses of straw are as feed and bedding in animal farming and as a soil improver on arable land. It has been shown that the available net amounts of straw, taking alternative uses and technical limitation to harvesting into account, are approximately 35% of the total production of straw biomass (Börjesson, 2007). Straw resources available are shown in Table 6.1. These regional potentials can be compared with the annual straw demand in the large-scale ethanol and biogas plant equivalent to 120 000 tonnes DM. Thus, the only county which has a calculated net supply that exceeds this amount is Skåne. However, also Östergötland is close to fulfilling this demand for straw.

Table 6.1. *Potential straw resources in Sweden (data adapted from Börjesson, 2007; Nilsson and Bernesson, 2009).*

County	Agricultural area (Cereals and oilseed) (ha)	Total straw supply (ton DM/yr)	Net supply for energy purposes (ton DM/yr)
Skåne	245 000	634 000	253 000
Östergötland	103 000	265 000	103 000
V. Götaland	220 000	445 000	93 500
Uppsala	87 200	180 000	82 800
Västmanland	64 600	123 000	52 700
Södermanland	61 100	130 000	48 300
Örebro	53 800	110 000	37 300
Stockholm	35 900	70 800	9600
Total			680 000

6.2. Scenario 2

The scenario outlined in the techno-economic evaluation includes the use of 24,000 ha of farm land for the production of hemp. This corresponds to 5% of the agricultural land in the region of Skåne. The set-aside land in the region was 6,000 ha in 2010 (Statistics Sweden, 2011), which would not be sufficient. If more farmland is to be used for energy crop production, the advantages of introducing crops like ley crops, hemp or reed canary grass, which increase the diversity in crop cultivation, have been stressed (EEA, 2006). The dominating crops used for the production of biofuels in Sweden today are cereals and rapeseed, both also dominating food/feed crops cultivated on 56% of farm land in Skåne in 2010 (Statistics Sweden, 2011). The loss of diversity in cultivation leads to increased risk of negative environmental impacts, and increased cultivation of already abundant crops only strengthens this development (EEA, 2006).

6.3. Scenario 3

In the forest impact assessment SKA-VB 08 (SFA, 2008) the potential recovery of forest fuel from different forestry operations (logging residues and stumps) was calculated for the period 2010-2019. The calculations are based on the base-line forestry scenario called "Reference" which corresponds to the current situation. The forest fuel potential considered here includes only logging residues from final felling since there are currently different concerns regarding the recovery of stumps and residues in thinning. The potential was calculated based on three different restriction levels which affect the final amounts. The third level includes ecological and technical/economic restrictions which are used in this assessment (see Table 6.2).

The amount of logging residues harvested annually is estimated on statistics for a 3-year average removal in 2008-2010 (SFA, 2012). On a national level, the current harvest of logging residues in final felling amounts to approximately 30% of the ecological and technical/economic potential, but the intensity in logging-residue harvest varies significantly among counties. Normally, the harvest is more intense in densely populated counties with large cities and district heating systems, compared with less densely populated regions (Table 6.2).

The amount of biomass needed in a large-scale, forest-based plant is assumed to be 200 000 tonnes DM per year. Based on the logging residue potential presented in Table 2, this amount could potentially be available in approximately 8 counties. When current logging-residue harvest is included, the net potential of available forest biomass will be sufficient in approximately 5 counties, which are Norrbotten, Västerbotten, Jämtland, Gävleborg and Dalarna. If the combined ethanol and biogas plant is down-scaled equivalent to an annual feedstock supply of approximately 150 000 tonnes DM, also Västernorrland, Värmland and Västra Götaland have a sufficient net logging-residue potential.

Table 6.2. *Estimated potential for forest biomass in the form of logging residues in final felling per county (data adapted from SFA 2008 and 2012).*

County	Ecological and technical/economical potential (1000 ton DM/yr)	Current harvest (1000 ton DM/yr)[1]	Current harvest / potential (%)
Stockholm	55	11	19
Uppsala	66	24	37
Södermanland	70	47	66
Östergötland	107	48	44
Jönköping	132	66	50
Kronoberg	133	27	20
Kalmar	130	65	50
Gotland	14	9	67
Blekinge	39	28	72
Skåne	117	54	47
Halland	76	17	22
Västra Götaland	247	85	34
Värmland	196	33	17
Örebro	106	63	60
Västmanland	57	56	98
Dalarna	219	31	14
Gävleborg	221	34	15
Västernorrland	227	59	21
Jämtland	283	50	18
Västerbotten	335	64	19
Norrbotten	290	40	14
Total	**3 170**	**910**	**29**

6.4. Scenario 4

Oat straw was identified as a large biomass resource in the county of Västmanland in the lake Mälaren region in Sweden and previous studies of co-production of biogas and ethanol have been using oat straw as feedstock (Dererie, 2011). However, this project shows that the available oat straw is hardly enough and therefore straw in general was also included. As can be seen in Table 6.1, the potential net supply of straw is higher than the 20 000 tonnes DM needed in the small-scale, combined ethanol and biogas plant in 7 counties in Sweden. In total, the straw potential could supply up to approximately 30 small-scale plants such as in Scenario 4. The total net supply of straw in Uppsala and Västmanland is estimated to be approximately 135 000 tonnes DM of which some 26 000 tonnes DM consist of oat straw (Nilsson and Bernesson, 2009).

6.5. Summary of biomass supply potential

A large-scale, straw-based, combined ethanol and biogas plant should preferably be located in Skåne, due to the significant amount of straw available for energy purposes. Another option is a location in Östergötland. Based on the technical implementation potential (see section 5.1.), a location close to Lund and to Norrköping seems the most suitable.

A large-scale, hemp-based, biofuel plant requires a significant amount of arable land for itscultivation, equivalent to approximately 5% of the arable land in Skåne. Siting in other counties in Sweden will lead to increased cultivation areas and transportation distances since both the biomass yields as well as the amount of arable land will be lower. Suitable locations in Skåne are close to Lund (as in Scenario 1) and Kristianstad, when also the technical implementation potential is considered (see Section 5.2). Another option is Malmö if, for instance, the incineration of waste is reduced in the future.

A large-scale, logging residue-based, combined ethanol and biogas plant could preferably be located on the Norrland coastline and in inland counties, such as Jämtland and Dalarna. These regions have a significant, unused biomass feedstock potential and a potential for integration with heat sinks in both forest industries and, to some extent, district heating plants in the larger cities (see Section 5.3). Due to the increased flexibility in feedstock supply, the most promising locations are, however, close to large ports along the coast.

A small-scale, straw-based, biofuel plant could be located in several counties in Sweden which have an extensive cereal production and a limited animal production, such in Mälardalen. Other potential locations include Östergötland, Västergötland, Västra Götaland and Skåne. All these regions also have a significant technical implementation potential in the form of district heating plants in small- to large-sized cities (see Section 5.4).

7. SUSTAINABILITY OF FEEDSTOCK

7.1. What is sustainable bioenergy feedstock?

When introducing large-scale use of biomass resources, it is important that cultivation and harvest is done in a sustainable manner. The idea of sustainable development was coined in the report Our Common Future published in 1987 (the Brundtland report). In the report sustainable development was defined as “development that meets the needs of current generations without compromising the ability of future generations to meet their own needs’’. Following the publication of the Brundtland Report, numerous attempts have been made to operationalise sustainable development. The most popular and common attempt is the division of sustainability into three pillars; economy, environment and society (Kemp and Martens, 2007).

For bioenergy, there are many environmental sustainability aspects to consider. In a study by (Buchholz et al., 2009) 35 different sustainability criteria related to bioenergy were identified; of these 16 criteria were associated with the environment, 15 with to social- and 4 with economic sustainability (Table 7.1). Another extensive work was recently published by the Global Bioenergy Partnership (GBP) in which 24 indicators were identified, sorted within the three pillars (GBP, 2011). According to GBP, the indicators can serve as a tool for policy makers and other stakeholders in the development and management of national bioenergy policies and programmes. However, to analyse all sustainability aspects is a difficult task, as many of the impacts are interconnected, dependent on local conditions and vary over time

Table 7.1. *Sustainability criteria identified by Buchholz et al., arranged according to the three pillars of sustainability; social, economic and environmental (2009)*

Social	**Economic**	**Environmental**
Compliance with laws	Employment generation	Adaptation capacity to environmental hazards and climate change
Food security	Microeconomic sustainability	Energy balance
Land availability for other human activities than food production	Macroeconomic sustainability	Natural resource efficiency
Participation	Economic stability	Species protection
Cultural acceptability		Ecosystems protection
Social cohesion		Ecosystems connectivity
Respect for human rights		Crop diversity
Working conditions of workers		Exotic species applications
Respecting minorities		Use of genetically modified organisms
Standard of living		Use of chemicals, pest control, and fertiliser
Property rights and rights of use		Soil protection
Planning		Land use change
Monitoring of criteria performance		Water management
Visual impacts		Waste management
Noise impact		Greenhouse gas balance
		Potentially hazardous atmospheric emissions other than greenhouse gases

7.2. Key environmental indicators for Swedish lignocelluose-based biofuel feedstock

All environmental sustainability issues can not be covered in this report, but a few important key issues have been selected, namely, soil carbon, nutrient balance and biodiversity. The selected issues can be seen as indicators for some of the criteria listed in Table 7.1, for instance, soil carbon is an indicator of soil protection and greenhouse gas balance. In the following, we will in a broad and generic manner discuss these indicators related to large-scale use of biomass for production of second-generation biofuels in Sweden. These feedstocks include residues from agriculture (e.g. straw) and forestry (e.g. tops, branches, stumps) but also dedicated energy crops such as willow, poplar, hemp, reed canary grass etc.

7.2.1. Soil carbon

Organic carbon in the soil is both the habitat and resource for most soil organisms. Therefore carbon content can often be used as a proxy for the ability of soil to provide ecosystem services. Promoting soil C means increasing soil biodiversity and soil ecosystem services (e.g. nutrient cycling, water holding capacity, soil structure and soil fertility), and thereby a more sustainable production system (SOILSERVICE, 2012).

Further, soil carbon can contribute to binding or release of carbon to the atmosphere, which can have a positive or negative effect on global warming. Dedicated energy crops, especially if perennial, can have a positive effect on soil carbon content; large root systems build large soil carbon pools. The effect is of course dependent on the initial state of the land prior to the planting of the energy crops.

When residues for biofuel production are removed, carbon is removed from the land. Had the residues been left to decompose it can be expected that a part of the carbon would have been transferred to the more stable, long-term soil carbon pool. Removing residues can therefore be seen as a missed opportunity for carbon capture. However, in agricultural systems the effect of removing straw for instance, is less obvious since soil carbon content of agricultural land is also strongly connected to management strategies such as crop rotation and ploughing (Röing et al., 2005).

Soil carbon changes and their connection to greenhouse gas balances of biofuels have lately been much debated in research, in the media and in policy making, especially in connection with indirect land use changes. This is further described in Chapter 8.

7.2.2. Nutrient balance

A balanced nutrient supply is another key factor for efficient and sustainable agricultural and forestry production systems. Some nutrients are limited resources, for example phosphorus originates from mines and some researchers say that we will soon reach a “peak phosphorus” and estimate that the mines will be depleted within 50-100 years (Cordell et al., 2009) while others estimate reserves 10 times larger than the Cordell et al. study (Elser, 2012). Other nutrients such as nitrogen are based on large fossil energy inputs. In other words, nutrients are valuable resources that should not be wasted.

Fertilisers can be lost through leaching into the surrounding environment, causing acidification and eutrophication. Excess use of nitrogen can also lead to the emission of nitrous oxide, which is a very potent greenhouse gas. Nutrients can also be lost through erosion, even if this is less common in Sweden than in other parts of the world. Loss of nutrients can have an impact on future growth potential, if the removed nutrients are not recirculated or compensated for.

Removal of forest residues affect the nutrient balance by nutrients being removed from the system as the biomass collected, but also due to turnover in the soil and soil compaction caused by forest machines. Nitrogen has often been in focus in nutrient balances since many forest soils in Sweden are short of available nitrogen. However, there are large geographic variations in nitrogen balance, which is due mainly to variation in atmospheric deposition of nitrogen originating from combustion emissions from sources such as power plants and road traffic and ammonia emissions from, for instance, animal housing (Bertills and Näsholm, 2000). Therefore, removal of nutrients may be negative, but could also be positive in areas with high loads of nitrogen (de Jong, 2012). Generally speaking, South Sweden has a larger deposition of nitrogen and thus the removal of residues could decrease the nitrogen loading, giving environmental benefits.

Removing straw from cereal production can, counter-intuitively, increase the nitrogen in the soil available to plants compared to leaving the straw in the field, at least initially. This is because when straw is incorporated into the soil, nitrogen tends to become immobilised as the straw decomposes, which can result in a lower availability of mineralised nitrogen in the soil. However, from a long-term perspective straw incorporation results in more nitrogen in organic form in the soil, leading to an increased mineralisation of nitrogen (Powlson et al., 2011).

For dedicated energy crops, it is important to use nutrients in a smart way so as to minimise their use and to minimise leaching and emissions. It is also important to consider the circulation of nutrients from the biofuel plant to the cropping system. As dedicated energy crops are not used for human consumption, it may be possible to use sludge or water from waste-water treatment plants, which contains many nutrients but is not permitted to be used in food production due to contamination risks. However, these organic waste materials must fulfil certain requirements regarding maximum levels of heavy metals etc.

In the biofuel production systems included in this study no organic waste products are recirculated back to the land used for agriculture and forestry, but only inorganic ash (Scenario 1-3). The digestion residues generated in the combined ethanol and biogas plants are separated into a solid and a liquid phase where the solid phase is combusted to generate process heat. The liquid phase is treated by conventional waste-water treatment methods. Thus, an interesting issue to analyse in future studies is how to improve the recirculation of nutrients and the resulting overall effects compared with the current handling of the organic waste products.

7.2.3. Biodiversity

Planting of dedicated energy crops or removal of biomass residues for energy production, can have an effect on the variation of genetics, species and habitats in an ecosystem. The maintenance of a high biodiversity is important for many reasons; all ecosystems are interconnected and we are dependent on functioning systems to provide us with clean air, fresh water, food etc, to protect future unknown resources, and “nature for nature's sake” are a few of the arguments (World Resource Institute, 2005). Further, biodiversity is connected to many other sustainability issues, for example, loss of biodiversity can increase the vulnerability of ecosystems to climate change (Rockström et al., 2009).

Dedicated energy crops can have many consequences for biodiversity, for example, planting short rotation forest can increase diversity due to reduced soil tillage, reduced use of agrochemicals and increased input of litter compared to annual crops. Also, short rotation forest can provide habitats for wildlife in an open farmland (Börjesson, 1999).

Dead wood in all forms is a very important substrate for a large number of forest species. Especially hardwood has proved valuable to rare and endangered organisms, while coniferous wood seems less important for these species. A general guideline is also that larger pieces of dead wood and wood from less common tree species are important for biodiversity. Another risk is that piles of hardwood residues can attract rare species and serve as catch traps, which is very unfortunate since the piles are later gathered and often burned as fuel. An increased removal of coniferous forest residues should, on the other hand, not be a threat to endangered species. However, a general risk with forest residue removal (tops, branches and stumps) is the damage done to the land during harvest, which can cause major negative consequences for biodiversity (de Jong, 2012).

7.2.4. Land use change

Increasing demand for biofuels can have effects on how we use our land resources. Land use change affect sustainability in many ways: the greenhouse gas balance, biodiversity, water use, nutrient balance etc, but also social and economic sustainability can be affected, for instance, increasing demand for land can cause conflicts over land use rights and cause global food prices to rise.

In the debate on land-use change, the term direct land-use change (dLUC) is used to describe changes connected to the field where the cultivation/harvest of the biofuel crop or residue is taking place. However, if the area was previously utilised for other purposes, that activity might be displaced to other areas. This type of indirect land-use change (iLUC) may occur in the same country where the feedstock is produced, but due to the international trading of products it is possible that they are displaced to other parts of the world, competing with local production of food, feed and with nature conservation (Di Lucia et al., 2012).

Until 2008, scientific studies limited their attention to dLUC and carbon stock changes, reporting positive greenhouse gas balances for most biofuels. In 2008, two studies (Searchinger et al., 2008; Fargione et al., 2008) initiated the on-going debate on iLUC. The studies take a marginal approach, assuming that at the end of the sequence of indirect events, land containing large amounts of carbon will be taken into use, that is, that there will be deforestation in tropical areas with peat soils. However, the studies have been heavily debated. The models used to assess iLUC are complex and contain numerous assumptions, therefore different models come to results which vary greatly (Ahlgren and Börjesson, 2011).

7.3. How is sustainability included in the standardisation and certification systems?

Sustainability of biomass feedstock for energy is addressed in several ways, e.g. in research, policy, standardisation and voluntary certification systems. Existing systems have various objectives, being developed for a specific sector (agriculture, forestry, etc.) or specific purposes (fair-trade, organic agriculture, etc). Examples of these certification schemes are IFOAM (International Federation of Organic Agriculture Movements) and FSC (Forest Stewardship Council).

Lately, several initiatives have been developed specifically for biofuel production chains. In the EU for example, the Renewable Energy Directive (2009/28/EC) set sustainability criteria for the production of biofuels, requiring proof of GHG reductions and stating that feedstock can not be acquired from land with high biodiversity and high carbon stocks. There is also on-going work within ISO and CEN to secure sustainability of biomass feedstock, as well as other national and international initiatives. For an overview of different systems see e.g. Scarlat and Dallemand (2011). An overview of certification systems for biofuels is also given in Höglund et al. (2013). Both studies conclude that greenhouse gas emissions from direct land use change, biodiversity and socio-economic aspects are covered in many of the systems, while indirect land use changes are not. However, there are on-going discussions in the EU to include iLUC in the Renewable Energy Directive. Another conclusion from the studies is also that further harmonisation of legislation, standardisation and certification, combined with additional measures for global monitoring and control is needed to ensure sustainability in bioenergy production.

7.4. Can we increase the use of biomass feedstock?

As pointed out by Bauen et al. (2009) much attention is at present directed to the possible negative consequences of bioenergy and land use, such as biodiversity losses, greenhouse gas emissions, and the degradation of soils and water bodies. However, production of biomass for energy can also generate benefits. For instance, forest residue harvesting can reduce nitrogen run-off, improve forest site conditions for replanting, stump harvesting can reduce the risk of root rot, thinning generally improves the growth and productivity of the remaining stand, removal of biomass can reduce wildfire risk. In agriculture, biomass can be cultivated in multifunctional plantations that can offer extra environmental services, e.g. willow plantations can clean the soil from heavy metal contamination.

However, it is important to define more exactly what is sustainable management and what is not in order to avoid negative consequences. In a study by de Jong (2012) it is concluded that the use of forest residues (tops, branches and stumps) can be increased if:

- The main out-take is from coniferous forest
- When needed, ash of good quality is returned to the soil
- Damage by forest machines is minimised by taking residues only from places with sufficient carrying capacity
- Forest residues are not taken in close proximity to areas with key biotopes or nature reserves.

In a recent publication by Mead and Smith (2012), 10 principles for sustainable nutrient management in forest bioenergy systems are developed and discussed. These include defining management objectives, use of site-specific mapping, not wasting resources and keeping track of off-site impacts. The authors conclude that nutrient management is central to sustainability, but will probably involve considerable costs.

Several studies also point out the global opportunities for the increased use of residues, increased productivity and increased crop cultivation on fallow and marginal lands. Some of these studies take into consideration the long-term sustainability in the estimation of the potential. See, for example, an overview in Batidzirai et al. (2012). The long-term potential for bioenergy depends largely on land availability, which depends on food-sector development (growth in food demand, population, diet, and increased crop productivity) and factors limiting access to land, such as water and nature protection (Bauen et al., 2009).

We believe that the answer to the above question, namely, can we increase the use of biomass feedstock for energy purposes is, yes we can, but we must take into consideration the different sustainability aspects, and accept that this consideration can involve extra costs. In the long run, maintaining sustainability will however pay off and is decisive for the shape of our common future.

8. LIFE CYCLE ASSESSMENT

8.1. Objective

The objective was to analyse the greenhouse gas (GHG) performance of ethanol and biogas production in the scenarios described in the previous sections. Each scenario includes a number of different cases that produce different amounts of biofuels, heat, electricity and in some cases pellets. All of the cases in the scenarios could not be included in the LCA due to time restrictions, and therefore one case from each scenario was chosen. The following cases were analysed:

- *Straw, large-scale* (Scenario 1 - Case S1C)
- *Hemp, large-scale* (Scenario 2 – Case 2F)
- *Forest residues, large-scale* (Scenario 3 - Case 3E)
- *Straw, small-scale* (Scenario 4)

These cases were selected because they were economically most profitable. Also in order for the cases to be comparable both ethanol and biogas had to be produced in all the cases.

8.2. Method

8.2.1. The renewable energy directive (RED)

The LCA-calculations were performed in accordance with the EU Renewable Energy Directive (RED) (EC, 2009). The RED was adopted in 2009 and sets mandatory targets for the EU member countries for bioenergy as a percentage of the total energy consumption and of energy consumption for the transport sector. The directive also contains a number of sustainability criteria for liquid and gaseous biofuels that should be met in order for the biofuel to count towards the targets set out in the directive (Ahlgren, 2012).
One of the criteria is that the biofuel must give a certain reduction of greenhouse gases (GHG) compared to a fossil fuel reference. In order for biofuel producers to prove this GHG reduction, they have to perform LCA calculations. The method for how these LCA calculations should be done is laid down in Annex V in the RED. The GHG emissions should be calculated as:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$$

where

E = Total emissions from the use of the fuel
e_{ec} = Emissions from the extraction or cultivation of raw materials
e_l = Annualised emissions from carbon stock changes caused by land use change
e_p = Emissions from processing
e_{td} = Emissions from transport and distribution
e_u = Emissions from the fuel in use
e_{sca} = Emission savings from soil carbon accumulation via improved agricultural management

e_{ccs} = Emission savings from carbon capture and geological storage
e_{ccr} = Emission savings from carbon capture and replacement
e_{ee} = Emission savings from excess electricity from co-generation.

The emissions are calculated as CO_2 equivalents (100 year), weighing together several greenhouse gases valued as:

CO_2: 1
N_2O: 296
CH_4: 23

This means that emitting for example 1 kg of nitrous oxide (N_2O) is considered 296 times more than emitting 1 kg CO_2. The emission factor for CO_2 from the combustion of bio-based material is zero. This is based on the argument that the same amount of carbon released during combustion is considered to have been taken up by plants during their growth. According to the formula above, the total GHG emissions are the sum of emissions from cultivation, land use change, processing, transportation and use of biofuels. Further, there are a number of emissions that can be subtracted, including emission saving from soil carbon accumulation via improved agricultural management (e.g. shifting to reduced or zero-tillage), emission savings from carbon capture and geological storage and emission savings from carbon capture and replacement (capture of CO_2 originating from biomass which is used to replace fossil-derived CO_2 used, for example, as carbonator in drinking soda).

Emission savings from excess electricity from co-generation (eee) can be accounted for but only under certain conditions. The electricity has to be produced in a system that uses cogeneration. The size of the cogeneration unit shall be assumed to be the minimum necessary for the cogeneration unit to supply the heat that is needed to produce the fuel. The saving in greenhouse gas emission associated with that excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit.
As the RED is a tool for policy regulation, it does not cover all aspects that may be of interesting when biofuel systems are evaluated from a scientific point-of-view. Therefore, in the discussion and sensitivity analyses a number of other aspects are highlighted, such as the effects of soil carbon changes, higher methane slip and nutrient compensation.

8.2.2. Functional unit and allocation

The functional unit of this study was 1 MJ (LHV) of produced ethanol, biogas or electricity.

In the production of biofuels co-products from the process are common. The environmental impact of the emissions should then be divided (allocated) between the main product and the co-product. The environmental impact was allocated to the fuels based on their lower heating value, in accordance with the RED methodology. Heat was also produced in some of the scenarios, but because the LVH of heat /steam is zero or below, no environmental impact was allocated to the heat.
If a product is classified as a waste or residue, it is not allocated any of the emissions. Agricultural crop residues and forest residues are, for example, not assumed to have any value and are not burdened with any of the emissions from the cultivation or forestry

operations. However, all operations and transports to collect the residues must be included in the calculations.

8.2.3. The source and quality of the data

Data for the LCA analysis are as far as possible collected from the techno-economic analysis described in previous chapters; and for the most part these data were sufficient for the LCA analysis. Regarding life cycle inventory data for inputs such as diesel, enzymes and chemicals, data were collected from Biograce (an EU project to harmonise greenhouse gas calculations on biofuels) as well as recent and relevant studies and reports.

8.2.4. System description

The analysis encompassed the cultivation of the energy crop or collection of by-products and the transportation to the biorefinery, and biorefinery inputs such as enzymes, chemicals and nutrients (Figure 8.1). Infrastructure, machinery and buildings were excluded from the study, as was the storage of substrates and the end-use phase of the fuels. The biogas produced was assumed to be upgraded for all scenarios, using the best available technique (BAT).
Figure 8.1 presents flowcharts for the four scenarios. Ethanol and biogas are produced in all scenarios. Scenarios 1-3 also generate electricity and heat internally; thus these scenarios are self-sufficient for the electricity and heat needed for the processes, while also producing surpluses that can be sold (Figure 8.1). The small-scale straw scenario 4 produces ethanol and biogas but also heat that is generated when the digestate is incinerated in a nearby CHP plant. The required electricity had to be sourced externally.

In all scenarios it was assumed that the digestate from the biogas production is dewatered and the solid fraction incinerated. The liquid fraction is sent to water treatment before release into environment. In this way, the nitrogen nutrients are not returned to agriculture or forestry. It was, however, assumed for scenarios 1-3 that the ash remaining after incineration was returned to the field or forest to recover some of the nutrients (especially phosphorus and potassium). Transportation and spreading of ash was not included since it was considered to have a small impact on the results. In scenario 4 the digestate was assumed to be incinerated together with other fuels such as waste products which is why the ash was not returned to the field in this scenario. The nutrient balance of the systems is treated further in the discussion.

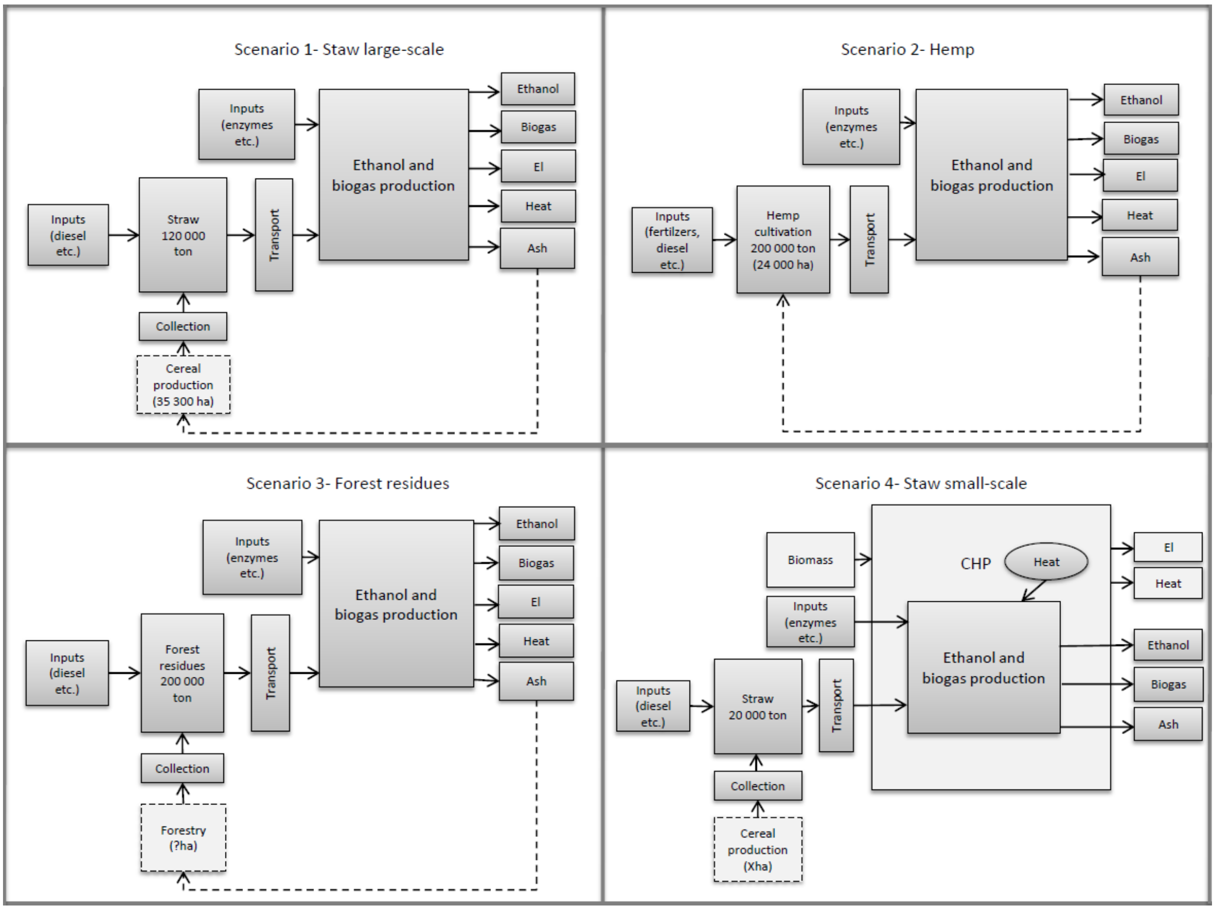


Figure 8.1. *Flowcharts for all four scenarios. The gray boxes represent subsystems that were included in the analysis while light-gray boxes represent supporting/background systems that were excluded. Straw and forest residues were considered to be by-products which implies that the environmental burden from primary production (crop cultivation/forestry) is not included. The digestate from biogas production is in all scenarios assumed to be incinerated to supply heat and electricity for the process, in some cases also excess energy is produced.*

As mentioned above, the functional unit was 1 MJ (LHV) of ethanol, biogas or electricity and no environmental impact was allocated for the heat produced. The environmental impact of collecting or cultivating biomass, transportation and biorefinery inputs was therefore divided over the energy in the different products in the scenarios. The amount of energy produced (excluding heat) in each scenario was 9.15, 10.4, 9.81 and 11.02 MJ (LHV) per kg dry matter (DM) biomass input in scenarios 1, 2, 3 and 4 respectively (Figure 8.2).

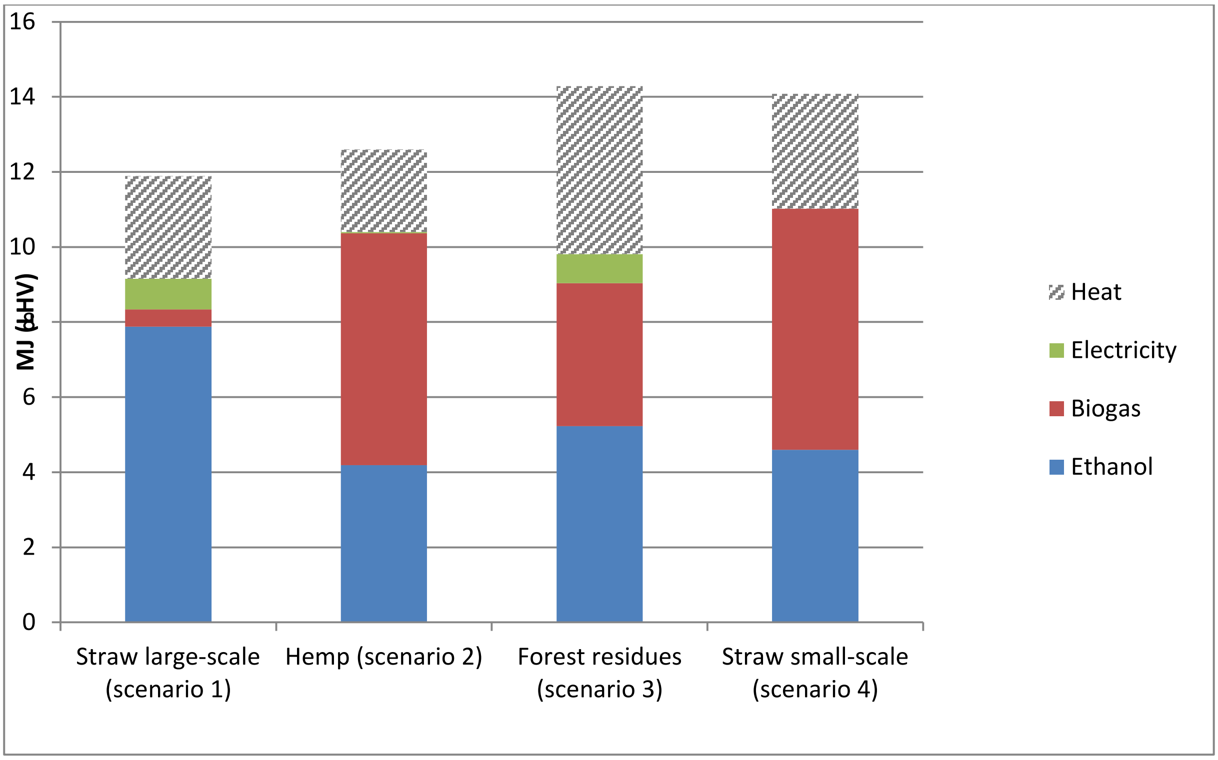


Figure 8.2. *Energy production from the four scenarios per kg DM biomass input.*

8.3. Data inventory

In this section data collection and assumptions made for each scenario are presented in detail. The following general data were assumed for the calculations in all scenarios (Table 8.1).

Table 8.1. *General data used in the LCA*

		Reference
Diesel MJ*l^{-1}	36	EC (2009)
Fossil fuel use kg CO_2-eq*MJ^{-1}	0.0839	EC (2009)
Methane MJ*kg^{-1}	50	Biograce (2012)
Methane kg*Nm^{-3}	0.708	Edström et al. (2008)
Ethanol MJ*kg^{-1}	26.81	Biograce (2012)

8.3.1. Collection of by-products and cultivation of hemp

Table 8.2. shows the energy use for the cultivation of hemp and the collection of straw and forest residues.

Diesel required for the collection and handing of straw for the processes up to unloading from storage in scenario 1 and 4 was estimated from Nilsson (1997) based on a straw yield of 2 tonnes per ha and 5% handling and storage losses. The amount of fuel used was estimated to be 7.5 litres per tonne DM straw, which equals 0.27 MJ per kg DM straw.

Diesel used in Scenario 3 for the collection of forest residues, forwarding, loading and unloading and comminution of forest residues was estimated from Lindholm et al. (2010a,b). Energy used in the manufacture of machinery was excluded and the figures were recalculated to represent secondary energy from primary energy figures. In Lindholm et al. (2010a,b) data for both northern and southern Sweden are presented, the main difference being the longer transport distance when forest residues are collected in northern Sweden. In the present study the figures for north Sweden were used, resulting in 0.21 MJ input energy per kg DM harvested.

LCI data for hemp cultivation were taken from Gissén et al. (2012) and Prade et al. (2012). Diesel used for field operations including stubble treatment, plowing, harrowing, sowing, rolling, spreading of fertilisers, chopping, compaction into silos and feeding into the biorefinery, together with primary energy input in fertilisers, machinery and storage, was estimated to be 10.2 GJ per ha, based on Prade et al. (2012) for autumn harvested hemp. The yield was assumed to be 10.2 tonnes DM per ha and, after accounting for 5% losses during storage and handling, 9.6 tonnes per ha are delivered to the biorefinery (Prade et al., 2011; Barta et al., 2013). Totally 1.06 MJ per kg DM hemp delivered to the biorefinery was used for cultivation and storage.

Table 8.2. *Energy use for collection of biomass residues and cultivation of hemp.*

	Straw large-scale (Scenario 1)	**Hemp (Scenario 2)**	**Forest residues (Scenario 3)**	**Straw small-scale (Scenario 4)**
$MJ*kg^{-1}$ DM delivered to biorefinery	0.27	1.06	0.21	0.27
$MJ*MJ^{-1}$ bioenergy produced	0.03	0.09	0.02	0.02

Fertiliser use for the cultivation of hemp is presented in Table 8.3. Greenhouse gas emissions from the production of N-fertiliser was assumed to be 5.1 kg CO_2-eq per kg N (Ahlgren et al., 2012), P-fertiliser 2.9 kg CO_2-eq per kg P and K-fertiliser 0.4 kg CO_2-eq per kg K (Gissén et al., 2012). The impact from pesticides, liming and seeds was estimated to be 121 kg CO_2-eq per ha (Börjesson et al, 2012b).

Table 8.3. *Fertiliser use in the cultivation of hemp and the GHG per kg DM hemp produced.*

Fertilizer		**Unit**	**Reference**	**g CO2-eq*kg^{-1} DM hemp**	**Reference**
N-fertiliser	143	$kg*ha^{-1}$	Gissén et al. (2012)	74.5	Ahlgren et al. (2012)
P-fertiliser	29	$kg*ha^{-1}$	Gissén et al. (2012)	8.7	Börjesson et al. (2012b)
K-fertiliser	115	$kg*ha^{-1}$	Gissén et al. (2012)	4.7	Börjesson et al. (2012b)

Direct and indirect N_2O emissions due to N-fertiliser use, N in crop residues, leaching and volatilisation has been estimated by Börjesson et al. (2012b) based on the guidelines in the IPCC (2006).

Crop residues left on the field contain nitrogen, some of which is eventually released as the potent greenhouse gas N_2O. For the straw scenarios (1 and 4) the decreased N_2O emissions when less straw is left on the field was accounted for. Avoided emissions were estimated to be 0.1% (IPCC, 2006) of the nitrogen in removed straw. Straw was assumed to contain 7 g nitrogen per kg DM (http://www.ecn.nl/phyllis).

8.3.2. Transportation of raw materials

All road transports were assumed to use a truck loading of 33 tonnes and a maximum loading volume of 110 m^3. Diesel use for transports and the properties of the truck were taken from Transport Research Institute (2010). The transport distance for scenarios 1 and 2 has been calculated for the techno-economic analysis and are presented in the previous chapters.

The straw in the large-scale straw scenario 1 was assumed to be transported 45 km with an empty return. Baled straw has a density of 175 kg per m^3 (Agriwise, 2012). With the maximal loading volume of the truck of 110 m^3, a maximum 19.3 tonnes of straw can be loaded. The loading capacity of the truck was therefore 58%. Average diesel use for transporting straw was estimated to be 0.60 MJ per tonne km based on Transport Research Institute (2010). Accounting for the DM content of straw of approx. 82% (Berglund and Börjesson, 2006) the total diesel use for transports, including the empty return, was 0.066 MJ per kg DM delivered to the biorefinery.

The hemp in Scenario 2 was assumed to be transported 53 km, with an empty return. With a loading capacity of 100%, 0.41 MJ per tonne km was estimated. Total diesel use for transport, including the empty return, was estimated to be 0.15 MJ per kg DM delivered to the biorefinery, accounting for a DM content of hemp of 31% (Prade et al., 2011).

The transport distance for forest residues harvested in northern Sweden was assumed to be 136 km (Lindholm et al., 2011). The density of forest residues was assumed to be 796.5 kg per m^3 and the DM content to be 54% (Lindholm et al., 2011). The high density allows for only approx. 41 m^3 forest residues to be loaded in a truck with a maximum loading capacity of 33 tonnes. 100% of the loading capacity (in weight) was therefore assumed to be used. Average diesel use was 0.41 MJ per tonne km, giving an average of 0.20 MJ per kg DM delivered to the biorefinery.

In the small-scale straw Scenario 4 the biorefinery was assumed to be located in Uppsala. Since only oat straw was used, straw has to be sourced in both the Uppland and Västmanland counties in order to obtain sufficient amounts. The transport distance was estimated based on Nilsson (1995) to be 85 km from collection site to biorefinery, with an empty return. Straw density and loading capacity was assumed to be the same as in scenario 1. Totally 0.12 MJ diesel per kg DM delivered was used for straw transport.

Table 8.4. *Energy use, expressed as MJ, for transport and transportation distance*

	Straw large-scale (Scenario 1)	**Hemp (Scenario 2)**	**Forest residues (Scenario 3)**	**Straw small-scale (Scenario 4)**
MJ*ton km^{-1}	0.60	0.41	0.41	0.60
DM content	0.82	0.31	0.54	0.82
MJ*ton DM km^{-1}	0.73	1.31	0.75	0.73
Transportation distance one way (km)	45	53	136	85
MJ *kg^{-1} DM delivered to biorefinery	0.07	0.15	0.20	0.12

8.3.3. Biorefinery inputs

Table 8.5. shows the biorefinery inputs of enzyme and nutrients. All nitrogen added was assumed to be in the form of ammonia, phosphorus as diammonium phosphate and sulphur as sulphur dioxide. In the small-scale straw scenario 4 manure was used instead of mineral fertilisers: totally 0.02 kg DM manure per kg DM substrate. The amount of inputs was taken from the techno-economic analysis presented in previous sections.

The enzyme application rates vary significantly depending on enzyme activity, substrate and process design (Novozymes, 2012). In the base case, enzyme dosage was based on recommendations by Novozymes (50 kg enzyme product per tonne of ethanol produced). This differs significantly from the dosages used in the techno-economic analyses in the previous chapters. Therefore enzyme requirements based on the experimental dosage (as used in the techno-economic analyses) was used in a sensitivity analysis. The dosage recommended by Novozymes is related to the amount of produced ethanol. As the amount of ethanol and other products varies among the scenarios, the dosage per kg biomass input varies (Table 8.5).

Table 8.5. *Input of nutrients and enzymes for the production process in the four scenarios.*

Input (g*kg^{-1} DM)	**Straw large-scale (Scenario 1)**	**Hemp (Scenario 2)**	**Forest residues (Scenario 3)**	**Straw small-scale (Scenario 4)**
Molasses	31.5	90.0	35.4	34.0
Enzyme	14.7	7.8	9.7	8.6
Nitrogen	2.3	8.4	7.6	0.0
Phosphorus	0.6	1.5	1.2	0.0
Sulphur	0.1	19.2	12.9	0.0

In Table 8.6 the inventory data for emissions in the production of the inputs are presented. It was assumed in accordance with Biograce (2012) that manure is not allocated any burden from animal production. The sources for the data for the environmental impact of the following substances are: molasses from Flysjö et al. (2008), nitrogen from Biograce (2012) and phosphorus and sulphur from Ecoinvent Center (2010).The LCI data on enzymes were provided by the producer (Novozymes, 2012).

Table 8.6. *Inventory data for biorefinery inputs and references.*

Fertilizer	Unit	kg CO2-eq*kg^{-1}	Reference
Molasses	kg	0.10	Flysjö et al. (2008)
Enzyme	kg enzyme product	8.00	Novozymes (2012)
Ammonia (as N)	kg N	3.23	Biograce (2012)
Diammonium phosphate (as P)	kg P	3.71	Ecoinvent Center (2010)
Sulphur dioxide (as S)	kg S	0.84	Ecoinvent Center (2010)

8.3.4. Biogas upgrading

The amine absorption technology (CApure by Läckeby Water Group, 2012) was used for the upgrading of all biogas. 0.5 kWh heat and 0.17 kWh electricity are required for the upgrading of 1 m^3 raw biogas. The methane slip in the CApure system is less than 0.1% (Läckeby Water Group, 2012). The electricity and the heat required for upgrading the biogas was assumed to be generated by the CHP at the biorefinery plant, with the exception of scenario 4 that uses purchased energy. Energy sources and energy use in the straw, small-scale Scenario 4 are explained below.

8.3.5. Energy use

In scenarios 1-3 all the energy needed in the processes was supplied internally since both heat and electricity are produced and therefore no input of electricity and heat was assumed in these scenarios. In Scenario 4 purchase of electricity was required (Table 8.7). The electricity was assumed to be Nordic electricity mix with a global warming potential of 35 g CO_2-eq per MJ electricity (Swedish Energy Agency, 2011).

Table 8.7. *Energy use in Scenario 4.*

	MJ*kg^{-1}DM Biomass	MJ*MJ^{-1} energy produced
Electricity	0.91	0.08

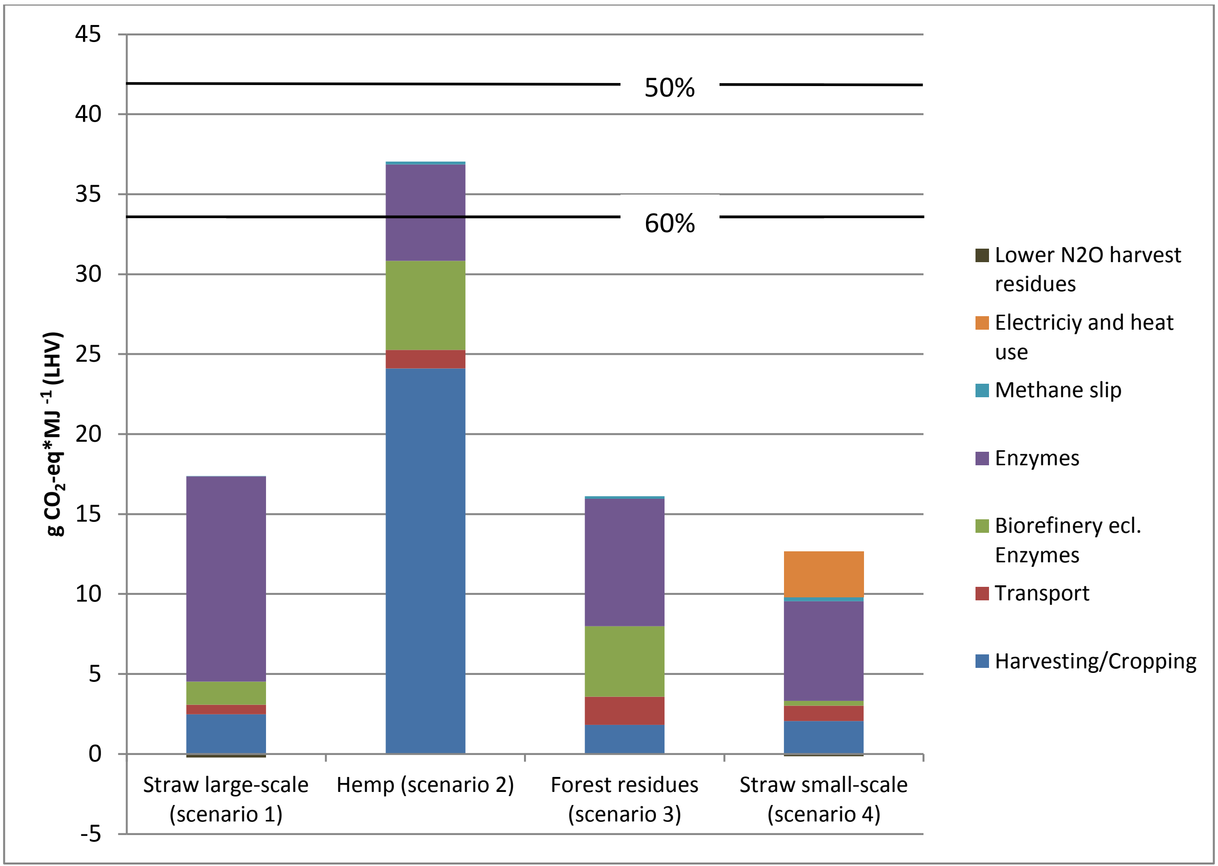
8.4. Greenhouse gas performance

Figure 8.3 and Table 8.8 present the greenhouse gas performance of the four scenarios in CO_2-eq per MJ (LHV). Scenarios utilising by-products (Scenario 1, 3 and 4) had a lower impact than the hemp scenario in which impacts from cultivation were allocated to the hemp, resulting in a significantly higher impact. For all scenarios the impact from biorefinery inputs was significant. 50-95% of the impact from biorefinery inputs came from the manufacture of the enzyme. This implies, for example, that scenarios S2A–S2D would have significantly lower GHG emissions than S2E and S2F since no enzymes were used when biogas was produced without preceding ethanol production. However, only combined ethanol and biogas production was compared with LCA.

The emissions from all activities, including for example, the production of enzymes and methane slip were combined as one figure, then divided over the amount of MJ produced. The results are therefore presented as g CO_2-eq per MJ, independent of the type of biofuel. Scenarios with high ethanol production will therefore have more emissions, such as those related to enzyme production. This is reflected in the results: for example, Scenario 1, which had the highest ethanol production also had the highest enzyme dosage per kg DM and therefore a high impact from biorefinery inputs. The impact from biorefinery inputs in the small-scale, straw Scenario 4 was lower than for the other scenario. One reason for this is that Scenario 4 had relatively low ethanol production (combined with the high total energy production of both biogas and ethanol) and therefore requires lower enzyme dosage. The other reason was that nutrients were added as manure which was assumed to be carbon neutral in accordance with Biograce (2012).

Methane slip was correlated to the biogas production, which explains why Scenario 1 had the lowest methane slip and Scenario 4 had the highest. However, the methane slip gave an overall small contribution to the total results. The lower N_2O due to removal of nitrogen with the straw also had a low impact.

According to the RED, greenhouse gas savings from the use of biofuels has to be at least a 35% reduction from a fossil fuel reference (EC, 2009). Using the fossil fuel reference from the directive 83.8 g CO_2-eq per MJ (EC, 2009) a biofuel with at least 35% savings should have greenhouse gas emissions no higher than 54.5 g CO_2-eq per MJ. All scenarios in this study have a lower greenhouse gas emission than the 35% reduction threshold. In 2017 the savings must be 50% and in 2018, 60%. These thresholds are marked in Figure 8.3. The hemp scenario 2 has higher greenhouse gas emissions than the 60% reduction threshold that will be required in 2018.



Figur 8.3. *Results of the scenarios studied, the black horizontal lines represent 50% and 60% reduction from a fossil fuel reference.*

Table 8.8. *Results of the scenarios studied, g CO_2-eq per MJ biofuel output.*

	Straw large-scale (Scenario 1)	Hemp (Scenario 2)	Forest residues (Scenario 3)	Straw small-scale (Scenario 4)
Harvesting/Cropping	2.48	24.1	1.82	2.06
N_2O emissions crop residues	-0.23			-0.14
Transport	0.61	1.18	1.75	0.95
Biorefinery inputs (excl enzymes)	1.43	5.57	4.42	0.31
Enzyme production	12.8	6.01	8.0	6.22
Methane slip	0.02	0.19	0.18	0.27
Electricity and heat				2.87
Total g CO_2-eq*MJ^{-1}	**17.2**	**37.0**	**16.1**	**12.5**

8.5. Discussion and sensitivity analyses

Performing an LCA implies making a number of assumptions. In the following, several key assumptions are discussed and analysed.

8.5.1. Enzymes

As mentioned, the enzyme application rates vary significantly depending on enzyme activity, substrate and process design (Novozymes, 2012). In the base case results, enzyme dosage was used, based on recommendations by Novozymes (50 kg enzyme product per tonne ethanol produced). This differs markedly from the dosages used in the techno-economic analyses in the previous sections. Further, two different types of enzyme products are used in the techno-economic analyses, here referred to as enzyme type 1 and enzyme type 2. Enzyme type 1 has significantly higher enzyme activity than type 2 and therefore less of type 1 was needed. Enzyme type 1 corresponds to the same type as recommended by Novozymes.

In the experimental data the enzyme dosage may be overestimated, as the experimental system is probably less optimized than an industrial process (personal communication Barta, 2012). Application rates in the experimental system are shown in Table 8.9. In the straw scenarios (scenario 1 and 4) enzyme type 1 was assumed to be used and enzyme type 2 in the hemp and forest residue scenarios. These figures are significantly higher than those recommended by Novozymes for enzyme type 1.

Table 8.9. *Dosage recommended by Novozymes and experimental dosage of enzymes, related to amount of ethanol output. Enzyme type 1 is assumed to correspond to the product Cellic Ctec3 (Novozymes), enzyme type 2 to Celluclast 1.5 L (Novozymes)*

	Straw large-scale (Scenario 1)	**Hemp (Scenario 2)**	**Forest residues (Scenario 3)**	**Straw small-scale (Scenario 4)**
Ethanol production ($g*kg^{-1}$ DM)	183	97	122	107
Biomass (kg DM * ton^{-1} ethanol)	3404	6399	5130	5840
Recommended dosage by Novozymes				
Enzyme type 1 (kg *ton^{-1} ethanol)	50	50	50	50
Experimental dosage				
Enzyme type 1 (kg *ton^{-1} ethanol)	204			101
Enzyme type 2 (kg *ton^{-1} ethanol)		1065	465	

GHG emissions from manufacture	**kg CO_2-eq *kg^{-1} enzyme product**	**Reference**
Enzyme type 1	8.0	Novozymes (2012)
Enzyme type 2	4.9	Novozymes (2012)

Using the experimental dosages of enzyme instead of those recommended, significantly increases the total global warming potential of all scenarios (Figure 8.4). This is especially significant for scenarios 1-3 which have experimental dosages 9-20 times higher than the recommended dosages. It is important to note that the experimental dosages for scenarios 2 and 3 were of type 2, which has a lower enzyme activity, which partly explains the higher dosage.

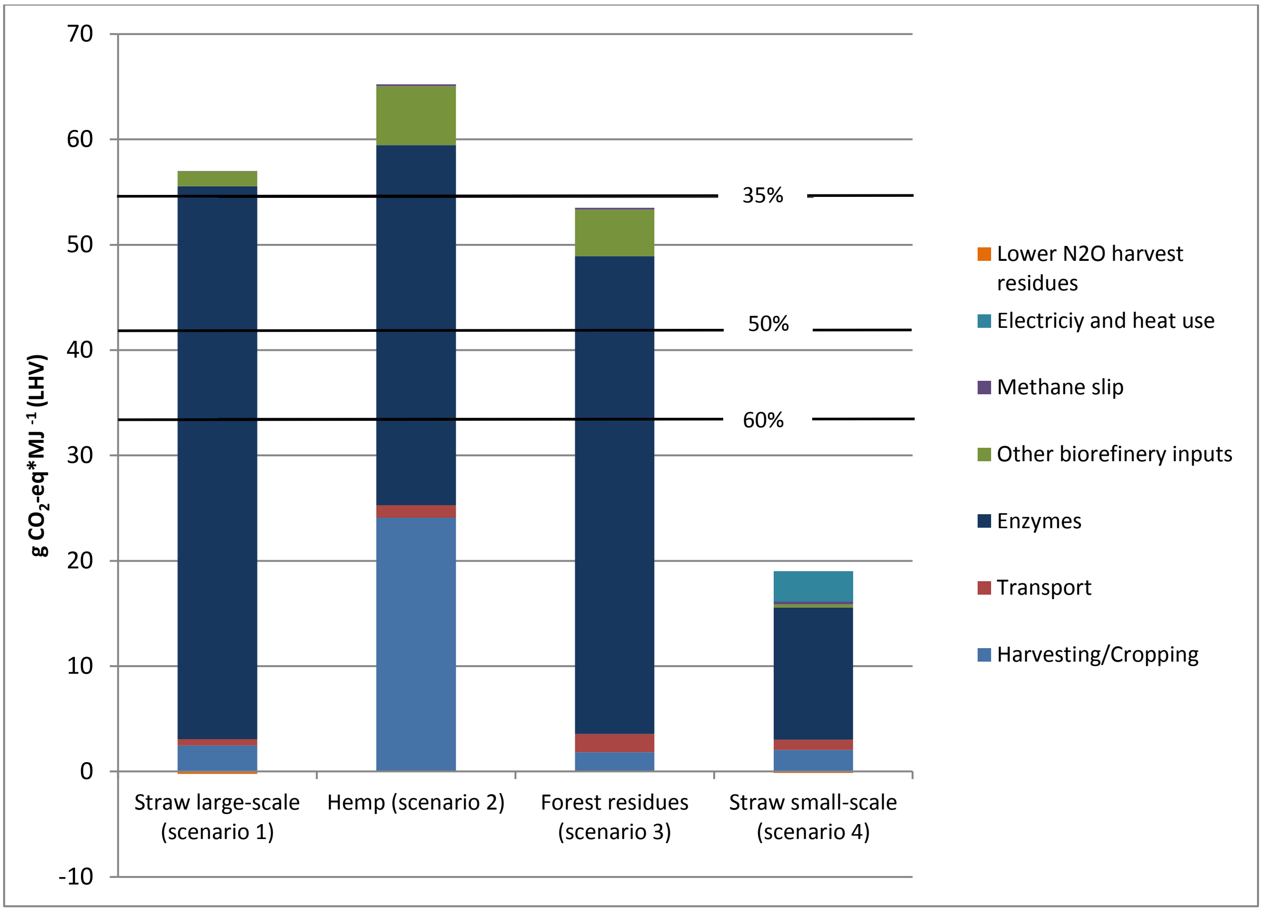


Figure 8.4. *Results of experimental dosages of enzymes, the black horisontal lines represent 35%, 50% and 60% reduction from a fossil fuel reference.*

These results show that the enzyme use is very important for the greenhouse gas performance of ethanol produced from cellulosic materials when using the same dosage as used in the techno-economic evaluation. The size of the emissions is, as shown, dependent on the dosage, but the emissions produced in the manufacture of the enzymes must also be kept track of. The manufacture of enzymes is by fermentation with microorganisms which requires inputs, such as water and nutrients. When fermentation is complete, the enzymes are separated from the rest of the liquid. Energy is needed in many steps of the process, from the production of raw materials to process energy for the fermentation tank and filtration process. More than 50 % of the global warming impact from enzymes originates from the energy used in their manufacture (Novozymes, 2012). One explanation for the large GHG emissions from enzymes in our study may be that the energy used for enzyme manufacture is based on fossil fuel. Manufacturing enzymes on-site in large-scale biorefineries would facilitate the use of bioenergy, which would be one possibility to reduce the global warming impact significantly.

Previous studies have also identified enzyme use as a significant contributor to the greenhouse gas emissions of cellulose-based ethanol production (Slade et al. 2009; Liptow 2011). MacLean and Spatari (2009) assess the contribution of enzymes and chemicals in the life cycle of cellulosic ethanol production. In their study different technologies were compared, two near-term scenarios and one representing a mature, futuristic technology. Enzyme use was assumed to be 9.6-10 kg cellulase (485 FPU per g cellulase) per tonne DM depending on production technology. Enzyme and chemical inputs proved to be dominating in the life cycles of ethanol both for global warming potential, approx. 30-35% (approx. 9 g CO_2-eq per MJ ethanol) of the global warming potential in the near-term scenarios. For the mature technology it is predicted that the contribution of enzymes and chemicals will decrease to approximately 11% of totally approx. 15 CO_2-eq per MJ ethanol.

The experience regarding enzymes at the demonstration ethanol plant in Örnsköldsvik is extensive (Lindstedt, 2012). SEKAB has in cooperation with Novozymes, ABEnzymes/Roal and other enzyme producers performed hundreds of hydrolysis trials in a 10 000 litre reactor over the past five years. Approximately 80% of the tests were based on coniferous biomass (e.g. spruce wood) and the rest were based on straw, bagasse, hard wood, corn stover etc. The dosage of enzymes varied depending on the design of the trials but the overall aim was to reduce the dosage and optimise the pre-treatment. This included acid hydrolysis adapted directly to the feedstock in hand. The results of a previous study, ended in 2011, show a reduced enzyme dosage from 15 FPU per g solid substance (SS) to 12.5 FPU per g SS, with a constant ethanol concentration. The dosage of enzymes has been reduced further by continued optimisation of the pre-treatment by improved accessibility to the enzyme, more efficient enzymes and optimal conditions for the enzymes, e.g. by improved stirring.

The current dosage of enzymes is about 10 FPU for coniferous feedstock and about 5 FPU for straw, bagasse etc. The aim is to reduce the dosage even further in conjunction with the development of new types of enzymes and SEKAB has tested new enzymes and mixes of enzymes from Novozymes before the enzymes have become commercially. The enzymes tested in the demonstration plant have not been optimised regarding the specific feedstock in use, which will be the case in future commercial plants. In these cases, a mixture of approximately five different and adapted enzymes will be used, improving the efficiency and reducing the dosage. The enzymes will also be produced on-site, mainly for economic reasons, and this will affect the GHG performance of the enzyme production and the complete biofuel production system.

8.5.2. Methane slip

In the analysis a methane slip of 0.1% was assumed, based on information from the producer (Läckeby Water Group 2012). Upgrading technologies for biogas can have substantially higher methane losses. In this report the impact of a 0.5% methane slip was analysed in a sensitivity analysis. Scenario 4 has a high biogas production relative to the other types of energy produced and a relatively low total global warming potential. Therefore, the total global warming potential would increase by 7% if the methane slip were 0.5% instead of 0.1%. The biogas production in the large scale straw scenario was relatively small which is why the increased methane slip did not affect the total results substantially.

8.5.3. Nitrogen compensation for by-product harvesting

When the by-products straw, and forest residues, are removed from the land nutrients are also removed. It was assumed that the ash (containing the potassium and phosphorus) is returned to the field and forest site in scenarios 1-3. However, since the nitrogen is released to the atmosphere during combustion it is not returned with the ash. In a sensitivity analysis it was therefore assumed that all nitrogen removed with the by-products was replaced by mineral fertiliser. It is important to note, however, that this assumption is very general and that the actual nitrogen compensation needed can be expected to vary among different production systems and locations. In scenario 4 the digestate was assumed to be incinerated together with other fuels, such as waste products, so a recovery of the ash to the field would be practically impossible. All nitrogen, phosphorus and potassium removed with straw in scenario 4 were therefore assumed to be replaced by mineral fertilisers.

Another solution to maintain a good nutrient balance would be not to incinerate the digestate, but to return it to cultivation. This would then also save energy for dewatering and waste-water treatment but would give less energy production.

8.5.4. Straw

The amount of nitrogen removed from the field when straw is harvested was estimated from the nitrogen content in straw which is approx. 0.5% of DM for grains and 2.3% of DM for oilseed crops (http://www.ecn.nl/phyllis, 2012). In scenario 1 approximately 15% of the straw used originated from oilseed straw and the remaining from grain (mainly barley and wheat). The average nitrogen content in 1 kg DM straw was estimated to be 7 g N. With a straw harvest rate of approximately 2 tonnes DM per ha, the nitrogen compensation would be 14 kg per ha. Scenario 4 utilised only oat straw, so the nitrogen content of the straw was estimated to be 5 g N per kg DM straw (http://www.ecn.nl/phyllis, 2012), phosphorus 1 g per kg DM straw and potassium 12 g per kg DM straw (SJV, 2011).

8.5.5. Forest residues

Nitrogen deficiency when forest residues are removed may occur in areas with low nitrogen deposition, especially in northern Sweden. In these areas nitrogen deficiency could result in a lower growth rate equivalent to 2-4 years of normal growth during one rotation (EPA, 2006). Egnell et al. (1998) calculated nitrogen budgets for different harvest rates and regions in Sweden and found that nitrogen compensation might be required in northern Sweden to sustain growth. In southern Sweden, however, nitrogen deposition is relatively high and removal of forest residues will most likely not affect the growth rate of the forest. Instead, the removal of nutrient-rich forest residues might decrease the risk of nitrate leaching into waterways and wetlands (Naturvårdverket, 2006). Compensation for losses of other nutrients (such as phosphorus and calcium), which result from the increased biomass removal, can be achieved by returning a suitable amount of the ash (Egnell et al., 1998).

Nitrogen content in branches and tops is approximately 4.5 g per kg (Hellsten et al., 2008). Assuming a DM removal of 26.3 Mg per ha (Lindholm et al., 2011) 118 kg N per ha should be compensated for during one rotation period. This is well below the highest recommended nitrogen compensation rate of 300 kg N per ha and rotation period (Egnell, 1998). Assuming that all nitrogen had to be compensated for, the nutrient compensation did have a significant impact and would increase the global warming potential of scenarios 1, 3 and 4 by 24%, 14% and 23%, respectively. It is, however, not likely that full compensation is necessary or, if it is, even beneficial. The results should be viewed as an indication of the possible impact of nitrogen compensation in situations when it is required.

8.5.6. Soil carbon changes

When using straw and forest residues for bioenergy production a greater share of the biomass is removed than in conventional agriculture or forestry. This alters the balance between the input and output of the soil carbon stock. In the long-term a new equilibrium of soil carbon is established (Cowie et al., 2006). In the RED methodology carbon-stock changes due to land-use changes should only be included if the land-use changes can be characterised as changing from one category to another category. The RED recognises seven land-use categories: forest land, grassland, cropland (including fallow land), wetlands, settlements, other land and multi-annual crops (Ahlgren, 2012). In this study, land use changes or land management changes involve, the removal of straw from cereal and oil seed production, removal of forest residues in forestry and cultivation of hemp on former croplands. None of these changes have to be accounted for according to the RED methodology.

Further, it was assumed that the digestate was incinerated, It can be expected that much of the lignin will be found in the digestate, so if it were returned to the field instead of being incinerated the impact on soil carbon due to biofuel production would be much reduced.

8.5.7. Soil-carbon changes due to straw removal

Straw that is incorporated into the soil decomposes, but part of the carbon in the straw will be transferred into the long-term soil carbon pool. The total amount of soil carbon depends on factors such as soil type, climate, management and moisture (Cowie et al., 2006). In this study it was assumed that by removing 60% of the biological straw harvest, 150 kg C of soil carbon is lost annually, as an average over 30-50 years, before reaching a new steady state (Börjesson et al., 2010). The biological harvest was estimated from field trials to be 4.2 tonnes DM per ha (Kätterer et al., 2011), 60 % of that, 2.5 tonnes per ha was assumed to be harvested. Based on a DM harvest of 2.5 tonnes per ha and an annual loss of 150 kg C per ha, soil C los per kg DM straw harvested was estimated to be 59 g soil C.

Soil carbon changes did have a significant effect on the total impact in the straw scenarios (1 and 4) in which the impact increased by 133-139%. The small-scale straw Scenario 4 has a slightly lower impact from soil carbon changes compared to the large-scale straw Scenario 1, the reason being that soil carbon losses were assessed as carbon lost per kg DM straw removed, and slightly more energy was produced from 1 kg DM in Scenario 4 compared to the large-scale straw Scenario 1. It is difficult to estimate soil carbon losses because of the uncertainties related to straw removal (as described above) and because of the influence of factors such as local conditions and management strategies. The result of this sensitivity analysis, however, indicates that soil-carbon changes may be of significant importance when the global warming performance of biofuels produced from straw is analysed.

8.5.8. Hemp cultivation and soil-carbon changes

No studies on soil-carbon changes due to the introduction of hemp cultivation could be found. The estimates made in this study were therefore very general and were based on assumptions made by Börjesson et al (2012b) and the figures presented in Börjesson et al. (2010).

Soil-carbon changes when hemp cultivation is introduced were analysed in two scenarios using two different land-use references, namely, unfertilised grassland and wheat cultivation with straw incorporation based on Börjesson et al. (2010). Soil-carbon changes with wheat as a reference were estimated to be 74 kg per ha when fertilisation with only mineral fertilisers (no return of digestate) is assumed (Börjesson et al, 2012b). The losses of soil carbon compared with the land-use reference of unfertilised grassland were estimated to be 424 kg C per ha based on Börjesson et al. (2010). The soil-carbon losses contributed a 7% increase of global warming potential with wheat cultivation as the reference and a 34% increase with unfertilised grassland as the reference (Table 8.8.).

As mentioned above, no studies on the effects on soil carbon of the introduction of hemp cultivation have to our knowledge been conducted. In a doctoral thesis about hemp cultivation for biogas, Kreuger (2012) briefly discusses soil carbon and soil structure when the whole plant is harvested for bioenergy. In some regions of Germany where maize cultivation for energy purposes has increase, the effects of harvesting whole maize plants for bioenergy decreased the average soil-carbon content, especially if crops like grass-leys or cereals with straw left on the field were being replaced (Möller et al., 2011). Before more qualified estimations of the effects of hemp cultivation on soil carbon can be made, more research is needed.

8.5.9. Soil carbon changes due to forest residue removal

The carbon accumulation in forest soils depends on climate, soil properties, water availability as well as forest management methods (EPA, 2006). Because the build up or loss of soil carbon depends on so many factors, estimating carbon loss due to removal of forest residues is complex. Therefore an estimation of soil carbon loss can give only a rough idea of which changes could occur in comparison with conventional forestry which only harvests the stem (Wihesaari, 2005).

Lindholm et al. (2011) modelled soil carbon changes when logging residues or stumps were removed, both in southern and northern Sweden. Three time periods were applied: a *short-term* of 20 years, *medium-term* of one rotation including a fallow period (77 and 120 years in southern and northern Sweden, respectively) and a *long-term* of two rotations in southern Sweden and three rotations in northern Sweden (231 and 240 years in southern and northern Sweden, respectively). In the *long-term* perspective removing loose residues results in a decrease in soil organic carbon (SOC) of 6.8 g CO_2-eq per MJ DM forest fuel in southern Sweden and 9.3 g CO_2-eq per MJ DM forest fuel in northern Sweden as compared to the reference scenario (conventional forestry) (Lindholm et al., 2011). Assuming that the lower heating value of forest fuel is 19.1 MJ per kg, 0.18 kg CO_2-eq per kg DM forest residues were estimated for northern Sweden. This value was used in the sensitivity analysis.

For the forest residue Scenario 3, accounting for the soil carbon losses increased the global warming potential by 113 % or by 18.2 CO_2eq per kg MJ. As a comparison, two Finnish studies Wihersaari (2005) and Repo et al. (2011) estimated the impact of changes in the carbon stock due to removal of forest residues. Wiharsaari (2005) estimated an impact of approx. 11.8 g CO_2-eq per MJ chip during a rotation period of 100 years, with a heating value of 18.2 MJ per kg DM, 215 g CO_2-eq per kg DM can be calculated. Repo et al. (2011) modelled carbon losses from 0 to 100 years. After 100 years the emissions from removing branches were 19.4 g CO_2-eq per MJ forest residues (they assumed a heating value of 19.3 MJ per kg DM), from this 383 g CO_2-eq per kg DM forest residues could be calculated. Both of these figures are higher than the ones estimated by Lindholm et al. (2011). It should be noted that both studies, Wihersaari (2005) and Repo et al. (2011) applied a shorter time perspective compared to the figure applied in the present study taken from Lindholm et al. (2011). In this study Lindholm also than the emissions in the medium term perspective (for northern Sweden, 120 years) to be 17 g CO_2-eq per MJ forest fuel which is equivalent to 0.33 kg CO_2-eq per kg DM. Including this figure for soil C changes would in our study mean the total emissions for scenario 4 would increase to 33 g CO_2-eq per MJ as compared to the base case without soil C changes that was 16 g CO_2-eq per MJ biofuel, an increase of approximately 100%.

8.5.10. Transportation distances in Scenario 4

Only oat straw was assumed to be used in Scenario 4 (small-scale straw). The straw was assumed to be collected in the area of Uppland and Västmanland of which only 1.2% of the total area is under oat cultivation (SJV, 2012). The biorefinery plant was assumed to be located in Uppsala. Available straw for bioenergy production from grain and oilseed cultivation in Uppland has been estimated by Nilsson and Bernesson (2009) to be 101 100 tonnes of straw, which is more than enough to supply the small scale plant of scenario 4 with an annual demand of 20 000 tonnes DM straw. For comparison the transportation distance was estimated (based on Nilsson, 1995) assuming that all available straw from all kinds of grain and from oilseed cultivation could be utilized in scenario 4. If all available straw could be utilized, instead of only oat straw, the transportation distance would be 10 km, with an energy use of 0.015 MJ per kg DM delivered to the biorefinery, which can be compared to the 0.12 MJ used in the base case (with a transportation distance of 85 km). The effects on the GHG emissions would be a 5.6% decrease of the total impact of the base case.

8.5.11. Results of sensitivity analysis

The results of the sensitivity analysis are summarised in Table 8.10 and expressed as percent change in GHG emissions compared to the base case, together with the total GHG emissions in the various sensitivity analyses.

Changing the enzyme dosages to the experimental dosages used in techno-economic analysis causes a significant increase of GHG emissions. With the experimental enzyme dosage all scenarios are well below the fossil reference value in the RED (EC, 2009) 83.8 g CO_2-eq, but scenarios 1 and 2 have GHG emissions higher than the 35% carbon savings threshold and scenarios 1, 2 and 3 have GHG emissions above the 50% threshold, which are the carbon savings threshold that will be enforced in 2017. As discussed above, changes in the soil carbon stock due to the land use changes relevant for this study, should not be included in the GHG accounting according to the RED (Ahlgren, 2012). However, if soil carbon changes were to be included in the GHG accounting the total GHG emissions of scenarios 1 and 2 are well above the 60% carbon savings threshold and for Scenario 3 the GHG emissions would be 34.3 CO_2-eq, which is slightly above the 60% threshold.

Table 8.10. *Results of the sensitivity analyses, expressed as percent change in GHG emissions compared to the base case, and as the total GHG emissions within parenthesis.*

	Straw large-scale (Scenario 1)		**Hemp (Scenario 2)**		**Forest residues (Scenario 3)**		**Straw small-scale (Scenario 4)**	
	GHG emissions (total)	Change from base case	GHG emissions (total)	Change from base case	GHG emissions (total)	Change from base case	GHG emissions (total)	Change from base case
Unit	g CO_2eq*MJ^{-1}	%	g CO_2eq*MJ^{-1}	%	g CO_2eq*MJ^{-1}	%	g CO_2eq*MJ^{-1}	%
Experimental enzyme dosage	+39.6 (56.8)	+231%	+28.2 (65.2)	+76%	+37.4 (53.5)	+232%	+6.32 (18.9)	+50%
Methane slip 0.5%	+0.1 (17.2)	+1%	+1.4 (38.2)	+3%	+0.9 (16.2)	+4%	+1.3 (13.6)	+11%
Nutrient compensation	+4.2 (21.3)	+24%	0.0	0%	+2.3 (18.4)	+14%	+3.5 (15.8)	+26%
Soil carbon changes*	+23.8 (41.0)	+139%	+2.7/12.7 (39.7/49.8)	+7/34%	+18.2 (34.3)	+113%	+19.8 (32.3)	+158%
Shorter transport (Scenario 4)							-0.84 (11.7)	-7%

* Soil carbon change was analysed in two scenarios for the hemp scenario 2 with the land use references: wheat (straw left on the field)/grassland representing the average change over 30-50 years. For straw, average change over 30-50 years. For forest residues, average change over 231-240 years.

9. CONCLUSIONS AND RECOMMENDATIONS

The overall conclusion of the analysis performed in this study is that integrated production of ethanol and biogas from lignocellulosic feedstock has the potential to give several benefits, compared with separate production systems. Examples of important benefits are:

- Increased biofuel conversion efficiency, expressed as biofuel output per amount ofbiomass input. Up to over 60% of the energy in the biomass feedstock can be transformed to ethanol and methane, which is similar to the biofuel conversion efficiency in, for example, thermal gasification.
- Increased, high value, energy carrier output per amount of biomass input. The output of ethanol, methane and electricity could in several process concepts be from 55% up to 65%. In addition, approximately 15-20% excess heat could be produced.
- High total energy efficiency, often between 70-85%, in combination with a relatively small fraction of excess heat. This leads to improved economy and increased opportunities to find appropriate heat sinks in the surrounding infrastructure.
- Increased profitability by increased output of high-value energy carriers. The production cost in systems based on straw is calculated to be approximately 4.50 to 5.10 SEK per litre of ethanol, and in systems based on forest residues to approximately 5.20 to 6.40 SEK per litre of ethanol. For comparison, the current ethanol sales price is approximately 6.50 SEK per litre.
- An increased number of options for integration of biofuel production plants with district heating systems and forest industries, due to the possibility to limit the fraction of excess heat produced.
- Improved greenhouse gas (GHG) performance per MJ of biofuel due to the increased proportion of biofuels produced per amount of biomass feedstock.

In addition to the benefits listed above, the integrated ethanol and biogas production systems analysed here are based on lignocellulosic feedstocks which normally fulfil current sustainable criteria in various standardisation systems. An increased harvest of biomass residues, such as straw and logging residues, will not lead to an increased competition for land use. However, cultivation of energy crops on farm land, such as hemp, may raise questions about land-use competition. Lignocellulose-rich energy crops do, however, normally have a better environmental performance than traditional food crops. Critical aspects related to the use of crop residues are changes in soil carbon, and, for logging residues, also in nutrient balance and biodiversity. However, the risk of negative effects of an increased harvest of residues from agriculture and forestry could be minimised with appropriate measures, for instance, avoiding or only partial recovery of residues on critical sites, nutrient compensation, etc. Also, increased cultivation of dedicated energy crops on fallow and abandoned land is an option.

The biofuel production systems based on straw and logging residues have a good GHG performance and the reduction of GHG's, compared with petrol and diesel, is calculated to be 80 to 85%. This is well above the required reduction level of 60% in future biofuel systems, stated in the EU renewable energy directive (RED). The GHG benefit of the hemp-based biofuel system is somewhat lower and equivalent to a GHG reduction of approximately 55%. Here, the cultivation phase is the main contributor to the life cycle emissions of GHG's. Other critical parameters in the GHG performance of integrated ethanol and biogas production systems are methane slip, soil-carbon changes and enzymes. Enzymes are shown to be the main contributor to the GHG emissions in systems based on straw and logging residues. The dosage of enzymes is here based on estimated levels in future commercial plants which is significantly lower than the dosages in current experimental trials. The dosage of enzymes is also critical in the techno-economic performance. Thus, enzymes have here been identified as an important parameter in the overall performance of future lignocellulose-based, integrated ethanol and biogas production systems.

Another important parameter in the economic performance of the biofuel production systems studied is the feedstock costs. For example, the biofuel production cost is roughly twice as high in the hemp-based system as in the systems based on biomass residues. The feedstock cost of hemp is about twice as high as straw and logging residues. Biofuel production based on hemp is therefore not profitable at current fuel sales prices.

The feedstock cost of straw and logging residues is based on the current average biomass price levels for district heating plants. The price level of logging residues, expressed per energy unit, is currently equivalent to a relatively high pulp wood price, thus an estimation is that the feedstock cost will not increase significantly in the near future since alternative types of forest biomass, e.g. thin stem wood etc, could be introduced as biofuel feedstock.

The economic performance of the combined production of ethanol and biogas is also greatly affected by the size of the biofuel plant. The production cost of ethanol in a small-scale, straw-based biofuel plant is roughly three times higher than in a large-scale plant. Small-scale co-production of ethanol and biogas is consequently not profitable today. This is mainly due to scale effects as the capital cost per unit of biofuel produced is significantly higher in small-scale plants than in large-scale plants. The large-scale plant in this study is approximately six times larger than the small-scale plants, expressed as biomass (straw) input. Thus, to reach profitability, the biofuel plants have to be large in scale under current conditions. The investment cost represents the main cost in the analysed biofuel plant alternatives, in particular regarding plants fuelled with biomass residues.

To maximize the profitability and the overall energy efficiency of future, combined ethanol and biogas production systems, in which also excess heat is produced, these systems should preferably be integrated with potential heat sinks. Thus, the location will depend on the available options of integration with, for example, district heating systems and forest industries. In addition, the location will depend on the potential availability of biomass feedstock. Regarding large-scale, straw-based biofuel plants, suitable locations are Skåne and Östergötland, where a sufficient amount of straw for energy purposes is available. In Skåne, the city of Lund could be an option for integration with the district heating system, and in Östergötland the city of Norrköping. In this case, the biofuel plant could preferably be integrated with the existing ethanol plant based on cereals.

Regarding large-scale, logging residue-based biofuel plants, suitable locations will be along the Norrland coast, and in inland counties such as Jämtland and Dalarna. In these regions, the amount of logging residues available for energy purposes is sufficient, and integration options exist in forest industries and, to some extent, in district heating systems in larger cities. A preferable location from a business point-of-view is in conjunction with large-scale ports which can provide greater flexibility regarding the supply of biomass feedstock.

The supply of biomass feedstock in the form of a dedicated energy crop, such as hemp, to a large-scale combined ethanol and biogas plant requires large areas of arable land for cultivation. For example, if such a plant is located in Skåne, approximately 5% of the arable land is needed for hemp cultivation. Regarding the siting of small-scale, straw-based biofuel plants, a significant number of options are available in several counties. Typical counties are those which have an extensive cereal production and numerous small- and medium-sized towns with district heating systems.

The research on biochemical conversion of lignocellulosic biomass into ethanol and biogas, respectively, have been substantial during the past decades, leading to a vast amount of knowledge gained within these various fields. However, the research focusing on an integrated co-production of ethanol and biogas is still limited, which implies that this concept is burdened with various kinds of biochemical and techno-economic uncertainties, even though existing knowledge regarding separate ethanol and biogas production can be utilised. From a commercialisation point-of-view, investors in new, large-scale, integrated ethanol and biogas plants need to handle technological risks, financial risks and market risks. The technological risks are normally reduced with more applied research together with the development of pilot and demonstration plants. Thus, more applied research and investments in pilot plants is needed to make possible a future development of commercial biofuel plants co-producing ethanol and biogas.

One kind of technological uncertainties concerns biochemical aspects of the process, such as the use of enzymes. Another example relates to the stillage after fermentation, which is a nutrient-limited material and therefore requires complementary feedstock materials or nutrient additions for successful biogas production. The process concepts included in this study assume incineration of the digestion residues after dewatering, which will generate process heat. However, from a sustainability point-of-view, it may be more attractive to refine the digestion residues to biofertilisers, especially if external nutrients are added to the process, leading to recirculation of nutrients and organic material back to arable and/or forest land. This issue needs to be analysed in more detail in future studies. Another biochemical aspect is the need of improving the quality of the gas and secure the stability of the biogas process, e.g. by avoiding sulphur-containing acids during pre-treatment and ethanol production, which may lead to the need of expensive, downstream processing steps.

From an investor’s perspective, some technological risks must therefore be reduced. Furthermore, investments in large-scale biofuel plants, as the ones analysed here, always include an inherent financial risk due to the large amount of capital needed. Therefore, some kind of investment subsidies will be needed for the first commercial plants to be built, in an effort to reduce the financial risk before the market has grown commercially and matured. The market risks include both competition with existing fuels, such as petrol and diesel, and their future costs, and political aspects including taxation of fossil fuels, incentives for biofuels etc. Consequently, the market risks could be significantly reduced by adequate political measures, especially long-term, stable policies for biofuels securing a growing commercial market and profitability in sustainable biofuel production systems.

The investment in lignocellulose-based co-production systems, such as the ones analysed here, could also lead to decreased risks compared with separate biofuel production systems based on a specific feedstock. The flexibility in feedstock, for example, opens up for a significant and diverse market, including various kinds of forest biomass raw materials (residues, by-products, stem wood etc) and agriculture biomass (residues, energy crops etc). Furthermore, the diversification in products also leads to operation on different markets, e.g. different biofuel markets, electricity markets and heat markets, which thereby leads to reduced market risks by diversification. In the future, lignocellulose-based co-production systems could be developed further into even more diverse biorefineries also producing high-value chemicals and compounds, which opens up for additional markets.

There are today three clear trends regarding the development of biofuel production systems. The first trend is the increased focus on sustainable production of biomass feedstock, illustrated by the development of several different international standards of sustainability criteria related to bioenergy and biofuel production. Long-term, successful biofuel production systems hence must fulfil these various criteria. The second trend is the increased focus on the competition for arable land and potential risks of negative, indirect land-use effects of an increased production of biofuels away from food crops. Future risk minimisation therefore involves the development of "low indirect impact biofuel systems". The third trend is about maximising the output of high-value products from the biomass feedstock, driven by increased feedstock costs and improvement of environmental performance. This development will most likely continue since the available amounts of sustainable biomass feedstock will be more and more valuable. These three trends promote innovative biofuel production systems, such as integrated production of ethanol and biogas from lignocellulosic biomass.

The overall conclusion based on the complementary analyses performed in this study is that in the near term increased funding for applied research regarding integrated production systems of ethanol and biogas from lignocellulose, and for the development of pilot and demonstration plants, is highly motivated. Furthermore, in the longer term, it is crucial that policy makers develop and introduce investment subsidies for the first large-scale commercial plants to be built, to reduce the financial risks. Finally, additional long-term stable and efficient biofuel policies are needed to reduce market risks for sustainable and resource-efficient biofuel production systems.

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