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LCA of transport fuels from short rotation forestry in a long term perspective

Master's Thesis in Environmental Systems Analysis

Markus Göranson

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Department of Energy and Environment
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46(0)31 7721000

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Summary

A life cycle assessment (LCA) has been carried out on biofuels for the transportation sector in Sweden originating from a feedstock of domestically farmed wood. When talking about biofuels today, there is a distinction between 1st generation's biofuels and 2nd generation's biofuels. Wood is often referred to as 2nd generation's biofuel feedstock. The benefits of 2nd generation's biofuels, compared to that of the 1st generation's, are for example a higher yield per hectare and a lesser need for fertilisers during the cultivation. The hard wood species salix was chosen as feedstock. The time frame was 30 years and the studied fuel alternatives were expected to have been introduced on a large scale, thus the studied fuel is considered being used in the background system. Prospective attributional LCA has been used throughout the study. The functional unit was 1 hectare*year and the chosen indicators for the environment were green house gases, energy efficiency and land use.

The life cycle included 3 major steps: 1. cultivation of wood; including soil preparation, harvest and termination of the cultivation, 2. conversion of energy into a specific fuel and 3. end use, which in this case meant power to the power train from the engine/motor.

The conversion of the harvested salix into transport energy was done in 2 major ways, but with 3 different outcomes:

1. Gasification with either;
    a. fuel synthesis resulting in DME/methanol, or
    b. electricity generation by burning the synthetic gas instead of synthesis, or
2. fermentation, where ethanol was the main outcome.

In other words: DME/methanol, electricity and ethanol were the main outcomes. Even though DME and methanol are two different fuels, the production was similar up to the very last step, thus the reason for putting them together as one outcome.

In the fermentation process, a large amount of lignin-fuel was by-produced. In fact the production of lignin was even larger than the produced amount of ethanol. A system expansion solution was therefore carried out for the lignin, which resulted in theoretically higher conversion efficiency.

Since the system was looked upon as a closed loop, meaning that it was self sufficient and that the exact amount of wood harvested was replanted, the only significant GHG's emitted could be traced to the manufacturing of fertilisers. The difference between the outcome alternatives was small and of a very low importance for the overall environmental performance.

The most energy efficient conversion was gasification with synthesis to DME or methanol followed by gasification to electricity and, as the most inefficient alternative; fermentation to ethanol. However, when the end use was counted in, the tables turned. Since the efficiency of an electric motor is higher than that of the combustion engine, regardless fuel, the overall efficiency of the gasification to electric motor path was more efficient than the other two alternatives.

Acknowledgements

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I would also like to thank the following people for bearing with me during my most self pitying hours: My wife Maria, my family, alibi tom and fellow “student ghetto”-friends. Thanks for your support!

Brighton, May 2009
Markus Goranson

List of abbreviations

CHP	**Combined Heat and Power**
CH_4	**Methane**
CO_2	**Carbon Dioxide**
DME	**Dimethyl ether**
GHG	**Green House Gas**
GWP	**Global Warming Potential**
ICE	**Internal Combustion Engine**
ICEV	**Internal Combustion Engine Vehicle**
ISO	**International Standard Organisation**
IPCC	**International Panel of Climate Change**
JRC	**Joint Research Centre, European Commission**
LCA	**Life Cycle Assessment**
N_2O	**Nitrous Oxide**
SOU	**Statens Offentliga Utredningar, Swedish Government's official investigations**
EU	**European Union**
VVBGC	**Växjö Värnamo Biomass Gasification Centre**
WTW	**Well-to-Wheel**

1. Introduction

In Sweden during the last 25 years, the use of fossil oil in the transport sector has increased with 40%, at the same time the use of oil has decreased in all other sectors (Swedish Energy Agency 2006). The fact that the combustion engine has undergone a lot of technical improvements during this period of time only appears to be an incentive for driving even more, or making bigger vehicles. Transport relies on fuel and fuel comes in 96% of the cases from fossil resources that are on the verge of being insufficient to meet the needs (Swedish Energy Agency 2008). The use of fossil fuels leads to an increase of CO_2 in the atmosphere, due to the fact that carbon in the fuel reacts with oxygen in the air when it’s being incinerated. And since fossil fuels originates from sealed storages beneath the earth crust, every drop of fossil oil means an addition of CO_2 when incinerated. Except for the tremendous climate threat regarding the accumulation of greenhouse gases in the atmosphere, the fact that the oil wells are drying out (Bentley 2007) demands a change in the way we see oil today. There are actually some reports saying that peak oil happened 2006 (Zittel et. al 2007). In order to solve this problem there are a range of strategies to turn to, of which one of them is simply replacing the fossil fuels with biofuels.

A lot of biofuel production today originates from agricultural annual crops, sorted under the name 1st generation biofuel. The fact that corn, rye, wheat, sugar cane and rape seed are being used to produce transport fuels, leads to increased crop prices (Kvartoft 2008) and the unavoidable ethical dilemma regarding that food is being burnt or processed not for eating, but for driving. Instead of using agricultural crops, ligno-cellulose, i.e. wood and residues from forestry and agriculture, is another option.

Apart for the ethical dilemma of using edible crops as fuel feedstock, there are of course other more quantifiable things that speak for the use of wood instead of agricultural crops for producing transport fuels in Sweden. The two most important ones are energy efficiency throughout the entire life cycle of fuel production together with the area efficiency, i.e. the land use.

To be able to compare different energy conversion processes with each other, a comparison tool is needed. There are different tools used to monitor comparisons between fuels of which Life cycle assessment (LCA) is an important one.

Today a lot of studies on transport fuels are done with well-to-wheel (WTW) studies, which is a partial LCA-study. There are a lot of problems related with those types of studies when used to assess technologies in a long time perspective.
Here are some examples:

- The detail level is too high and tied to present products.
- Using background systems of today, a distorted picture over future possibilities is generated.
- Land use isn’t considered in spite of being a limiting factor regarding the implementation of a fuel based on a renewable feedstock.
- Allocation between co-products is done rather than looking for system expansion possibilities.
- Short term studies are used for long term decision making.

1.1 Purpose and method

The purpose of the study is to analyse the inherent performance of wood as feedstock for different fuels and processes overlooking a closed system. Throughout this study, all the process steps as well as background systems use the same feedstock, which leads to a clear insight in how a limited area of cultivated salix covers the need of energy inputs such as electricity, heat and liquid fuels during the entire process chain. By using LCA to monitor the different conversion technologies, from the very first cuttings of the feedstock to end use and ultimately termination of the cultivation, this could be achieved in a transparent way. The overall energy efficiency together with green house gas (GHG) emissions for different fuel conversion technologies will be compared with each other given an agricultural area of 1 hectare land. The overall energy efficiency means in this case the efficiency throughout the entire life cycle of the studied fuel. In other words: the chosen indicators for the environment are GHG emissions, energy and land use.

1.2 Conditions for Bio energy crops in Sweden today

Today, around 70000 hectare of the agricultural land in Sweden is used for cultivating crops designated to energy production of any kind. In total there are 3,2 M hectares of arable land, and most of it (almost 2,7 M hectares) are under cultivation, the rest is used as pasture (SOU 2007:36). Not all the cultivated land is used efficiently and around 600000 hectare that originates from both pasture land and agricultural land could be used for energy crop cultivation, including the present 70000 hectare, without converting cultivated land used for cereal crops (Johnsson 2008). There are things that speak for a decrease in 1st generation's bio fuels production though. There will most likely be less production of 1st generation biofuel based on Swedish energy crops in 2009, due to the present price level (Johnsson 2008). Ever since 1998 the interest in cultivating cereal crops has been decreasing and fallow lay land is increasing and when looking upon the situation from a 25-year retrospective, around 10 % of the former cultivated land has been taken out of production (SOU 2007:36). The beliefs are that future investments in renewable energy will increase the need for energy crops and both decrease the ineffectively used land and make way for more efficient crops (SOU 2007:36).

Switching from fallow laid land to salix could be a rather beneficial move for a farmer in Sweden today. The EU has ever since the political reform of agriculture in late 2003, been giving a financial support to farmers choosing to cultivate any kind of energy crop, except for hemp and sugar beets (Swedish board of agriculture 2006). There is also a rather big support to collect from the Swedish government when establishing a salix plantation that covers most of the investment costs (Agrobransle 2008).

1.3 Feedstock

Looking upon wood as feedstock for biofuels, a distinction between softwood and hardwood is made. Salix (see figure 1-1) is an example of hardwood and spruce is an example of softwood, which are both options for feedstock alternatives for transport fuel production in Sweden. What makes salix a good alternative is e.g. its short rotation period of only 3-5 years, the easy harvesting procedure and the homogeneous quality compare to forest residuals from softwood (Swedish board of agriculture 2006). Compared to 1st generation's biofuel feedstock, salix has a much lower net energy input, which means that the ratio between output and input is greater. The yield per hectare is higher for salix compared to annual crops, which also means less land has to be claimed for cultivation to meet the energy need (Concawe/Eucar 2007). Another important advantage compared to annually harvested crops, is the lower demand for N-fertiliser, resulting in lower emissions of the greenhouse gas N_2O (Crutzen et al. 2008).

Salix purpurea L.

Figure 1-1 Salix Plant

Compared to other ligno-cellulosic feedstock alternatives, e.g. spruce and aspen, salix demands a bit more fertilisation and therefore cultivation is more energy consuming (Börjesson 2007a). On the other hand it has nearly as high yield per hectare and a 6-7 times shorter rotation period compared to that of spruce and aspen (Bioenergiportalen 2008). Today, salix is mostly used as an energy source for combined heat and power plants (CHP) and small domestic heaters (Agrobransle 2008).

Short rotation forestry is also a very good alternative compared to cutting down more "mature" forests from another point of view. In Sweden there is a national strategy carried out to prevent mature forests from being devastated (Swedish Forest agency & Swedish Environmental Protection Agency 2005). There lays a great risk within energy forestry not replanting as much as being cut down, this problem is often referred to as a *carbon sink removal*. Since an area of "green lungs" is removed in order to be converted into fuel, the amount of carbon dioxide emitted when the fuel is being incinerated has access to less area where the photosynthesis can take place. This might be causing a greater load than if forests were left and fossil fuels were used instead. In a case like that, an addition of CO_2 has taken place and the equilibrium between the atmosphere and the oceans is being moved (Kirschbaum 2002).

Salix plantation in Sweden

Today most of the salix is cultivated in the southern parts of Sweden. When salix was introduced as an energy crop in the early 1990s, the crop wasn't suitable for frost, especially not in the growth phase during the summer months (Swedish Board of agriculture, 2006). Since then the crop has been refined and is soon possible to cultivate in northern Sweden (Börjesson 2007b), something which is being examined and tested today (Örnsköldsvik 2008).

It's very hard to say how much of the available arable land could be used for cultivation since a good share of the land for economical or rational reasons is not likely to be cultivated (Johnsson 2008). About 7% of the arable land in Sweden consists of areas with a high percentage of humus in the soil. These areas are former wetlands, e.g. peat lands or dried out lakes and should be avoided as cultivation land for annual crops. When the field is ploughed oxygen reacts with the organic content in the soil resulting in higher emissions of green house gases than in normal agricultural soil. Since the soil is ploughed in intervals of between 3 and 5 years, short rotation forestry is therefore a better alternative than annual crops, although the best choice is leaving those areas as pasture land (Swedish board of agriculture 2008).

The constituents of wood

Wood goes by the name of ligno-cellulose because of its constituents. It consists of 3 major materials: cellulose, hemicelluloses and lignin. Both cellulose and hemicelluloses are carbohydrates. Cellulose molecules are simply long chains made out of glucan units. Hemicelluloses as well as cellulose contain glucan, but also other sugars, mainly xylan. The hemicelluloses molecules are about 40-50 times smaller than the cellulose molecules and are wrapped around the cellulose giving it its characteristics in tension and elasticity. Lignin consists of phenol propane units and it glues together the cellulose fibres, giving the wood its mechanical strength (Lehtikangas 1999).

1.4 LCA methodology

Life cycle assessment is performed in order to get a holistic view over a product or process. In other words, the life cycle can be explained as the use of resources and the amount of emissions connected with that studied process or product from its cradle to its grave (Baumann & Tillman 2004); e.g. in this case everything from preparing land for cultivation of salix to the use of the produced biofuel in an engine.

As mentioned before there are problems connected with how LCA is being performed on biofuels today. Since this study will handle a future scenario, there's no point in looking at renewable fuel with its present background system, thus it has to be a prospective LCA. There are two suitable methods to use; **prospective consequential** LCA or p**rospective attributional LCA**. For this study, prospective attributional LCA is used.

Prospective attributional LCA is used in order to come up with answers to the question: Which are promising technologies in different possible future states? (Hillman 2007). A question like that opens up for a lot of assumptions regarding background systems. LCA of present bio fuel technologies often use a background system where either coal or natural gas is being used for electricity production and where all transportation is done with diesel as fuel. When using a prospective attributional LCA, assumptions are done in a medium to long term time perspective, resulting in a background system where the studied fuel already has been introduced. In other words, renewable energy is assumed to be already introduced in the background system (Hillman 2007).

Allocation and system expansion

Allocation means that when the same process results in two or more products, the environmental load of the process has to be shared between those products (Baumann & Tillman 2004). Allocation is a rather discussed issue, simply because it could be misused leading to misleading results. There are two main ways to allocate environmental impacts to a product; either physical or economical. In the ISO 14044:2006 guidelines for how to deal with in and out flows, it´s clearly stated that allocation should be avoided as far as possible. Instead, a system expansion for the by-products or a higher detail level should be used.

System expansion means that the studied system is credited with benefits from production or *avoided* production from an external process that uses a fuel or raw material similar to the studied system's by-product (Bauman & Tillman 2004). This will be further explained in chapter 3.3 dealing with by-products from the fermentation process.

1.5 Concentration of Green house gases in the atmosphere

This study focus on the green house gas emissions; carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (IPCC, 2008).

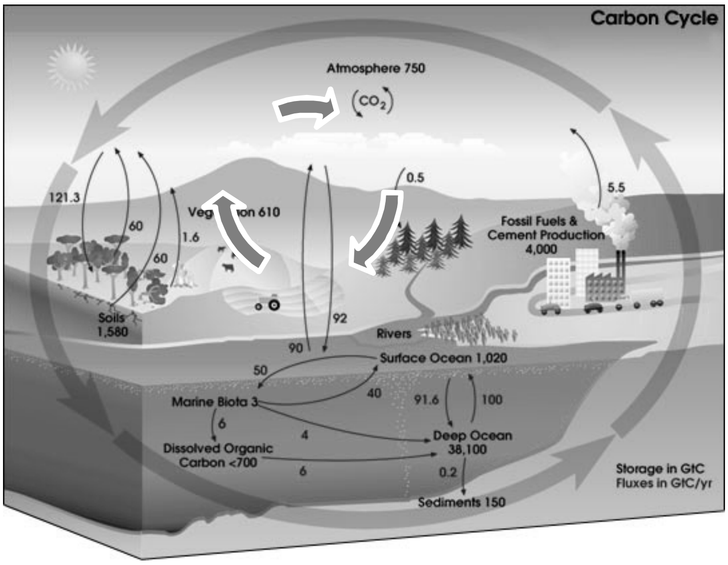

Figure 1-2 The carbon cycle

Carbon dioxide (CO_2)

The biggest difference between use of conventional fossil fuels and renewable fuels is the accumulation of carbon dioxide, CO_2, in the atmosphere. When comparing a fossil fuel with a renewable fuel on end use level, the local emissions from the exhaustion pipe are not that different between an alternative fuel vehicle and that of a conventional diesel or gasoline car. To understand the difference, one must take a look at the carbon cycle in figure 1-2. Carbon can be found in fossil forms, as a part of biosphere and in the oceans. In the biosphere plankton and trees are absorbing CO_2 and transform it into oxygen and carbohydrates. Since those autotrophs are consumed by animals, the carbon is being transferred throughout the food chain. When organisms of any kind die, bacteria and fungus decompose the organic material, releasing carbon to the atmosphere as either CH_4 or CO_2 (Miljöportalen 2008). The oceans act like a big storage for carbon since CO_2 from the atmosphere is taken up by the water and carbonic acid is created, although it's a matter of centuries to reach equilibrium[1] between concentrations of CO_2 in the oceans as well as in the atmosphere. The carbon uptake by the atmosphere is simply much faster than that of the oceans (Kirschbaum 2002). There is also an even slower cycle, practically immeasurable, where dead organic matter on the seafloor is slowly sedimenting and turns into fossil fuel (Nasa Earth Observatory 2008). The carbon found in fossil fuels is not an active part of the carbon cycle until it's brought up to the surface as crude oil. When using fuel from cultivated wood, almost no carbon is added to the carbon cycle.

Methane (CH_4)

Apart from CO_2, methane (CH_4) is another green house gas that is a part of the carbon cycle as mentioned above. CH_4 is created when organic material is decomposed in an anaerobic environment, i.e. lack of oxygen. A great deal of the emissions of CH_4 can be traced to leakages from cultivation of rice, sewage, the natural gas industry and the meat industry (Miljöportalen 2008). An increase of the global temperature could release huge amounts of CH_4 trapped in areas with permafrost that starts to defrost, causing an acceleration of the global warming. The ocean floor contains lots of trapped CH_4 as well, which is likely to be released if the temperature in the oceans increase, since it's very sensitive to temperature changes (SMHI 2008).

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[1] Equilibrium means in this case concentration of CO2 in the atmosphere just above levels similar to that of pre-industrialisation CO2-levels.

Nitrous oxide (N_2O)

The only greenhouse gas of significance, not containing any carbon, is nitrous oxide, N_2O. The pollutant sources are mainly combustion of fossil fuels, agricultural soil management and production of acid chemicals. According to IPCC, 60% of the globally emitted N_2O every year originates from natural biological reactions in water and soil. The remaining amount of emissions originates from the human related actions mentioned above (U.S Environmental protection agency 2008).

2. Goal and scope definition

2.1 Goal and Scope

In this project, LCA will be used to compare different type of transport energy, converted from the energy harboured in a specific ligno-cellulosic crop. The main processes that will be compared are fermentation and gasification of the cultivated hardwood *salix*. The studied factors are greenhouse gas emissions, energy efficiency and land use. Fermentation of salix wood generates ethanol with biogas and lignin as by-products. In a gasification process either electricity or DME, methanol and Fischer-Tropsch diesel can be produced. The outcome depends on if the produced synthetic gas is fed to a gas engine or if it's converted into a liquid fuel. Depending on outcome, a surplus of heat is also being produced. The time frame is 30 years, which is needed in order to have the technologies large scaled implemented. Using the functional unit, the LCA result of an apple could be compared with that of an orange; or for that matter -electricity with ethanol. The functional unit chosen for this project will be the transport energy originating from 1 hectare*year. The reason for involving land area is simply because land is truly a limited resource and will definitely continue that way.

2.2 Limitations

The geographical boundaries for the energy production in this study constitutes of the Swedish borders, furthermore neither crops nor liquid fuels nor electricity is assumed to be imported and the national electricity grid isn't used for input. The construction of plants, trucks and infrastructure is not considered in the analysis. Furthermore, the spare parts and electricity needed for the maintenance of machines and vehicles used in the process are not included in the analysis either. Chemicals externally produced for processes are not considered. No cost calculations will be done.

2.3 Main view over the studied system

The major flow chart in figure 2-1 shows 2 different main pathways for cultivated salix; gasification or fermentation, ending up in 3 different end product categories. The arrows in between the boxes represent the flows of energy. The first step is the cultivation of salix, covering everything from the first soil preparation to on site chipping of the harvested wood.

1. Gasification is used to transform the energy of the harvested salix into a synthetic gas, which can be further refined in two major ways:

   A. The synthetic gas can be transformed into dimethyl ether (DME), methanol or Fischer-Tropsch diesel. Except for the fuel a surplus of heat is produced. The total energy efficiency for DME is almost the same as for that of methanol, but Fischer-Tropsch diesel is a slightly more inefficient alternative (Rudloff 2008). Therefore, the synthesis step for Fischer-Tropsch diesel will not be further examined in this study.

   B. The synthetic gas is burned in a gas engine producing electricity and a surplus of heat.

   The gasification step needs electricity which is being produced in path B regardless of end product, which means that even when path A is considered, a small amount of electricity is produced in path B for internal use in the gasification process.

2. The fermentation pathway is a combination of enzymatic hydrolysis and fermentation of wood chips to produce ethanol, with biogas and lignin fuel as by-products. The process is in need of heat and electricity, which is produced in a small combined heat and power (CHP) facility. The by-products from the fermentation and hydrolysis are exported and used as a substitute for wood or natural gas as fuels for a CHP-plant.

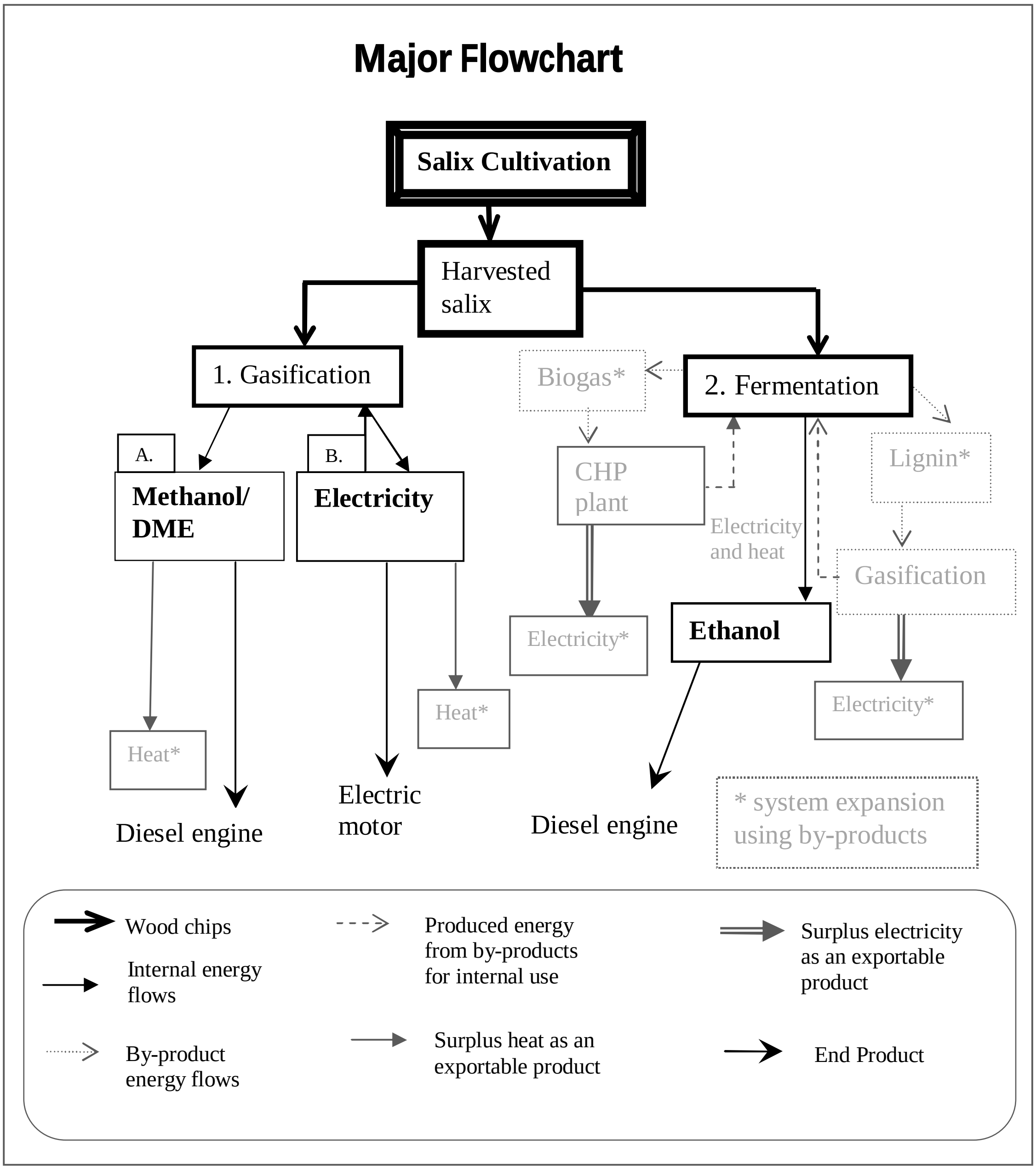


Figure 2-1 Flowchart of the major system

As end use, the engine is considered, meaning that energy loss due to friction, aerodynamics, car auxiliaries and transmission isn't counted for. For ethanol and methanol/DME a diesel engine is chosen since the efficiency is higher, although ethanol today is used with gasoline in various concentrations in ordinary Otto engines (Weiss et al 2000). For electricity an electric motor is considered. The overall efficiencies from agricultural land to engine power will be compared to each other.

2.4 Previous studies

There are different studies made about using ligno-cellulose feedstock for converting its harboured energy to alternative fuels. However, none of those studies consider a closed system and most of them use waste wood as feedstock. Here are some examples on studies together with their major assumptions.

Life Cycle Assessment of Willow Production (Börjesson 2006)

The study covers the salix cultivation and is based on present data for the background system. Diesel is used for harvesters and tractors and the electricity is generated by turbines fuelled by natural gas.

Effects of using a systems approach for biofuel greenhouse gas emissions evaluation (Wetterlund et al. 2008)

The study includes different technologies of energy conversion from ligno-cellulosic feedstock. The feedstock is forest residuals, which means that there are no assumptions about a created carbon stock which is obtained by a plantation. Both electricity from gasification, liquid fuels from gasification and ethanol from fermentation is covered in the study. Different background system scenarios are presented.

Well-to-wheels analysis of future automotive fuels and power trains in the European context (Eucar/Concawe 2007)

The extensive wtw-report from Eucar/concawe/JRC includes a vast variety of energy conversion routes for future automotive fuels. Farmed wood is considered as one of the feedstock alternatives and all the processes used in this study are represented in the Eucar/concawe/JRC-study. The background system though is based on the situation today. The electricity is calculated based on an origin of nearly 50% fossil fuels and 37,5 % nuclear, but in some technologies, electricity from biomass fuel processes is used. That makes the comparison between different technologies within the same study more difficult.

3. Inventory analysis

All collected data and assumptions must be made visible and structured, this is what is being done in the inventory analysis. First, the cultivation is considered, secondly gasification resulting in either methanol/DME or electricity and thirdly ethanol production through simultaneous saccharification and fermentation, also resulting in important by-products. After looking upon the three different outcome alternatives, end use is considered, i.e. combustion engines and electric motors. In the background systems, the energy converted in the studied process is being used. In other words, the studied fuel is supposed to be implemented in the infrastructure. When studying gasification, end products from both path A and B (figure 2-1) are being used, regardless of what path is being monitored. One of the reasons for that assumption is that trucks and harvesters used throughout the life cycle of each major outcome are assumed to be equipped with internal combustion engines. In other words, methanol or DME from path A is used in the life cycle based on path B. The other reason is that a small amount of electricity is produced in path B even for the life cycle based on path A, in order to avoid importing electricity from the electricity grid for internal use. The plantation is situated near the fuel plant, meaning that the assumed transports are, just like both Börjesson (2006) as well as Concawe/Eucar (2007) implies, very small. Wood for the conversion processes isn't taken anywhere else but from the plantation.

3.1 Salix plantation

The cultivation of salix is based on "Life cycle assessment on Willow-Production" (Börjesson 2006). Adjustments regarding use of bioenergy instead of fossil fuels have been made throughout the cultivation chain. This means that all processes and vehicles, except for production of fertilisers, use energy refined in either a gasification or a fermentation process. Tractors and harvesters are powered by internal combustion engines (ICE). When electricity is chosen as end product, the fuel for the tractor is assumed to be methanol or DME. Figure 3-1 shows the process on the next page.

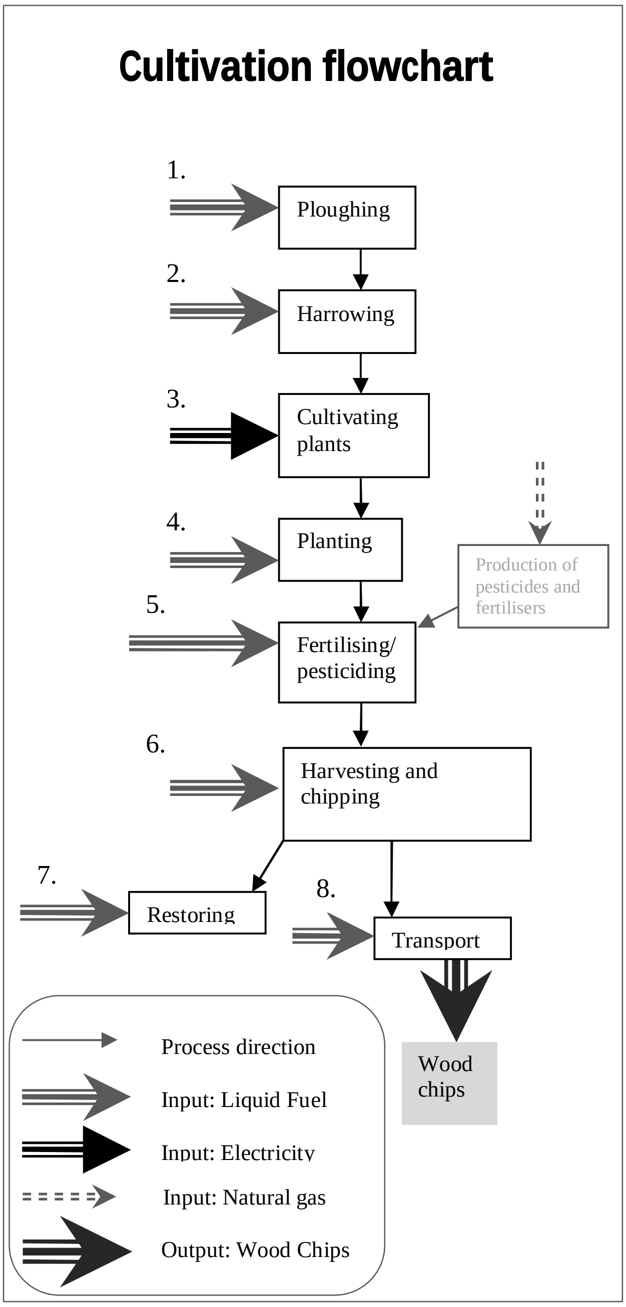


Figure 3-1 The cultivation process

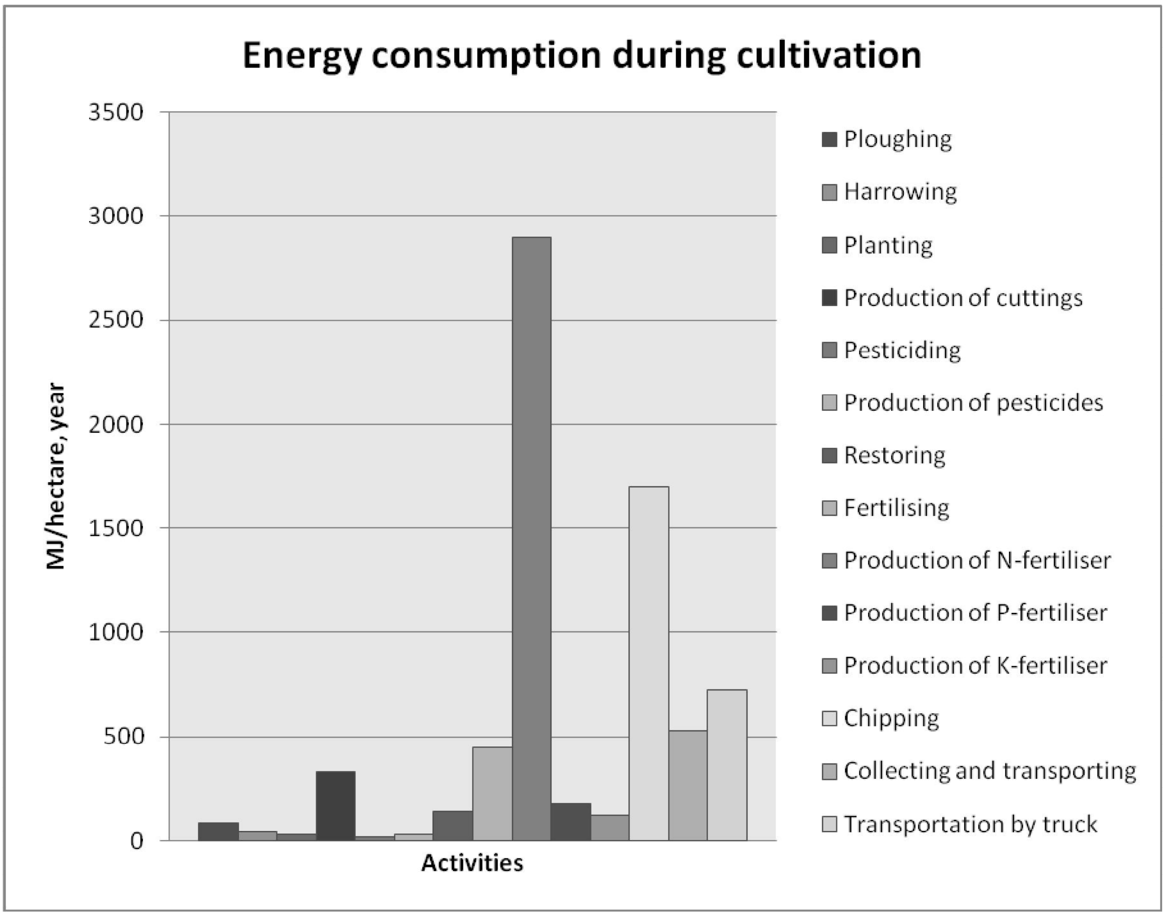
1. Ploughing is the first step of preparing the land chosen for salix cultivation.
2. The second part of the soil preparations is harrowing, which is, just like the previous step, done with an ICE tractor.
3. Cuttings of the chosen species are being cultivated so that they can form roots and be replanted in the soil.
4. Once the cuttings have formed roots, they can be planted, which is done using a tractor.
5. Different kinds of fertilisers are used in order to increase the yield. Pesticides are also used together with mechanical weed prevention.
6. A harvesting process that includes chipping of wood is done on site with an ICE tractor. No other chipping is needed.
7. After about 25 years, the salix cultivation is to be terminated. All roots and stumps have to be milled down, in order to prepare the land for whatever new crops decided for cultivation.
8. All transports of wood chips are done with either DME/methanol or ethanol fuelled trucks.

During the first stage of the fuel production cycle, salix is cultivated between 3 and 5 years before it is harvested. 3 different energy sources are used during cultivation; liquid fuels, electricity and natural gas. The reason for using natural gas, which is a fossil fuel, is that the production of P-fertiliser depends on it as an important raw material[2] (Yara 2007).

Data for the machines used for transport and harvesting is based on “life cycle assessment on Willow production” (Börjesson 2006), but adjusted for the use of DME/methanol or ethanol. Today both Volvo Trucks and Scania have got trucks fuelled by either DME or ethanol with almost exactly the same efficiency. For this study, the same energy efficiency is assumed for tractors and harvesters, irrespective of fuels.

All energy inputs throughout the cultivation process can be seen in graph 3-1 on the next page.

[2] However, since the timespan for this study is 30 years, there is a possibility that the natural gas will be replaced by biogas further on.



Graph 3-1 The energy inputs regarding all the stages throughout the cultivation phase

Establishing

The cultivation is established based on a few criteria, since the previous land use is of great importance. First of all, the land chosen is either fallow laid land, inefficient pasture land (Johnsson 2008) or open land prior used for cultivation, nowadays overgrown with bushes and small trees. In other words, the cultivated area is not forestal ground since cutting down forests to fast leads to a displacement of the equilibrium in the carbon cycle. Deforestation and decay of biomass is 17, 3% of the entire present anthropogenic GHG emissions (IPCC 2007). There are also possibilities that a large amount of carbon is released from the soil when there is a change in land use from uncultivated or cultivated land.

No other ligno-cellulosic material except the farmed salix is used as feedstock in the study.

Fertilising and weed controlling

Production and use of fertilisers are, together with the previous mentioned change in land use, the only parts of the analysed system contributing with additional GHG emissions, of which N_2O is the most severe one. Fertilisers are used to meet the need for kalium (K), nitrogen (N) and phosphor (P). N_2O emissions can be traced to the production of N-fertilisers as well as to increased reactions in the soil as a result of using fertiliser. New catalytic filters are being installed that will decrease the amount of N_2O emissions from the production, thus improving the LCA results rather much from present. Some factories has already installed filters and reported much lower emissions (Yara 2007).

An improvement of 70 % less N_2O emissions in the production of N-fertiliser is assumed (Börjesson 2008). The single most important raw material for producing N-fertilisers is natural gas (Yara 2007).

Production of K- and P-fertilisers are very hard to monitor and do not contribute to the overall GHG-emissions and energy consumption as much as that of N-fertiliser. Therefore, raw data from a present study is being used (Börjesson 2008).

Harvesting and chipping

The yield is assumed to be 10 dry tonnes substance salix per hectare (Börjesson 2006), but can vary between 7-11 dry tonnes of substance per hectare depending on location and soil quality. The wood is harvested and chipped on site using a combined harvester and chipping machine. The machines are fuelled with either DME/methanol or ethanol depending on if the studied technology is based on gasification or fermentation. The energy consumption and the GHG-emissions from the manufacturing of the harvest vehicles will not be considered, nor the production/building of the trucks used for transportation.

Transportation

By the size of the plant and the amount of wood needed for the annual production, a transport distance of 50 km for the harvested salix is assumed (Concawe/Eucar 2007). When a process based on fermentation is studied, ethanol is used as fuel for all transport. When a process based on gasification is studied, all transportation is assumed to use DME/methanol as fuel. The same efficiency as for today’s best diesel engines is assumed, meaning the amount of energy per ton*km is the same irrespective of fuels.

Closure and restoring

A salix plantation has a life period of maximum 30 years, and after that the plantation can be restored to open arable land or replanted with new salix cuttings. The stumps and roots near the surface have to be ploughed and milled down directly after the final harvest at spring. The large system of roots further down in the ground needs years to be completely decomposed and will therefore be a problem for deeper soil preparation (Danfors et. al 1997).

3.2 Gasification

Gasification is a process suitable for both liquid fuel and electricity production. The wood chips are fed into a bubbling pressurised bed of dolomite where the wood is being deconstructed under heat into a synthetic gas that consists mainly of carbon monoxide, methane and hydrogen (Ecotraffic & Nykomb Synergetics 2003). The synthetic gas can either be:

a. converted into liquid fuel, or
b. burned in an incineration chamber equipped turbine, generating electricity.

The energy conversion process up to that point is the same regardless of end product (Chrisgas 2008). Figure 3-2 describes path A, which is the synthesis path and Figure 3-3 describes path B, the electricity path. Data for the gasification plant is taken from a study by Ecotraffic & Nycomb Synergetics (2003) carried out for the municipality of Trollhättan. The size of the plant is a demonstration plant of 229 MW. Some minor adjustments regarding the electricity input had to be made in order to make the plant self-supporting. An addition of 12% more wood for internal steam and electricity production is needed in order to make the process self-supporting, resulting in a small reduction of the conversion efficiency. That assumption increases the plant size to about 257 MW. The efficiency assumption for the electricity production is based on a similar gasification plant (Wetterlund et al. 2008).

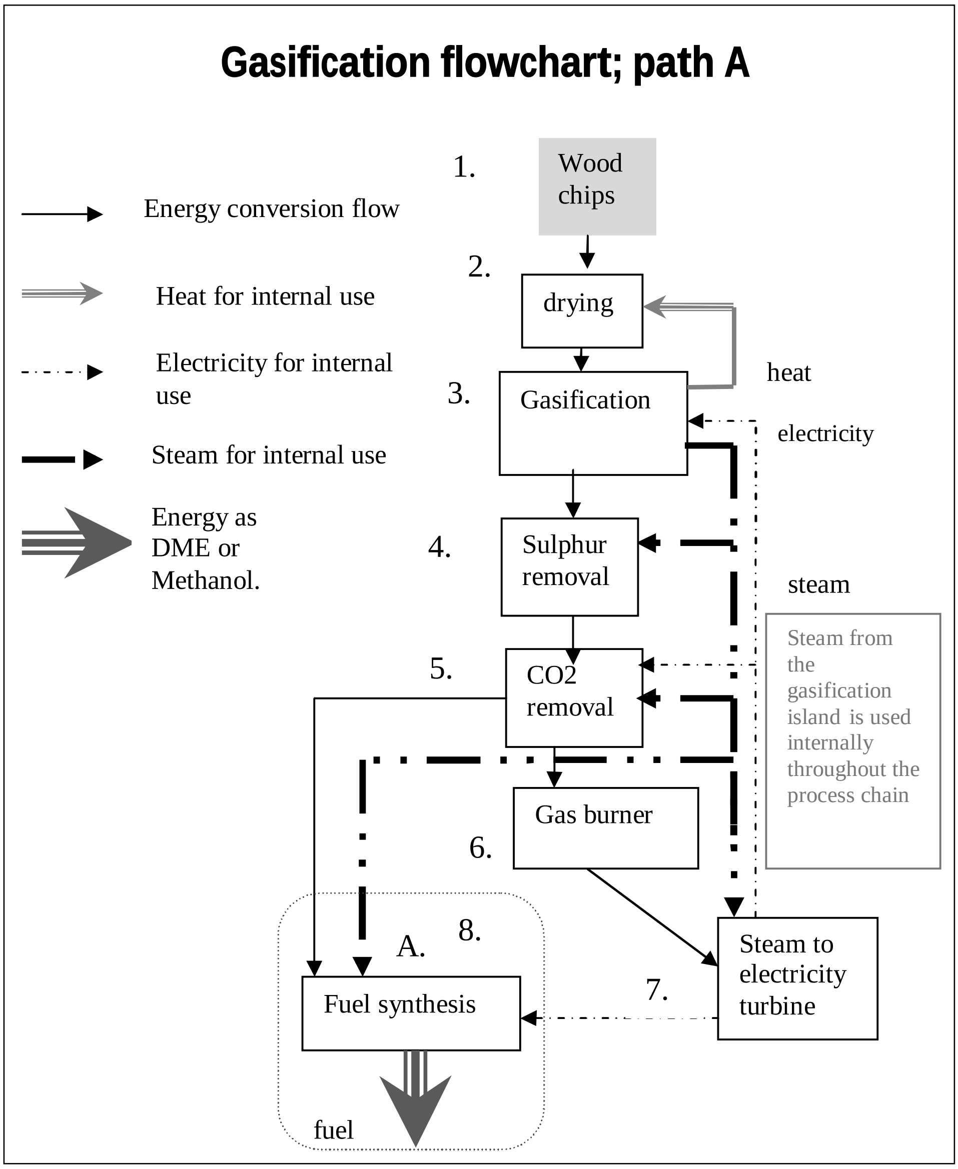


Figure 3-2 Gasification flowchart with fuel synthesis into DME/methanol

The following numbers explain the gasification to liquid fuel process steps found in figure 3-2. Number 8 is further explained under the headline “A. Conversion of the synthetic gas” after the part below.

1. The wood chips from the salix plantation are fed into the gasification process.
2. The first step is drying of the wood chips, which is done with heat from the gasification island in the process.
3. The second step shows the gasification island where oxygen, steam and recycled synthetic gas reacts with the wood chips resulting in a synthetic gas and heat. The heat is used internally.
4. The gas is treated in order to remove unwanted sulphur.
5. CO_2 is removed from the synthetic gas.
6. A small amount of the synthetic gas is burned in a gas engine
7. Hot steam left from the gasification process together with heat and steam from the gas engine is being transformed into electricity for internal use through a turbine (Ecotraffic & Nykomb Synergetics 2003).
8. The synthetic gas is converted to either DME or methanol.

A. Conversion of the synthetic gas

The last step before the fuel is transported to end use, synthesis, is a conversion process in order to transform the synthetic gas into a usable fuel such as DME or methanol. The synthesis step could be described very briefly as letting the synthetic gas pass through a catalyst (Ahlvik &Brandberg 2001).

B. Heat and power production

The path up to carbon dioxide removal is the same as in the gasification to liquid fuel process, which has already been explained on the previous page.
As can be seen in Figure 3-3, there is one process step less than in figure 3-2.

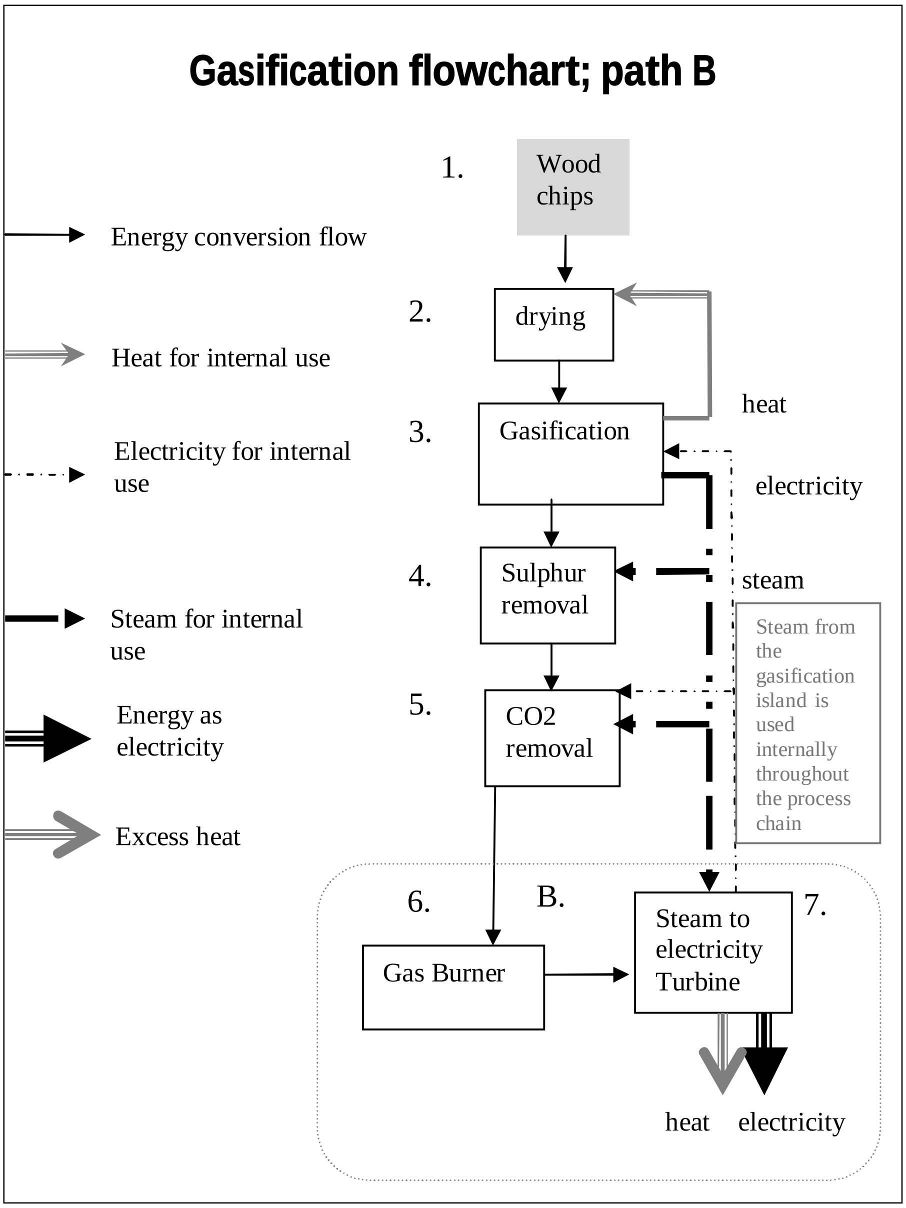


Figure 3-3 Gasification flowchart with electricity generation

Step 6 and 7 shown in figure 3-3 will be explained below. The rest of the process steps have already been explained since they are similar to those in figure 3-2.

6. All of the synthetic gas is being burned in a gas engine.
7. The steam is fed into a turbine and electricity is generated together with excess heat.

The heat can be exported and used in a district heating grid.

Data for the conversion efficiency is taken from an up scaled version of Växjö Värnamo Biomass Gasification Centre (VVBGC) (Wetterlund et al. 2008).

Energy inputs and outputs

Gasification -path A. Fuel synthesis

Figure 3-4 shows the energy input and output flows from the gasification plant with fuel synthesis. The synthetic gas to electricity process (VVBGC, 2008) is used partially even for the liquid fuel production in order to meet the internal need for electricity. There would be a possibility to handle the excess heat in a system expansion similar to the process explained in the next chapter. Since lignin is much easier to handle together with the fact that an export of heat is in this case only possible if a district heating grid is connected to the plant, the excess heat is considered a by-product rather than assuming it a part of a system expansion. The wood chips are assumed to have a humidity of between 45-56 %, which has to be decreased to 30 % in order to keep low oxygen combustion during the gasification. The drying is done in a fluidised bed with super heated steam integrated in the plants steam system (Ecotraffic & Nycomb Synergetics 2003).

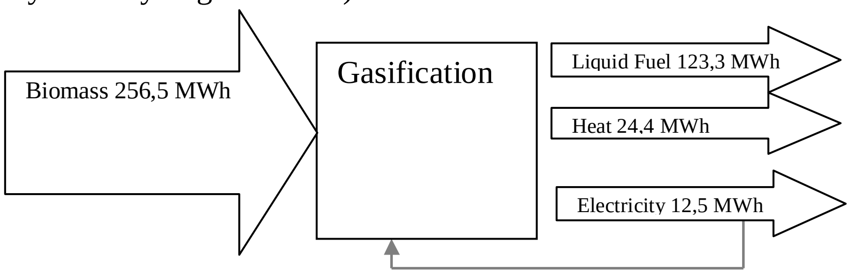
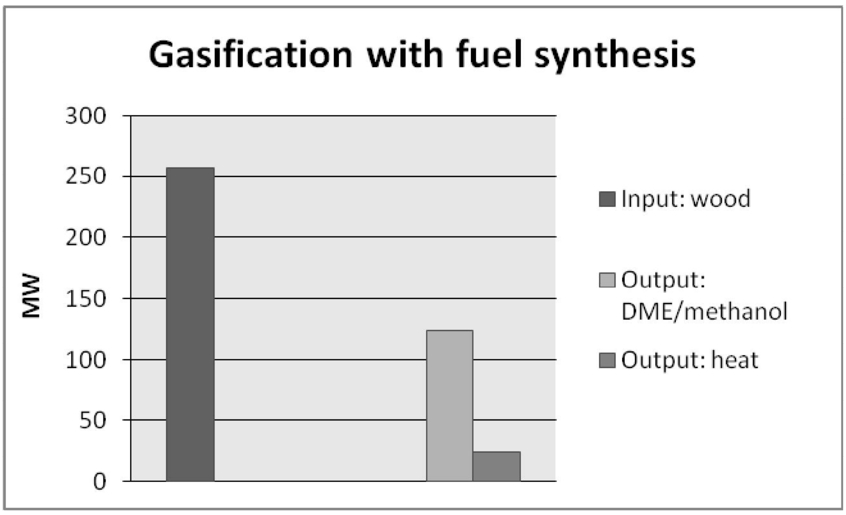


Figure 3-4 Input and output energy from the gasification plant; fuel synthesis

Both DME and methanol are produced out of the same synthetic gas. The same catalyst is used for both fuel alternatives, although slightly modified to immediately dehydrate the gas when producing DME. Thus, DME is the result of a faster conversion from the synthetic gas, leading to less energy consumption. According to Ecotraffic & Nykomb Synergetics (2003) the difference in process efficiency is about 6% for the benefit of DME. The lowest efficiency is assumed to represent both end products.

Data for the drying of wood chips is a bit uncertain since it´s rather dependent on the background system (Ecotraffic & Nykomb Synergetics 2003). The excess of heat could therefore serve as a supply for inner use in the drying stage, which can be seen in graph 3-2.



Graph 3-2 The input energy and the output energy from the gasification with the synthesis step

Gasification -path B. Electricity generation

The same amount of input energy as for path A is assumed, even though there is no shortage of electricity for internal use, since electricity is the main outcome. A different plant is used for modelling path B than that of path A. Instead of using data from Biomeet II, data from up scaling plans of VVBGC is used (Wetterlund et al. 2008). Since the conversion process is similar up to the produced synthetic gas, the conversion efficiency of VVBGC is used for modelling path B.

A large excess of heat is produced along with the electricity, which can be seen in figure 3-5. Due to the difficulties in estimating the need for heat in the drying of raw material mentioned on the previous page, the same amount of heat as for gasification to DME/methanol, 24,4 MW, serve as a supply for inner use for this path as well. In other words, at least 85,6 MW of heat is exportable.

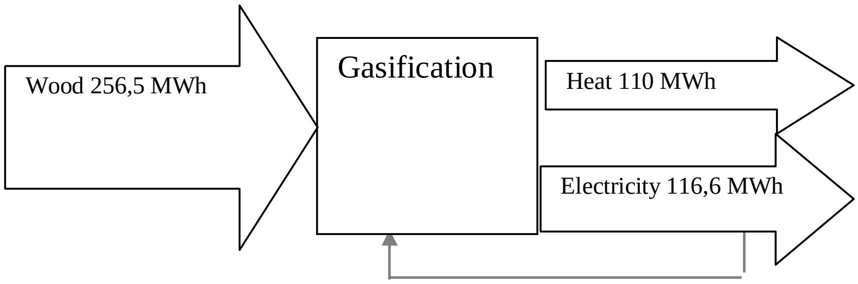
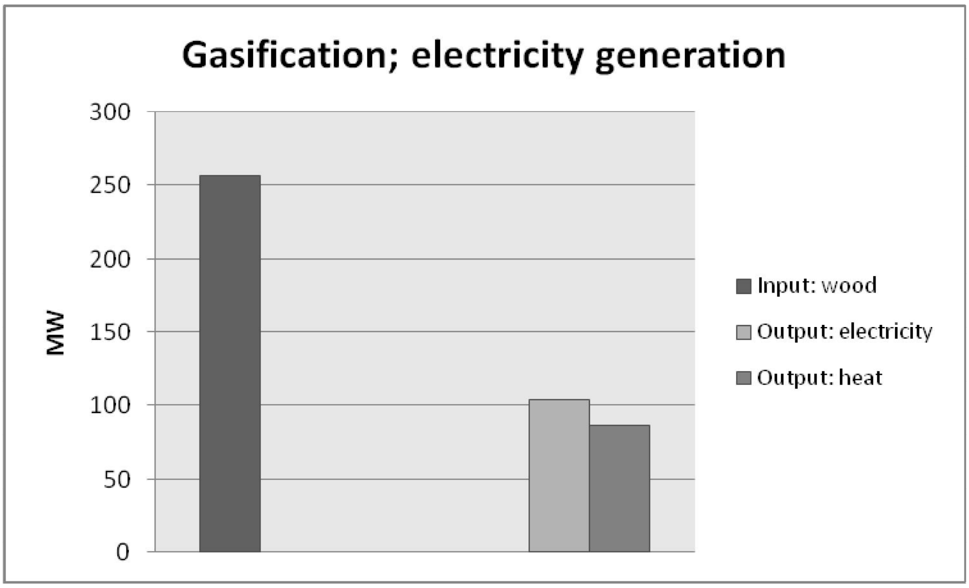


Figure 3-5 Input and output energy from the gasification plan; electricity generation

In order to be able to export the heat, the gasification plant must be situated near an area where district heating is needed. In this study no system expansion for heat is made.



Graph 3-3 The graph shows the exportable outputs after the internal electricity need is subtracted together with the heat for the drying of wood chips

3.3 Fermentation

One of the most promising technologies for converting cellulose and hemicelluloses into ethanol today is based on enzymatic hydrolysis and fermentation. When integrated, the entire process is called simultaneous saccharification and fermentation (Sassner et al. 2005). Data for the process used in the study is based upon up scaling plans for the only fermentation plant with ligno-cellulose as feedstock existing in Sweden today run by SEKAB (Fransson 2007). The data is based on using forest residuals as feedstock (Wetterlund et al. 2008). Forest residuals contain mostly softwood, which differ from salix regarding levels of hemicellulose sugars within the ligno-cellulosic composition[3] (Sassner et. Al 2007). The adjustments are further explained on the next page. The total power of the plant is 222 MW (Wetterlund et. Al 2008).

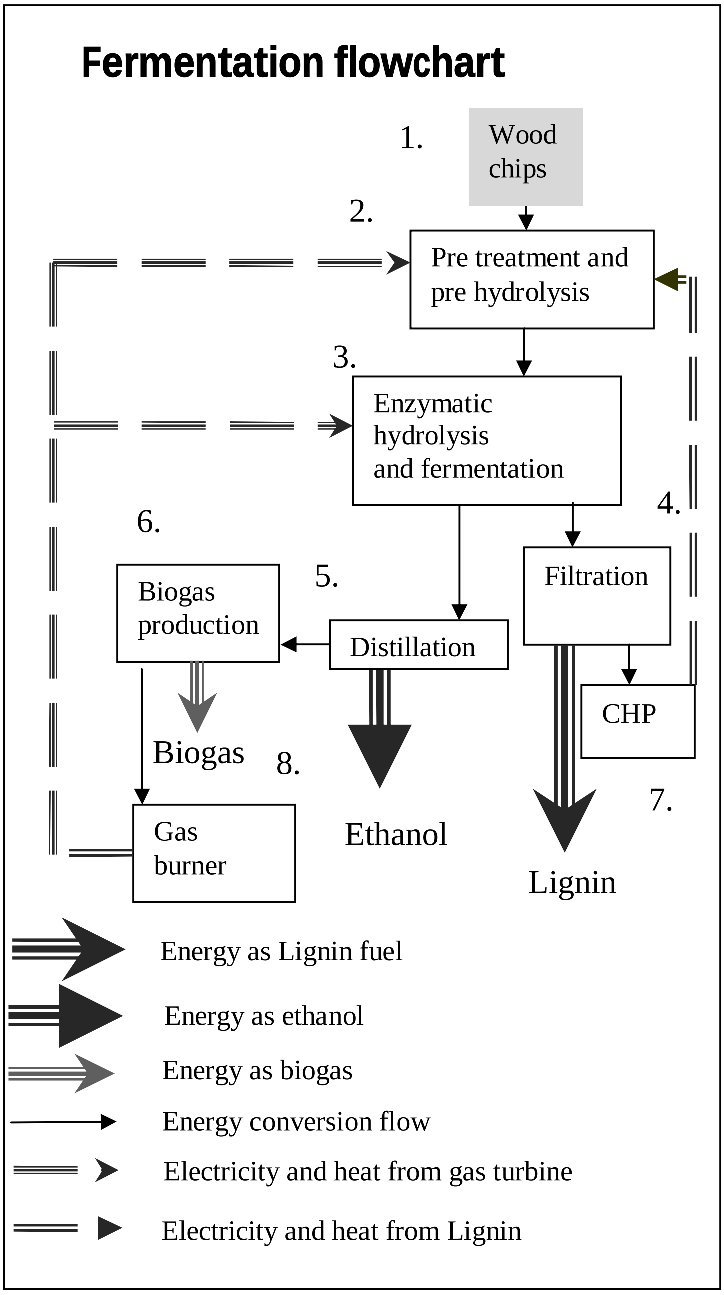


Fig 3-6 Fermentation flowchart with a CHP plant and a gas burner for the by-product handling

Figure 3-6 describes the process very briefly. The arrows symbolise the conversion flow of the energy.

1. The wood chips from the salix plantation are fed into the fermentation process.
2. The first step is the pre-treatment, which consists of a short heating process, followed by the pre-hydrolysis, which makes the hemicelluloses leach out.
3. Enzymes are added and the cellulose is cleaved into a sugary solution, leaving a residue to be further treated.
4. The solid residue consists mostly of lignin, which is filtered out and can be used for internal or external energy production.
5. Water and ethanol gets separated in the distillatory by heating up the mash from step 3, letting the water condensate (Sekab 2008).

[3] Apart from that there are also difficulties overlooking the overall GHG-emissions since the forest residuals aren't from cultivated areas.

6. Biogas is extracted[4] from the solids and liquids that are still in the slurry after the distillation (Sekab 2008).
7. The excess of lignin can be burned in a CHP-plant to meet internal needs and/or be exported either as heat and power or as fuel replacing wood in a gasification process (Wetterlund et. al 2008).
8. The biogas can be burned in a gas burner to meet the internal need for heat and power or be exported. The process is further explained in figure 3-8.

Apart from the earlier mentioned differences in rotation period between hardwood and softwood (chapter 1.3), there are also differences in the composition of cellulose, lignin and hemicelluloses –the main constituents of wood. When it comes to fermentation, the differences are of such a great importance that the process needs to be adjusted in order to increase process efficiency. During the pre-treatment phase salix can otherwise release acetic acid which can reduce the yeast fermentation capability (Sassner et. Al 2007). On the other hand, there can be even bigger differences between different salix-clones than between hardwood and softwood species regarding the contents of hemi celluloses, which clearly speaks of difficulties around using exact data for efficiency estimations today (Börjesson 2007b). Börjesson (2007b) doesn’t distinguish between hardwood and softwood since the technology is at an early stage. The same conversion efficiency for salix as for waste wood is therefore assumed in the fermentation process.

Energy inputs and outputs

There are 3 major inflows of energy to the fermentation process: electricity, steam & heat and biomass (Fransson 2007). In order to keep a closed system, the inflows of electricity and heat has to be internally produced with the by-products as fuels. Figure 3-7 shows flows of energy going in and out of the fermentation plant.

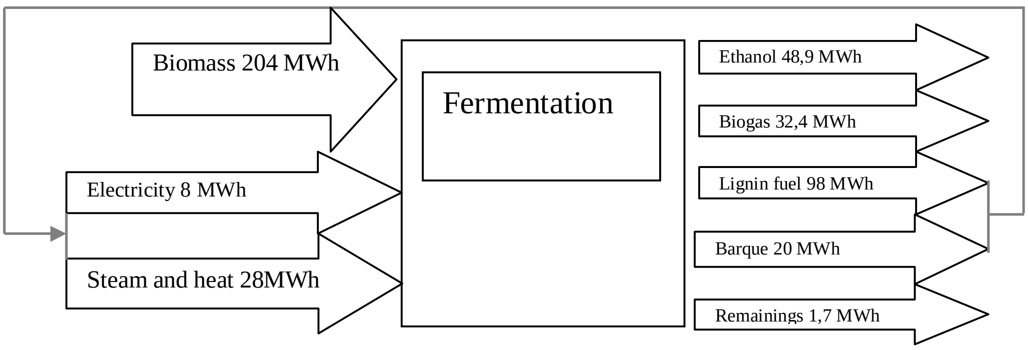


Figure 3-7 Energy input and output for the fermentation process

[4] Data about what method is being used isn’t available, but most likely a combination of anaerobic and aerobic digestion (Gasföreningen/SBGF/SGC 2008).

By-product handling

The amount of energy in the co-products from the fermentation process is actually much larger than the produced ethanol itself, as shown in table 3-1. The most significant part of the by-products is hydrolysis residue consisting mainly of lignin. According to recent studies, lignin has characteristics making it a really good substitute for wood chips in a CHP-facility (Eriksson 2005). The heating value for lignin is almost similar to that of wood. Therefore, the lignin fuel is assumed to be a substitute for wood, producing the shortage of electricity through gasification needed for the process. The conversion rate for the lignin to electricity process is based on data from Sydkraft AB for VVBGC (Wetterlund et. Al 2008). The possibility for exporting and even replacing wood is promising and allows a system expansion for the by-products.

MWwood, in	**204**
MWelectricity,in	**8**
MWheat,in	**28**
MWethanol, out	48,9
MWbiogas, out	32,4
MWlignin, out	98
MWbarque, out	20
MWsecgrade ethanol, out	1,7
Mwlosses, out	39

Table 3-1 Input and output energy with shortage of energy for the fermentation process highlighted.

There are two options to choose between in the handling of by-products for internal use:

1. Electricity and heat production from a CHP-plant using biogas, where the deficit is covered by a gasification plant fuelled with lignin. The excess lignin fuel is exported.
2. Electricity and heat production from a gasification plant fuelled with lignin, leaving the entire biogas excess available for export, together with half of the original amount of lignin fuel.

The option 1 will be described on the next page, but the second option is similar to the path B alternative described in chapter 3.2. The only difference is that lignin fuel is used as fuel instead of wood.

Combined heat and power plant; biogas

In order to produce either electricity or heat needed in the fermentation process, a CHP plant is used. Rya CHP in Gothenburg is chosen as a model for combustion of biogas (Göteborg Energy 2008). The ratio between heat and electricity is assumed to be chosen so that the conversion efficiency is as high as possible. The excess of electricity can therefore be exported. Figure 3-8 shows the energy conversion from biogas to heat and electricity.

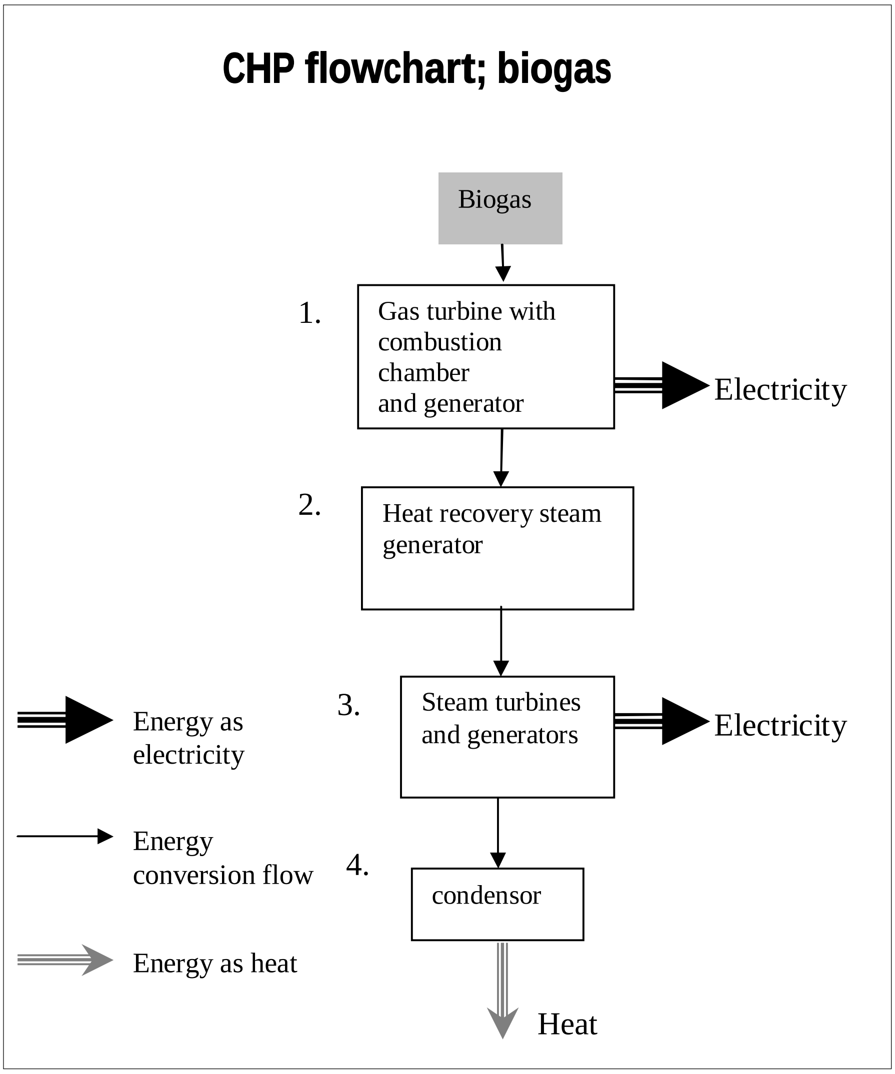


Figure 3-8 Flowchart of a CHP-plant with biogas as fuel.

1. Biogas is fed into the gas turbine, were the shaft drives the electricity generator. Half the total amount of electricity is generated here (Göteborg Energy 2008).
2. The flue gas from the turbine is feed into a boiler were the heat is transferred into a water-to-steam cycle.
3. The superheated steam is fed to the steam turbines driving the generators were the rest of the electricity is generated.
4. The steam flowing out of the turbine is led through a condenser stage where cold water from a supposed district heating grid is being reheated and can circulate back into the grid with a temperature around the boiling point.

Figure 3-9 shows the overall efficiency for the biogas to heat and electricity conversion.

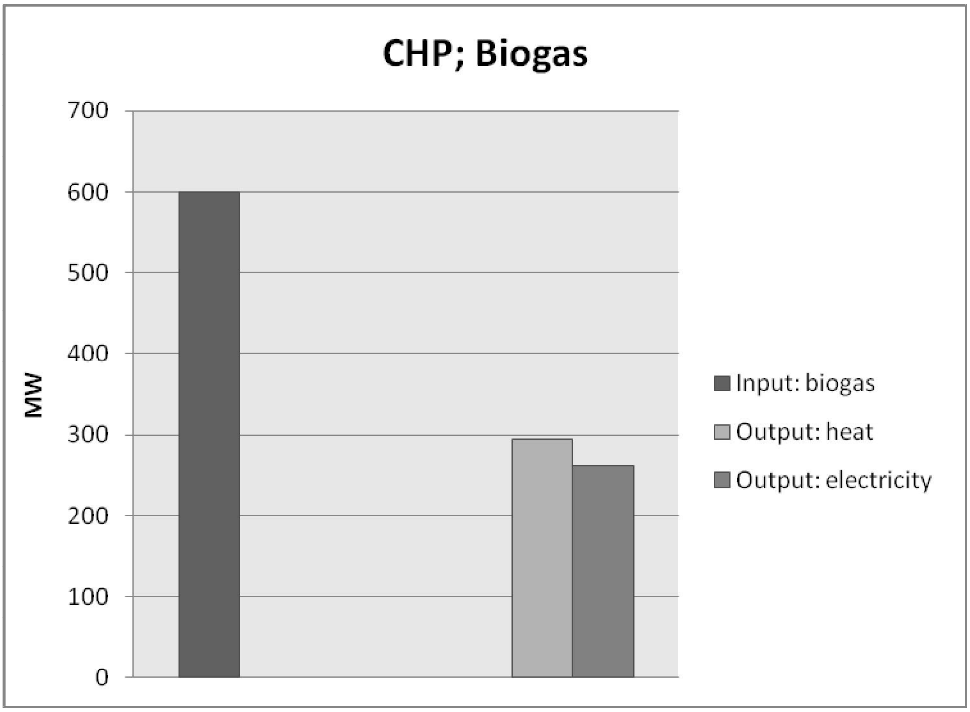


Figure 3-9 Input of the by-produced biogas and outputs of converted energy from the CHP-plant.

It could be discussed which one of the by-products is best suitable for export and therefore is to be used as little as possible in electricity and heat generation chain. There are of course pros and cons with both of the options, opening up the situation for discussion and further assumptions. Option 1 has the highest conversion efficiency. Assuming that handling a single by-product for export is more efficient than two is in favour for choosing option 1. Another fact worth considering, which also speaks for option 1, is logistics and the need for a fully functional infrastructure for biogas. The storage of biogas is far more complex than that of lignin fuel, which is in favour for using biogas internally. The excess of electricity is also bigger for the combined biogas and lignin fuel option. Table 3-2a and table 3-2b show the difference in conversion efficiency between the two options.

product	MWh	Percentage
Ethanol	48,9	23,97%
Biogas	0	0,00%
Lignin	69,92	34,28%
Heat	0,00	0,00%
electricity	26,86	13,16%
		71,41%

Table 3-2a Energy efficiency using Option 1

product	MWh	Percentage
Ethanol	48,9	23,97%
Biogas	32,4	15,88%
Lignin	33,16	16,25%
Heat	0	0,00%
electricity	21,40	10,49%
		66,60%

Table 3-2b Energy efficiency using Option 2

System expansion and land use credits

The alternative of exporting the lignin left from the hydrolysis also comes with a possibility to expand the system and consider the by-product a substitute for using salix in CHP-plants. Given that background, all of the lignin left to export is assumed to be used as an energy source for external CHP-plants instead of cultivated salix. By doing that assumption, a reduction of the cultivation area could be made. Since the amount of energy harboured in a specific area of salix dedicated for use in external CHP-plants can be replaced by the same amount of energy harboured in the produced lignin from the studied process; that amount of wood could be added to the analysed area without claiming more agricultural land, see fig 3.10.

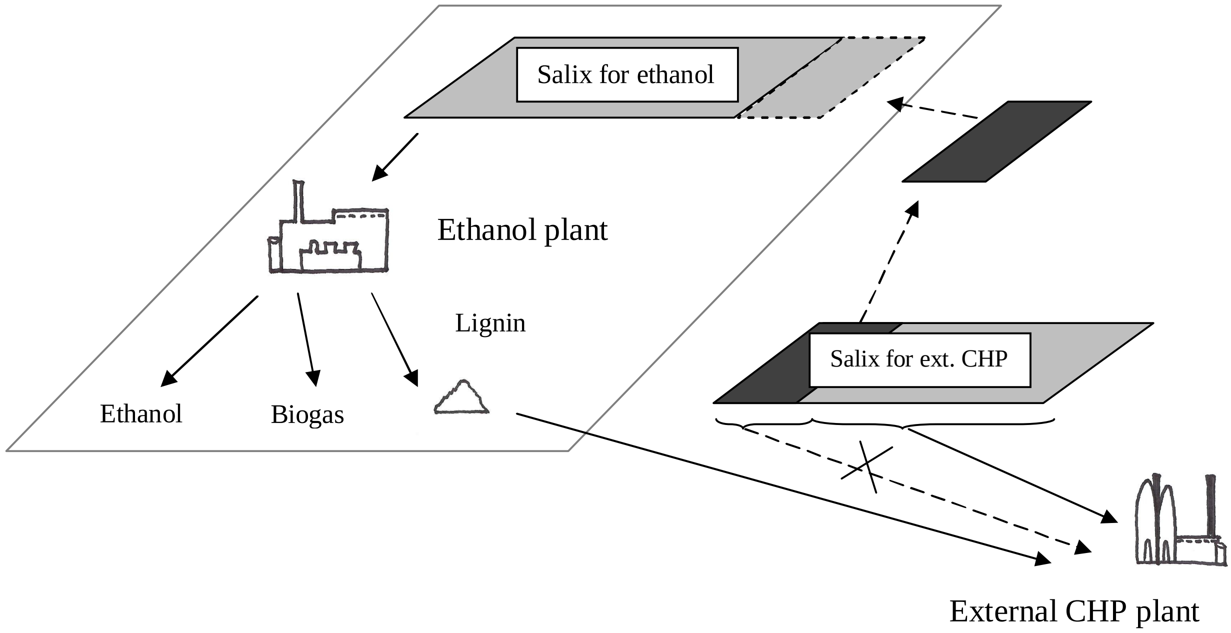
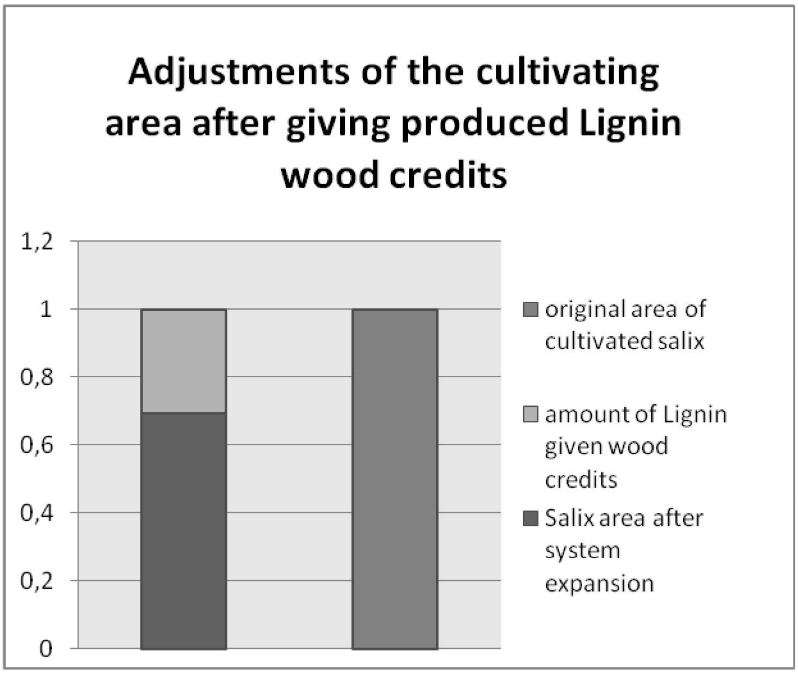


Figure 3-10 Conceptual model of the system expansion for lignin fuel replacing wood chips in external processes.

After giving lignin wood credits, an adjustment in the cultivation area and ethanol yield is necessary in order to be able to compare the gasification and fermentation paths with each other. The best way of making that adjustment is assuming the original salix area, but using the new ratio between the ethanol yield and the lignin-adjusted salix area. The result is a higher ethanol yield/hectare and year, which can be seen in graph 3-4.



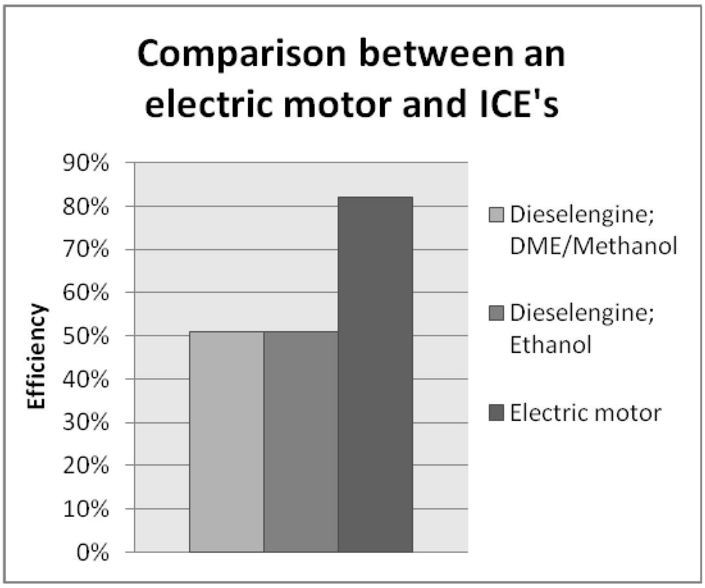
Graph 3-4 Improvement in conversion efficiency after system expansion

3.5 End use categories

The efficiency for engines will be assumed equal, despite different fuels.
The energy consumption and the GHG-emissions from the car or truck production will not be considered in the system, nor will the maintenance as mentioned earlier in the chapter.

Cars

Since it's hard to tell the efficiency of cars 30 years from now, focusing on the engine rather than the efficiency of the entire vehicle is a more transparent choice. Most car manufacturers today consider the diesel engine being the future alternative for ICEV's instead of the Otto engine. Both Swedish car manufacturers Volvo cars and Saab are positive about methanol as fuel for ICEV's and are doing research regarding engine conversions (Ecotraffic & Atrax 2007), and ethanol has already been tested as fuel for diesel engines (BSR 2008). Graph 3-5 shows the different overall efficiencies for respective end use (Weiss et. Al 2003).



Graph 3-5 Comparing energy efficiencies for different end use categories

The EU-commission's target for new cars the year 2012 is set to 125 g CO_2/km. The future EU-demand for emissions of CO_2 is assumed to be tougher. An article published by the European Parliament on the European commission's decision regarding emissions of CO_2 from passenger cars suggests that for the year 2025, a decrease in fuel consumption will lead to emissions at 70 g CO_2/km –or less, i.e. for new cars (European Parliament 2007). Last year a project was carried out presenting the first turbo diesel ICEV fuelled with E95, consuming around 0,5 l/10 km (BSR 2008). Assuming total combustion, the emissions of CO_2 from the exhaustion pipe is about 76 g/km for that vehicle.

Trucks and harvesting machines

Trucks for the transportation of wood and fuel use DME/methanol as fuel for gasification paths and ethanol for the fermentation path. Scania has got fully functional ethanol engines for smaller trucks today and Volvo has got DME engines for similar vehicles. Since Scania has made ethanol engines for busses for almost 20 years, it is assumed that the step to bigger engines will be rather easy.

The efficiency is assumed to be the same as for diesel engines today, since the difference is only a bit more than one percent for the benefit of diesel as fuel (Colton 2008).

4. **Results**

The results for this study will be presented as green house gas emissions per hectare and year, energy efficiency and fuel production and land use. The efficiency will be presented stepwise, starting with cultivation, followed by the three conversion paths, ending with overall efficiency when end use is included.

4.1 Green house gas emissions

In order to be able to compare the different emittant's impacts, a characterisation system is needed.

Classification and characterisation

Inter-governmental panel for climate change (IPCC) has carried out a comparison system where every potential green house gas is being given a specific coefficient of its global warming potential (GWP). That coefficient, CO_2-equivalent, is equal to the global warming potential the studied gas has compared to that of CO_2 (Concawe/eucar, 2007). The values are time-span dependent, meaning that they are based on how fast the emission will disperse in the atmosphere (IPCC 2007). Table 4-1 shows the most recent CO_2-equivalents, used in this study (IPCC 2008).

Greenhouse gas	**t CO_2eq/ t**
Carbon Dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298

Table 4-1 CO_2-equivalents

Since the studied system is closed, the only emissions that contribute to higher over all concentrations of green house gases in the atmosphere are emissions during use and production of different kind of fertilisers together with the production of acids, enzymes and yeast for the fermentation process. The acid production isn't included in this study since the amount of acids used in the process is low. Earlier studies of the fermentation process at SEKAB (Wetterlund et. Al 2008) doesn't include the production of acids, since no data is available (Flink 2008). For the same reasons, emissions regarding yeast and enzyme production are not part of this study either.

When using N-fertiliser, a considerable part of the nitrogen reacts with oxygen in the soil, resulting in emissions of N_2O, see figure 4-1. There are two kinds of nitrogen carriers in fertilisers, NH_4^+ and NO_3^- both of them results in N_2O due to either access to oxygen or lack of the same. Since these are also natural processes, it's hard to predict the amount of produced N_2O caused by fertilisers. Recently a paper was carried out saying more N_2O is generated from the soil than IPCC estimates (Crutzen et al. 2008), something which will be highlighted in the sensitivity analysis in chapter 5.

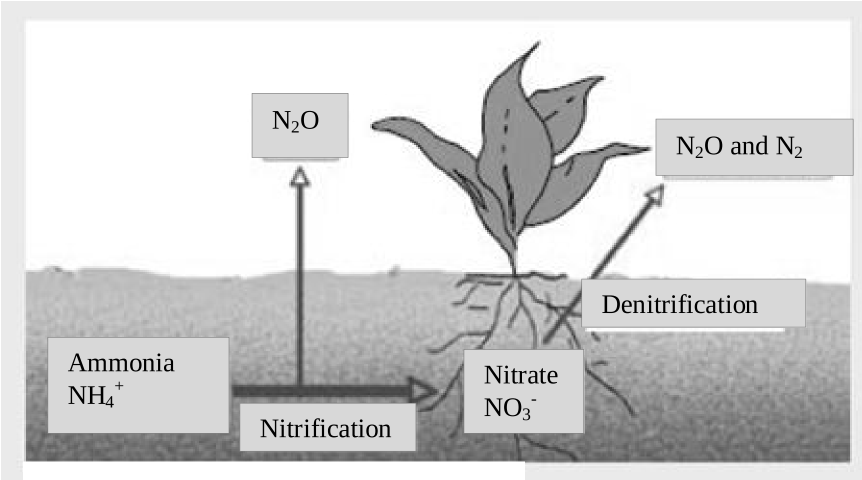
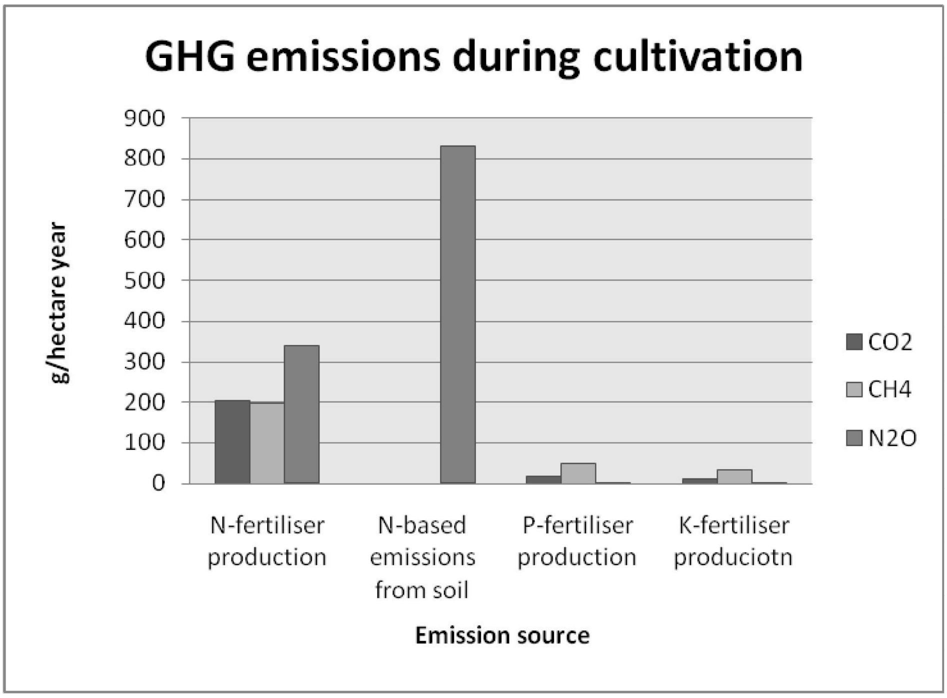


Figure 4-1 Nitrification and denitrification in the soil

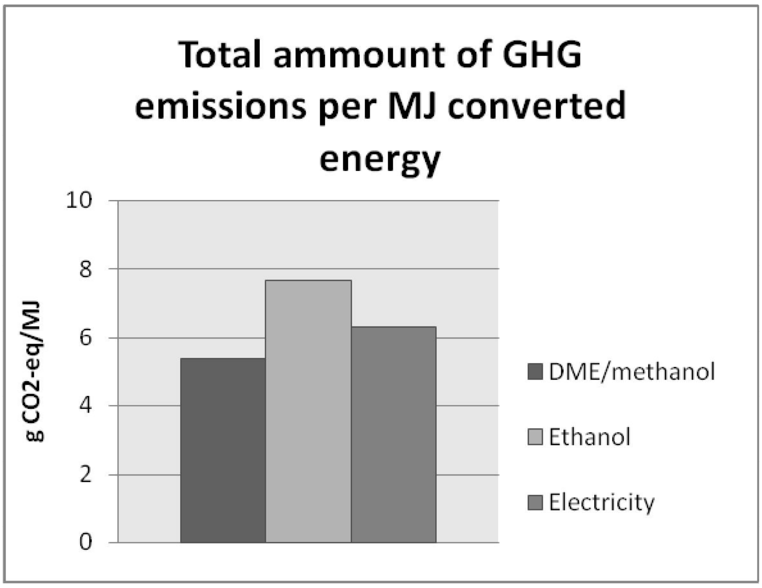
GHG emissions during the life cycle

The following two graphs show the amount of GHG's emitted during cultivation and refining of energy, i.e. fuel production or electricity generation. Graph 4-1 presents emissions during the cultivation showing that the heaviest environmental load is the emissions from the soil due to the soil reactions between nitrogen and oxygen.



Graph 4-1 GHG-emissions related to production and use of fertilisers

Graph 4-2 shows the total amount of GHG's emitted per refined MJ fuel or MJ electricity based on IPCC's CO_2-equivalents. However, compared to the amount of emitted GHG's per MJ fuel or MJ electricity originating from crude oil, the emissions aren't of a big significance. Irrespective fuel, the total amount of GHG-emissions is just below 360 kg CO2-eq/hectare, year.



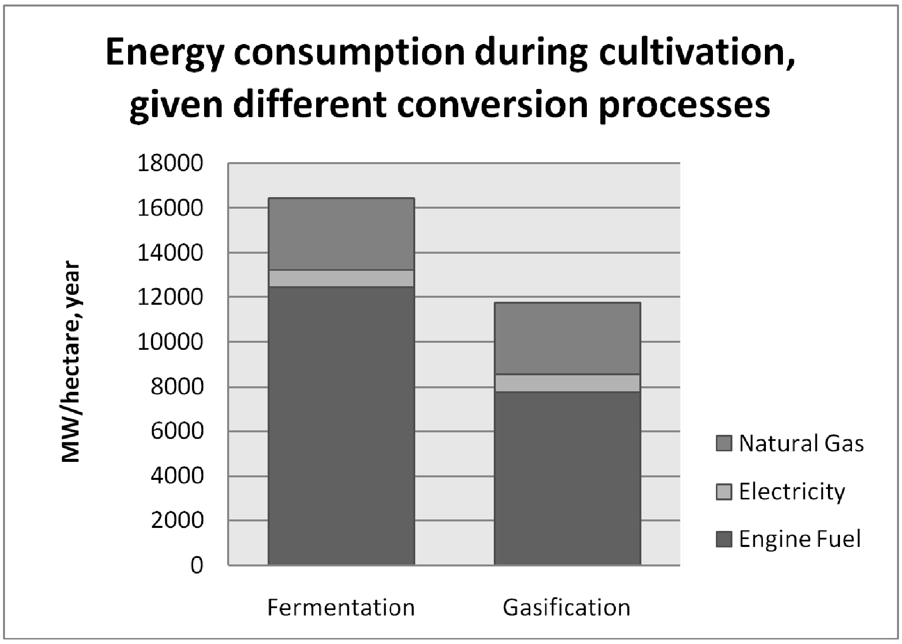
Graph 4-2 CO_2 equivalents per MJ converted energy

4.2 Energy efficiency

Cultivation of salix

Most energy consumed during cultivation of salix comes from using liquid fuels in the tractors and harvesters. The only external energy source used is natural gas. Regarding the liquid fuels used in the process, the lower conversion efficiency of ethanol affects the overall efficiency, making it slightly more inefficient than DME/methanol.

Graph 4-3 shows the difference in energy consumption during cultivation given what technology is being monitored; gasification or fermentation. The ethanol process demands nearly 60% more energy than the process for DME/methanol. If the consumption of electricity and the natural gas for the production of N-fertiliser are taken into account as well, the difference is around 40%.

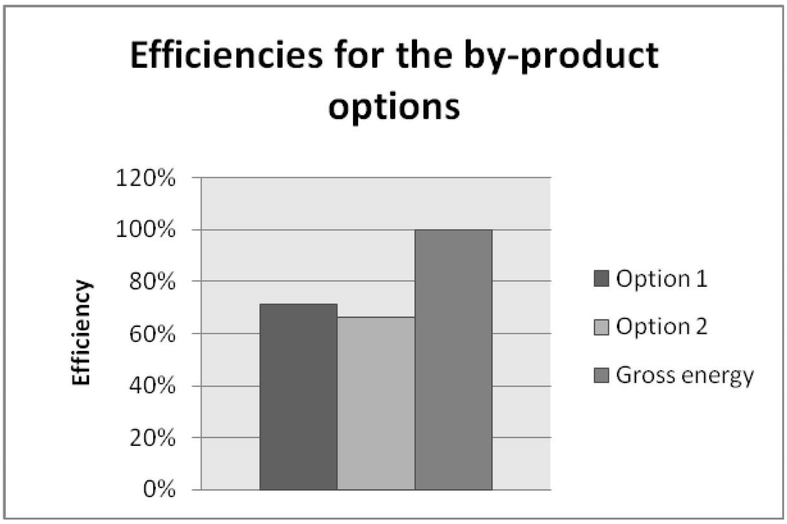


Graph 4-3 Consumed energy during the cultivation depending on what technology is being studied.

All in all, in the entire ethanol production chain, cultivation consumes 12% of the entire energy content in the harvested salix. The number for DME/methanol or electricity production is 8%. The amount of energy harboured in the harvested salix will henceforth be presented as gross energy.

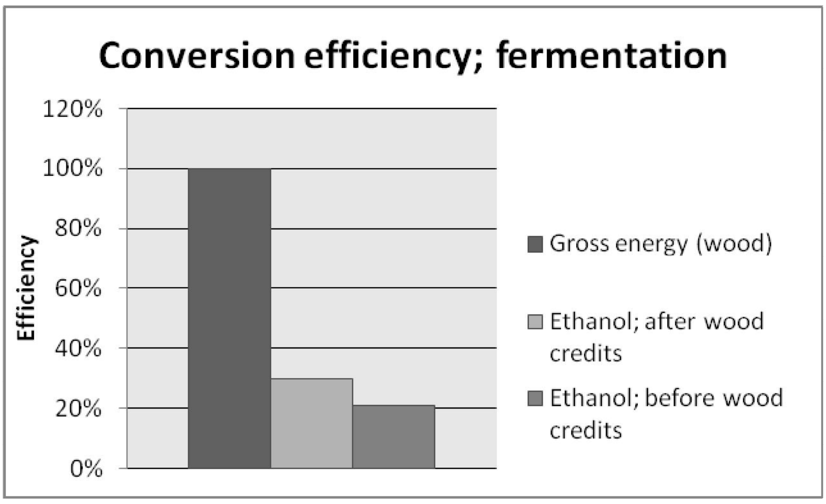
Fermentation conversion efficiency

The energy efficiency for the fermentation process is highly dependent on a combination of a CHP and a gasification facility, since the energy contentious by-products are suitable as fuels. The energy efficiency includes the sum of all by-products left after system expansion (see chapter 3.3). Graph 4-4 shows the energy efficiency for each option, where the energy harboured in both ethanol, lignin, biogas and excess electricity is counted in. Option 1 is based on chosing both biogas and lignin for internal electricity and heat and Option 2 is based on using only lignin, leaving both biogas and lignin left to export. The biogas is burned in a gas engine that generates electricity and the lignin fuel is gasified and the synthetic gas is also burned in a gas engine that generates electricity.



Graph 4-4 Energy efficiency depending on which by-product is being used for heat and power production

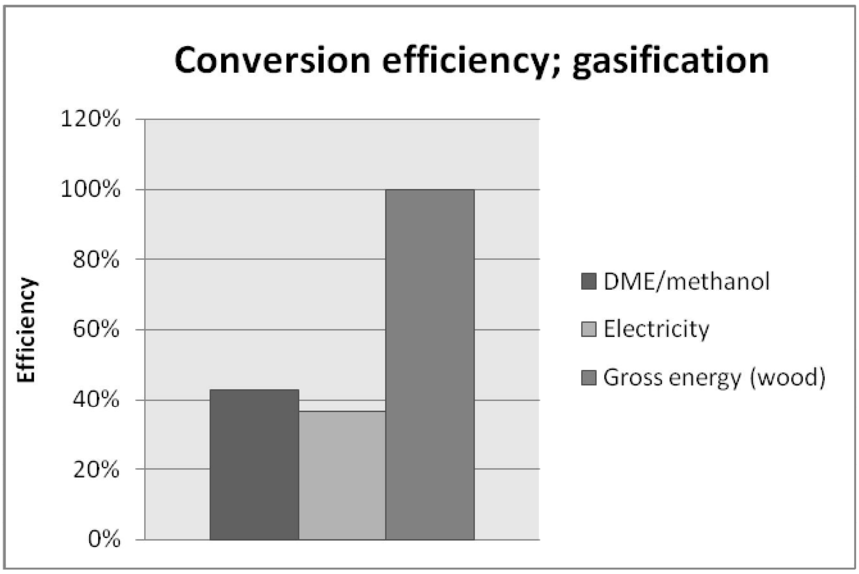
The system expansion explained in chapter 3.3, were the by-produced lignin fuel is being given wood credits that led to an increase in ethanol yield, also contributes to a higher energy efficiency. The conversion efficiency gain is shown in graph 4-5. The system expansion is done after subtracting the lignin fuel needed for internal use after choosing option 1 in the by-product handling. A comparison is done between the gross energy and the energy in the produced ethanol.



Graph 4-5 Conversion efficiency for ethanol production depending on the possibility for system expansion

Gasification conversion efficiency to either liquid fuel or electricity

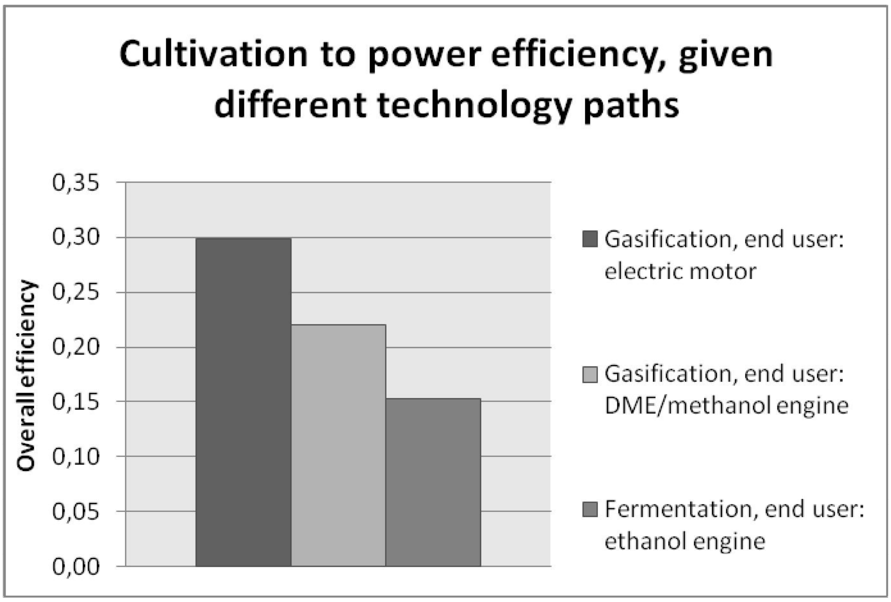
The energy efficiency for the DME/methanol process doesn't depend on any system expansion since the need for electricity in order to make the process self sufficient is solved by adding more wood from the start (see chapter 3.2). Graph 4-6 shows the conversion efficiency for producing DME/methanol or electricity from the synthetic gas from the gasification process. A comparison is done between the gross energy and the produced DME/methanol and electricity.



Graph 4-6 Conversion efficiency given different end products from the gasification process.

End use and overall efficiency

Graph 4-7 shows the overall efficiency from “well to engine power”. This study includes the engine or, in case of electricity, the motor. Thus, the losses of friction and aerodynamics associated with a moving vehicle aren’t included. There are also differences, although not taken into account, in transmission efficiency between choices of the power source for the benefit of the electric motor (Weiss et al. 2003).



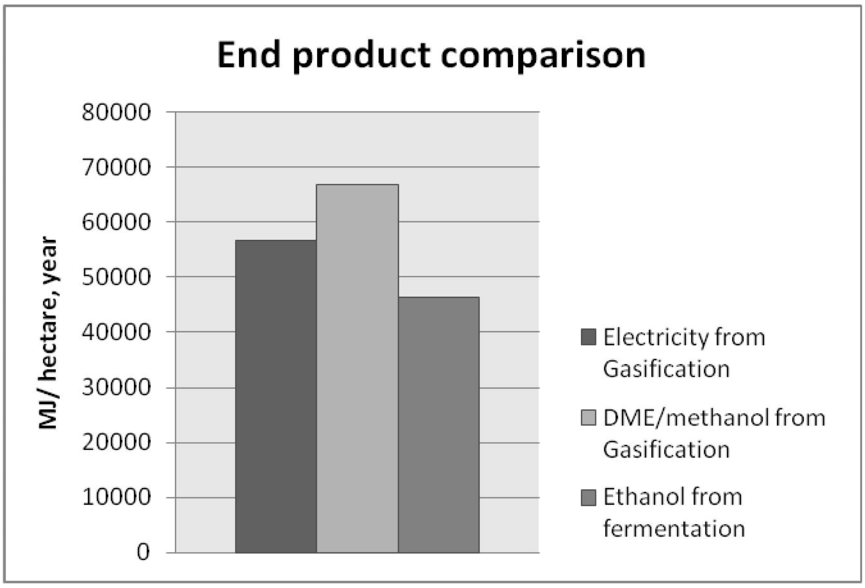
Graph 4-7 Efficiency from well to engine given different end products

Just as graph 4-7 implies, the efficiency of using one big central engine to produce power and heat instead of using small local combustion engines, e.g. ICEV’s, is higher. Twice the energy[5] can be generated from the same area of salix cultivation if the right technology is chosen, since the overall efficiency for the ethanol path is half of what is achieved if electricity is chosen as end product.

[5] On the end use level

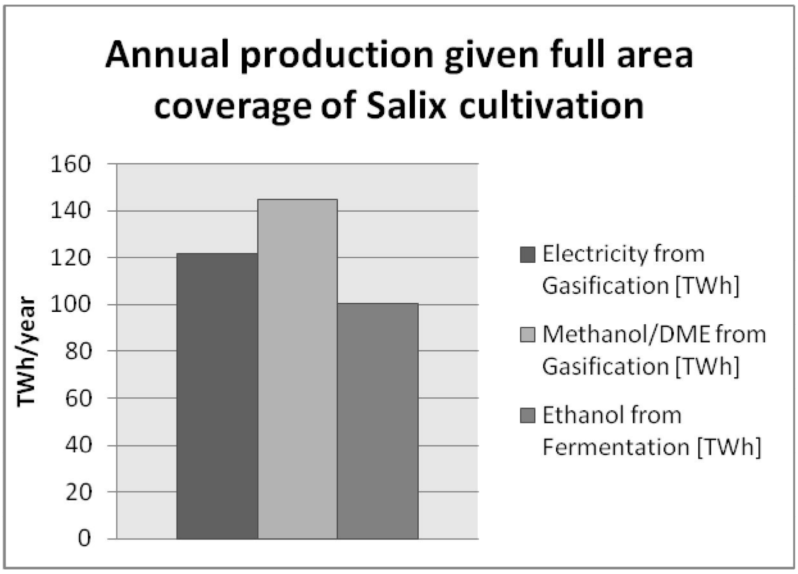
4.3 Fuel production and land use

A comparison of conversion efficiency between electricity from gasification, DME/methanol from gasification and ethanol from fermentation shows that fermentation falls a bit behind gasification as a conversion method, which can be seen in Graph 4-8. The conversion efficiency is the difference between the amount of gross energy in the harvested salix per hectare and year and the amount of converted energy per hectare and year. The conversion efficiency for wood to ethanol is around 30%, from wood to electricity around 36% and from wood to DME/methanol around 43%.



Graph 4-8 Energy left in the different end products after conversion.

Graph 4-9 shows that if all available land mentioned in chapter 1.2 is used for biofuel production, the annual production of either type of biofuel chosen or the electricity generation will almost cover the present need for energy to the transport sector, which was 130 TWh for the year 2007 (Swedish Energy agency 2007).

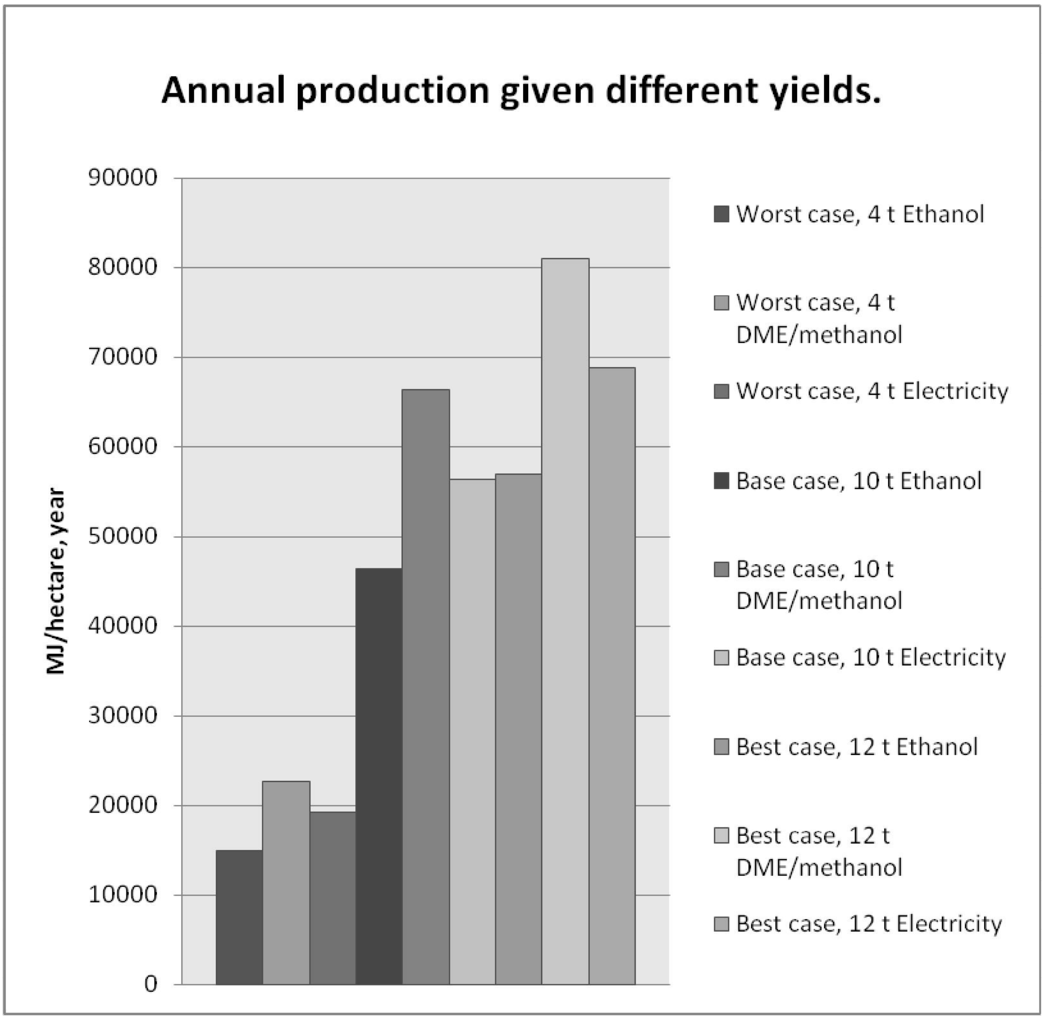


Graph 4-9 Annual production of biofuels if all available land is cultivated

5. Sensitivity analysis

The data used in the study is based on different reports and studies. The results could therefore vary a lot. Some of the variables can actually make a significant change in land use, emissions and energy efficiency. Therefore, a worst case scenario will be presented together with a best case. The data used in the study is referred to as base case.

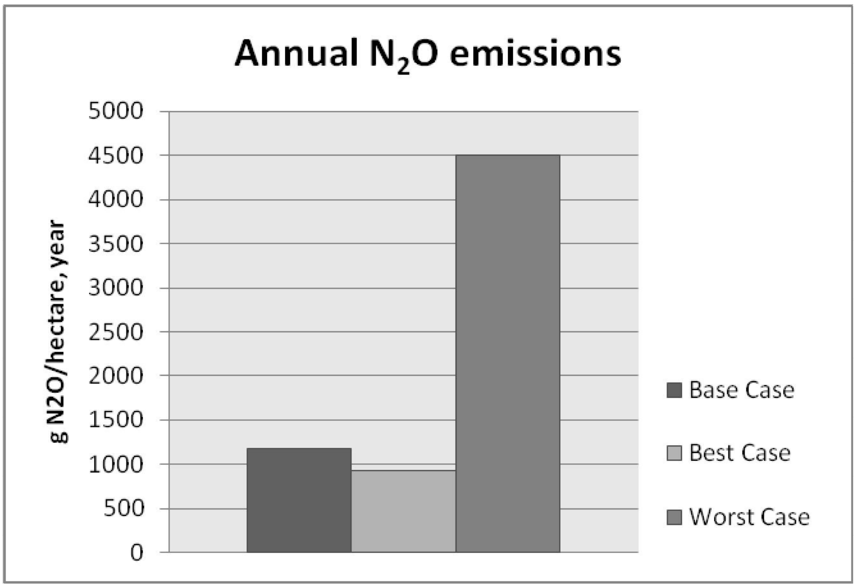
An ongoing process today is refining salix to get species that fits in whatever geographical area and soil considered. According to a recent publication, yields up to 12 dry tonnes/ hectare, year of salix is expected from the newest salix clones (Sweko Viab AB 2007). On the other hand, in the poorest conditions with an unwisely chosen salix clone, the yield could drop as low as to 4 dry tonnes/ hectare, year (Swedish Board of Agriculture, 2006). The yield per hectare has no impact on the conversion efficiency for the gasification or fermentation processes, but has of course a greater importance for the amount of refined energy per hectare. Graph 5-1 below shows the production alternatives given the worst and base case scenarios; with yields of 4 and 12 tonnes dry salix/hectare, year.



Graph 5-1 Worst and best case scenarios compared to base case given different yields

The single most important source of GHG-emissions, given that only the cultivated wood is used in the process, is fertilisation. A big part of Europe's fertilisation producers doesn't use the catalytic filters assumed in the study. The worst case is no further improvements, best case is 90% percent less N_2O from the production of N-fertiliser and the base case is what's being used in the study, i.e. 70% less N_2O emissions from the production.

The difference in soil denitrification and nitrification varies a lot. IPCC recommends using a conversion factor of 1%, while the most recent paper in the matter is saying up to 5% (Crutzen et al. 2008). Since that differs very much from what's being used, IPCC's recommendation is used in the case study, but the conversion rate suggested by Crutzen et al. (2008) will be considered in the worst case scenario. In the best case scenario the same rate as in the case study will be used.

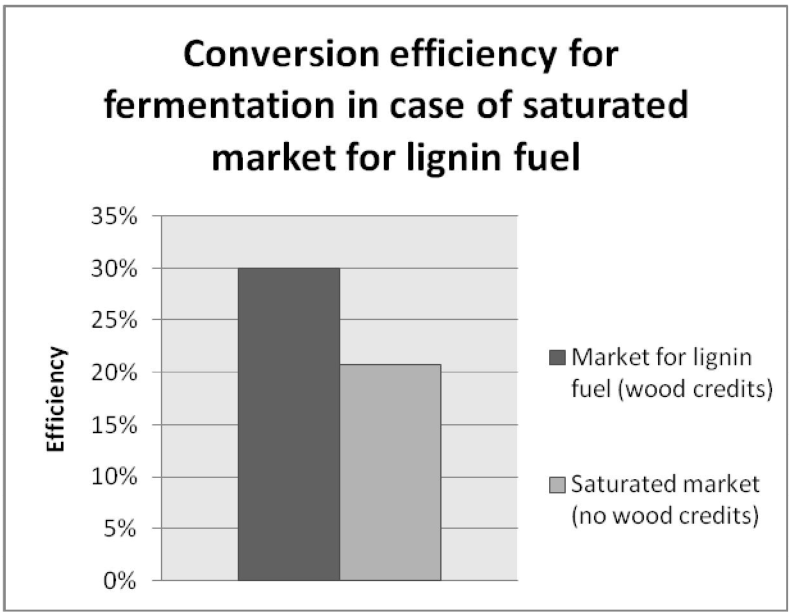


Graph 5-2 N_2O emissions given full production improvement (best case) and 5 times higher soil emissions (worst case).

A common alternative for N-fertiliser in Sweden today is sewer sludge. 10 % of the total sludge production in Sweden is used on 65-70 % of the salix cultivation area (Bioenergiportalen 2008), which means that 10% of the total sludge production covers an area of around 10.000 hectare (Swedish board of agriculture, 2006). Since available cultivation area is up to 600.000 hectare, the total sludge production would have to be 6 times as large as today in order to cover everything. It's in other words very hard to count on the sludge as a substitute for the N-fertiliser.

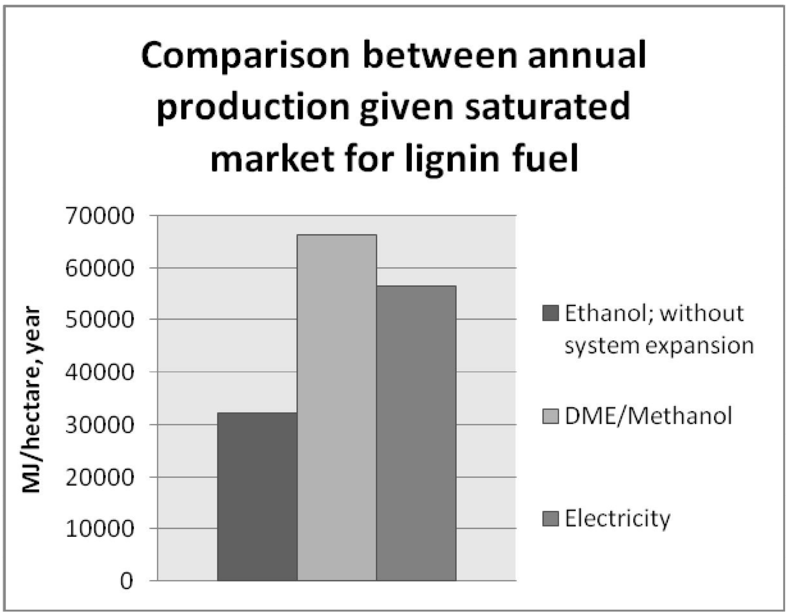
The N-fertiliser production needs natural gas as a raw material for the process. If assumed that the biogas from the ethanol production is used instead, the amount of biogas produced is nearly ten times bigger than enough for covering the amount needed for the production of N-fertiliser.

Fermentation of ligno-cellulose is still in an early development stage. The only plant up and running in Sweden today is just a pilot plant, using softwood as raw material. What will happen if all available area is used for cultivating salix? Will the market for district heating be saturated? The efficiency for a wood to ethanol process may vary between 20 and 30% depending on if the market for district heating in the area of the plant is saturated or not, which can be seen in graph 5-3.



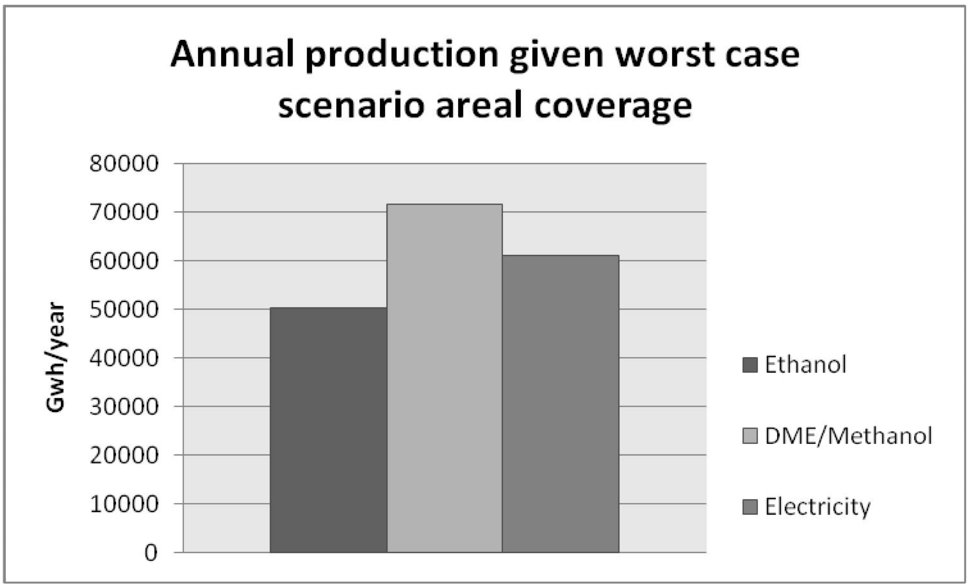
Graph 5-3 Conversion efficiency fermentation when system expansion isn't possible

A comparison of the non wood credited ethanol production and the rest of the end products can be seen in graph 5-4.



Graph 5-4 Ethanol production without system expansion compared to end products from gasification.

Since a lot of the available land might not be suited for cultivation, due to scattered and too small fields or the geographical position being too far up north, a worst case scenario of 50% area decrease is assumed. The base case scenario is 100%, since 100% coverage is physically possible, although not economically feasible today. Since there are no cost speculations done in the study, further assumptions in economically feasible solutions aren’t considered. Graph 5-5 shows that the amount of energy from around 300000 hectare of arable land is between 50000 and 70000 GWh/year depending on what process is being considered.



Graph 5-5 Annual total fuel or electricity production given poor area coverage

6. Conclusions

The three different energy conversion alternatives examined in the study differ in many ways. The outcomes are electricity and two liquid fuels coming from two completely different processes. All the alternatives have their shares of pros and cons, but electricity seems to be the most efficient alternative given the high efficiency of the end use.

Ethanol from fermentation

Ethanol stands out from the other two end product alternatives in more than one way. The fermentation process co-produces two different fuels besides ethanol; biogas and lignin. The overall efficiency is therefore dependent on how these by-products can be used.

+ Biogas is co-produced and can be used as fuel for producing heat and electricity for internal use; the excess of both fuels can be exported and used externally.
- Inefficient energy conversion compared to that of electricity, only around 30% of the initial energy is left for end use (including system expansion).
- The energy conversion of the end use is rather inefficient, which pulls down the overall efficiency to around 15% of the initial energy.
- Dependent on the market for district heating in order to reach maximum efficiency.
-The least area efficient choice, i.e. more hectares of land is needed in order to reach a certain amount of converted energy than the other two outcome alternatives.
- The highest level of GHG emissions /hectare, year.

DME/methanol from gasification

The process of creating either DME/methanol or electricity is similar up to the handling of the synthetic gas, which makes it rather easy to convert the process based on the desired outcome.

+ The highest conversion efficiency, around 43%.
+ The most energy efficient outcome from a gasification process.
- The energy conversion of the end use is rather inefficient, which pulls down the overall efficiency to around 22%.

Electricity from gasification

+The conversion efficiency is higher than that of fermentation, around 36 %.
+The highest overall efficiency among the three alternatives, reaching 30%, simply because the efficiency of the end use is much higher than that of the other alternatives.
+ The most efficient land use.
+ Bringing a huge possibility to lower the energy demand for the transport sector dramatically.
+ A fairly large deal of heat from the process can be used for domestic heating.

7. Discussion

30 years from now on the legislation around CO_2 emissions will be more stringent, possibly resulting in smaller engines and/or less single transportation. Since 75% of all energy consumed in road traffic is represented by cars today, the choice of engine has of course a big influence on the total energy consumption of the transportation sector (Swedish Energy Agency 2003). So what is the best choice?

According to this study, electricity seems to be the best option seen from an energy efficiency point of view as well as from GHG-emissions and land use. There are a lot of important issues not taken into account in this study though. An entire new fleet of electric vehicles has to be constructed, together with a huge amount of batteries, if there is to be a technology change from today. On the other hand, ethanol might be the most inefficient alternative, but it can actually be used already in today's cars regardless of engine type –Otto or diesel.

To end this study I would like to pose a question regarding the concept of biofuel, furthermore I would like to add a few suggestions about future research.

Biofuel – what makes it sustainable?

A fuel isn't by definition sustainable only because it's originating from biomass. If 2nd generation's biofuels are being commercially available, what will happen when the replanted biomass is far from the amount being consumed? The situation when salix (or other ligno-cellulosic crops with a short rotation period) is being cultivated and used is under control, since the amount of biomass being used is brought up for that specific reason. The effects when 50-year old forests are being knocked down for the same reason are worse and harder to monitor. Since Sweden is a forestal country with a very small population in proportion to its area, there is chance that a change from fossil fuels to 2nd generation's biofuels is able without severe deforestation as a result. The risk lies within oil-dependent economies that are densely populated.

Future studies

Environmental performance

Only GHG, land use and efficiency were covered in this study and there are more areas that have to be examined. The emissions connected with combustion are not only GHG-related; acidification, tropospheric ozone and particle concentration in the fumes are also important target areas. Another important issue is the fact that salix cultivations of between 300000 and 600000 hectares will very much affect the open landscape where it’s established; biologically as well as visibly. New biotopes of cloned salix will be introduced on a large scale, which calls for further examination.

Implementation on a large scale

The focus on this study has been on the inherent possibilities of salix as a feedstock for energy conversion and no cost calculations of any kind were made. The available land is only roughly estimated and the studied plants’ size can be referred to as demonstration plants. A good next step could be to examine how these technologies, together with a more precise calculation over available land could be implemented and to what costs.

The possibility of bio-combinates.

When looking upon gasification and fermentation together, the possibility to combine those two technologies together is a great opportunity to co-produce two or three different fuels and on the same time secure the system expansion that is crucial for boosting up the overall efficiency of the fermentation process. The geographical position for a bio-combinate like this is also really important for the overall efficiency since one of the major by-products is heat that could be exported into a district heating net. From a feedstock perspective, the whereabouts of a huge plant like this must be good agricultural land available for salix plantation.

Production and maintenance of an electric carpark.

For what we have seen in this study, electric motors are much more efficient than internal combustion engines. The batteries needed for an electric car haven’t been examined and is of course crucial for the performance of an electric car. The production, maintenance and recycling of batteries are really important for the overall environmental performance of an electric car.

Restrictions in single transportation

There is most likely not enough energy for everyone to enjoy the luxury of single person transportation on a global level. Attractive public transport systems or restrictions for single person transportation could both be important target areas for further research.

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Images, Figures and Graphs

Cover image http://www.greenoptimistic.com/wp-content/uploads/2008/06/biofuel.gif, 2008-10-15
Figure 1-1 http://sv.wikipedia.org/wiki/Bild:Cleaned-Illustration_Salix_purpurea.jpg, 2008-10-15
Figure 1-2 http://earthobservatory.nasa.gov/Features/CarbonCycle/carbon_cycle4.php with an added figure by M. Goranson 2008, 2008-12-16
Figure 4-1 Yara (2007)
Table 4-1 IPCC 2008
All other images, graphs and tables by M. Goranson