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Energy requirement assessment of bioenergy combine scenarios for cellulose based biofuel production

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ABSTRACT

Second generation biofuels are a good alternative to replace fossil fuel in the transport sector, such as ethanol production from lignocellulose. The technology is not working at full scale yet, partly due to high investment costs. To reduce these costs, one possibility is the integration of ethanol production in a combined heat and power plant (CHP).

This report studies the feasibility of this combination, from a technical point of view, checking if the requirements for ethanol production are fulfilled if ethanol production and CHP's are integrated. The scenarios with 4,5 ton/h of straw and 8 ton/hour of wood pellet can generate between 2,18 and 2,52 ton/h ethanol, and assuming that Sweden has the potential to produce 1,5 million ton/year of biofuel, it could be possible to replace around 12% the fossil fuel consumption.

This assessment indicates that the steam requirements of lignocellulose based biofuel production can be integrated with an existing CHP.

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My deepest gratefulness is for my family who are always giving me their absolute assistance and love.

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Uppsala, June

DEFINITIONS

Bioenergy is energy produced from biofuels. It comprises electricity, heat and a wide range of transportation fuel. (FAO, 2010)

Biofuel is energy produced directly or indirectly from biomass. Biofuels can include for example, liquid biofuels i.e. fuel derived from biomass for transportation uses, gaseous biofuels such as methane gas, and solid biofuels like fuel wood, charcoal etc.(FAO,2010)

Biofuels from municipal waste include municipal solid waste incinerated to produce heat and/or power, and biogas from the anaerobic fermentation of both solid and liquid municipal wastes (FAO, 2004).

Biomass is material of biological origin excluding material embedded in geological formations and transformed to fossil. Sources of biomass include energy crops, agricultural and forestry wastes and by-products, manure or microbial biomass (FAO, 2010).

UNITS

bar= bares (Pressure)

°C= Celsius (Temperature)

K= Kelvin (Temperature)

KJ= Kilo Jules (Energy)

Kg= Kilo grammars (Weight)

GWh/year= Giga Watt hour per year (Power)

TWh/year= Tera Watt hour per year (Power)

MW= Mega Watt (Power and Work flow)

KW= Kilo Watt (Power and Work flow)

KJ/Kg= Kilo Jules per Kilo grammars (Enthalpy)

ton/h= tonelades per hour (mass flow)

Kg/s= Kilo grammars per seconds (mass flow)

k =Kilo = 10^3

M =Mega, Million = 10^6

G =Giga = 10^9

T =Tera = 10^{12}

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1. INTRODUCTION

1.1. The Fuel Situation in the World and in Sweden.

The International Energy Agency projects the world energy demand will rise up by 40% between 2007 and 2030 (IEA, 2009). The world economy is based on the energy sector, i.e. today, based on non-renewable and unsustainable fuels. Our society needs energy, although this energy is currently not environmental friendly (e.g., Erbach & Wilhelm, 2009).

The global temperature is increases over time, a phenomenon called global warming. Its causes are not fully defined, there are many proposals, but most of the studies show that the global warming is linked with CO₂ emissions. By increasing greenhouse gas concentrations into the atmosphere, particularly CO₂, global temperature is also rising. The main cause of CO₂ emission increase is the burning of fossil fuels (Nordell, 2003). Biofuels from biomass would be a good solution to reduce the CO₂ emissions, since they are carbon neutral, thereby avoiding an increase of atmospheric CO₂ levels.

Energy consumption has increased briskly in the last 40 years, mainly in the transportation, residential and commercial sector. Figure 1.1.1 shows the growth in these sectors, more than 50% in transportation and almost 100% in the commercial sector.

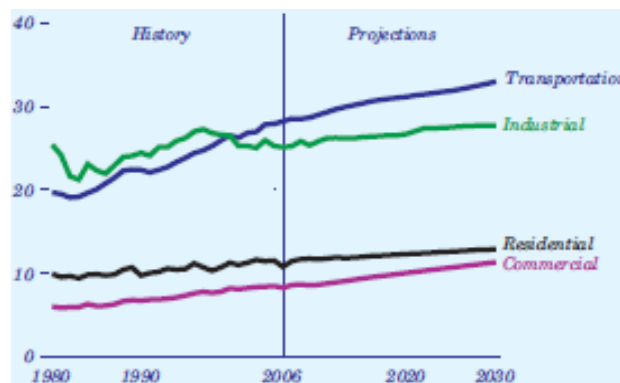


Figure 1.1.1. Energy Consumption by sector. Quadrillion Btu. EIA. (U.S. Energy Information Administration) [http://www.globalbioenergy.org/uploads/media/0806_EIA - Annual_Energy_Outlook_2008.pdf](http://www.globalbioenergy.org/uploads/media/0806_EIA_-_Annual_Energy_Outlook_2008.pdf)

Currently one of the controversial issues concerning the society, is fuel dependence, above all in the transportation sector. It is in this area where the fuel consumption has been rising drastically in the last 35 years, as is shown in figure 1.1.2. Use of renewable energy in this sector has also increased in the last years. Liquid biofuel is an attractive solution to decrease CO₂ emissions in the transportation sector (Ladanai & Vinterbäck, 2009). There are several studies which confirm the high capacity of biofuel to reduce fossil fuel consumption and CO₂ emissions (e.g., Weiss et al., 2007; Dornburg et al., 2004; Patel et al., 2003; Reindhard & Zamarek, 2000; Wihersaari, 2005).

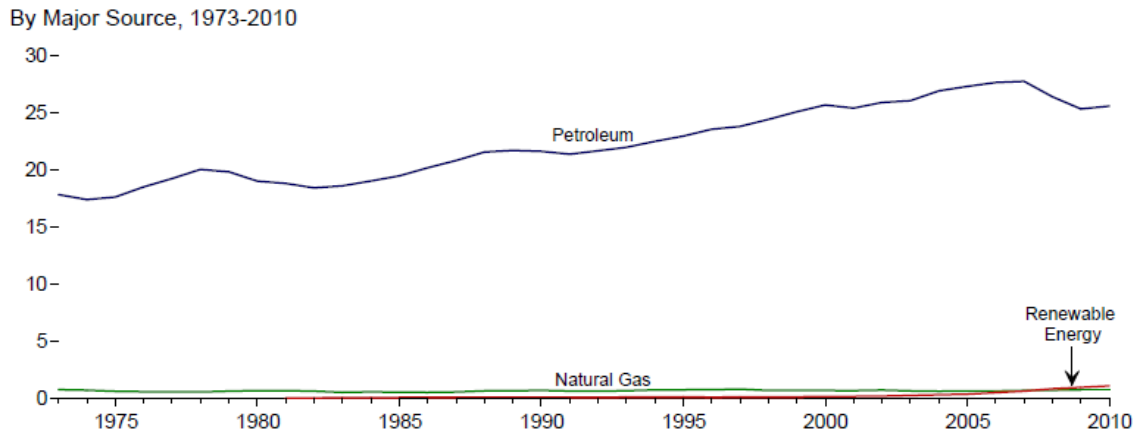


Figure 1.1.2. Transportation Sector Energy Consumption in USA. Quadrillion Btu. EIA. (U.S. Energy Information Administration) www.eia.gov/totalenergy/data/monthly/#consumption.

The demand for fuel transportation is increasing, raising the amount of CO₂ in the atmosphere. Carbon dioxide (CO₂) is the main Greenhouse Gas (GHG). Its annual emissions have grown more than 80% between 1970 and 2004, especially in the last 10 years. (IPCC)

The situation in Sweden is similar. The amount of energy has increased since 1970. Some sectors like Industry, Residential and Services need the same quantity of energy than in the 70's. As other countries, the energy use in transportation has increased by 71% in the last 40 years. (Swedish Energy Agency)

The Swedish fossil fuel dependence is less than for most developed countries, particularly in the industrial sector and in residential and services sectors. In the last 40 years the use of fossil fuels has been reduced by over 47% (Swedish Energy Agency and Statistics Sweden).

Nevertheless the fuel consumption is high in the transport sector, obtaining more than 92% of its energy from petroleum products. Therefore it is in this sector where we have to work, in order to reduce fuel dependence and also to achieve the 2020 European targets. (Swedish Energy Agency and Statistics Sweden).

The 20/20/20 targets involve (European Commission Policies):

- "A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels". Sweden has as a goal to reduce its emissions by 40% by the year 2020, and no have net emissions of greenhouse gases into the atmosphere for 2050(Swedish Energy Agency).
- "At least 20% of EU energy consumption to come from renewable resources". In Sweden this percentage raise until 49%, as a consequence its goal should be at least 50% of the total energy use (Swedish Energy Agency).

Main goals are renewable electricity production and the industrial use of biofuels.

- In the transport sector renewable energy use must be at least 10%. Swedish target is to be independent of fossil fuel by 2030. As far as I am concerned, if this aim will be achieved will depend on the biofuel production development.
- “A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency”.

Ways of bringing about these targets involve government decisions, such as increased taxes in some sectors, new Acts (legislation) to reduce emissions and improve public transport, and research in renewable energy uses. (Swedish Energy Agency)

Bioenergy is a good solution to replace fossil fuels, but it must be managed carefully and in a sustainable way¹, or its environmental effects might be devastating (Gnansounou, 2010). The way in which bioenergy processes are regulated affects whether or not bioenergy is deemed sustainable (FAO, 2008 a). These regulations focus mainly on economic, environmental and social impacts of biofuel production (figure 1.1.8) (IEA, 2010). There are several initiatives to manage the production and the market of biofuel in a sustainable way (e.g., Palmujoki, 2009).

Traditionally, wood fuels (biomass) are used to cook and to heat in every house; they constitute the oldest energy source. Currently they represent the largest single source of energy in developing countries. (FAO, 2008 a, FAO 2008 b).

Bioenergy, particularly in liquid biofuels for transportation, have showed a rapid growth over the last few years, due to the decrease in fossil fuel reserves, the increase in oil price and, and the new policies that have been implemented in the OECD countries (Organization for Economic Co-operation and Development) for instance subsidies, blending and market share mandates (FAO, 2008 b).

¹ Sustainable way: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987)

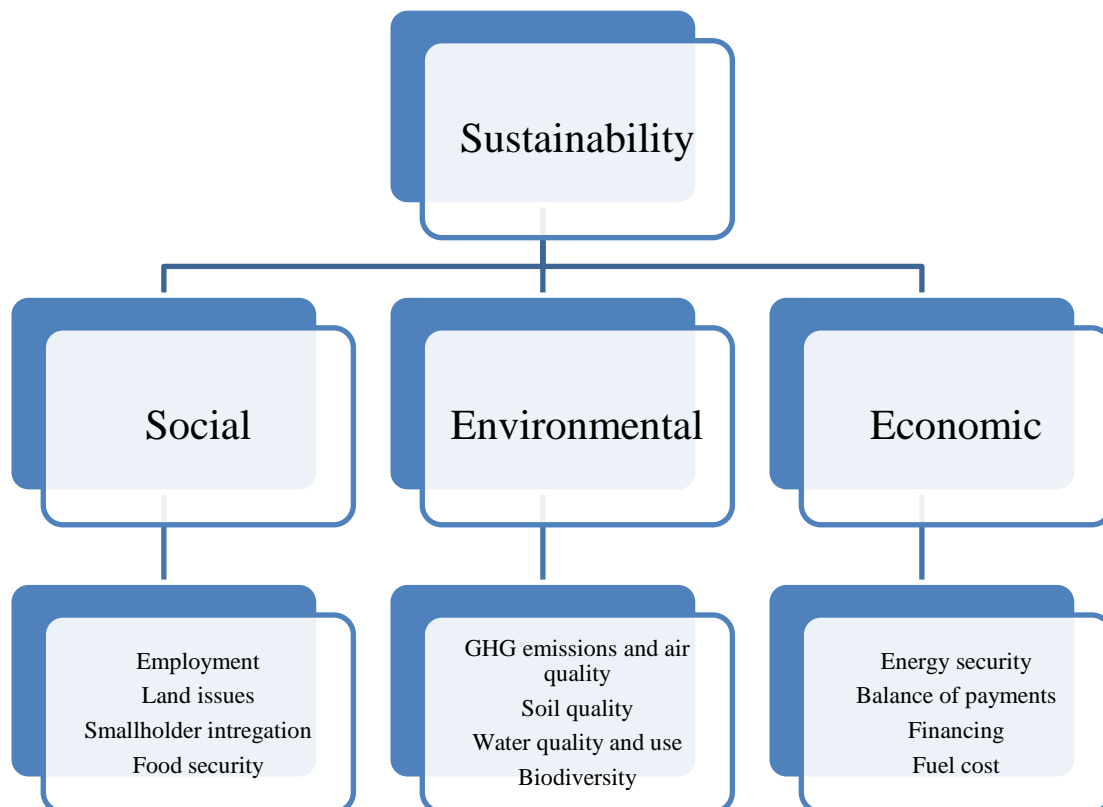


Figure 1.1.3. Social, environmental and economic aspect of production of biofuel in a sustainable way (Based on, IEA 2011).

1.2. Biofuels

Biofuel denotes any kind of fuel originating from biological sources. There are different classifications. Depending on the raw material, it is possible to distinguish three kinds of biofuel: first generation, second generation and third generation biofuels. First generation biofuels, their feedstock comes from food crops. Second generation biofuels are produced with non-food bio-feedstocks. Currently, there are some research initiatives for biofuel production with algae, that are starting to be called third generation biofuels, but this is not the generic name (Altprofits website). According IEA criteria, there are two types of biofuel: conventional biofuels (first generation ones) and Advanced biofuels (second and third generation ones) (IEA, 2011).

Biofuels

Ethanol

Biodiesel

1st
Generation:

Corn
Cane
Maize

2nd

Generation:
Switchgrass
Cellulosic
Gasification

1st

Generation:
Palm
Soybeans
Rapessed

2nd

Genration:
Jatropha
Gasification

(3rd

Generation):
Algae

Figure 1.2.1. Types of biofuel and raw material. (Based on Altprofits Website)

Currently, most of the ethanol production comes from first generation biofuels, especially from USA with corn feedstock, and from Brazil with sugar cane raw material (IEA, 2011). However, this production carries several issues. Its raw material competes with food production, increasing food prices, and it is difficult to scale-up due to restraints on land areas available for cultivation.

For this reason, second generation biofuels presents a wonderful alternative, since they overcome the two main bottlenecks for first generation biofuels (Altprofits). Second generation biofuel advantages are showed in the next figure (Figure 1.2.2)

In spite of being a good alternative for replacing fossil fuel, better than first generation biofuels, they are not yet available on a fully commercial scale (IEA, 2010). It can occur in the coming 5-15 years (Hellegers et al., 2008)

Algae has many advantages, such as, superior yields, not directly affecting the human food chain like second generation biofuel, grown in places that are not suitable for agriculture, enhanced efficiencies or reduction in cost. But the main drawback high cost in their developing technologies and it is in the research phase. With Algae, biodiesel production is profitable (Altprofit website).



Figure 1.2.2. Advantages of second generation biofuels vs. first generation. (Based on Altprofits website)

1.3. Ethanol and Methane are Fuels Compatible with Petrol Engines.

Internal combustion engines, such as, gasoline ICE, diesel ICE, jet turbines and rocket turbines, and external combustion engines, meaning, steam engines, steam turbines and electric motors are used to transform stored energy into kinetic energy. However, only three of these engines are compatible with passenger vehicles, gasoline ICE², diesel ICE and the electric motor. Biomass can be used as a biofuel source, obtaining different types of fuels. Relation between biomass and fuels are showed in the Figure 1.3.1. (Huang & Zhang, 2011b)

Ethanol is a suitable fuel to use in gasoline ICE vehicles due to its physical and chemical characteristics. Nowadays, ethanol is blended with gasoline, not up 10%. But this percentage has to increase in order to replace fossil fuel in the transport sector. Minor motor changes are required to run on high-blends of biofuel, and minor changes in developing distribution systems, since ethanol is liquid; it is compatible with fuel station storage. Governments have the possibility to enhance the situation, promoting the development and use of new technologies, such as, flex-fuel vehicles which are compatibles with high percentage of ethanol (Worldwatch Institute, 2006).

² ICE: Internal combustion engines. Nowadays, automobile uses nonrenewable fuels and internal combustion engines.

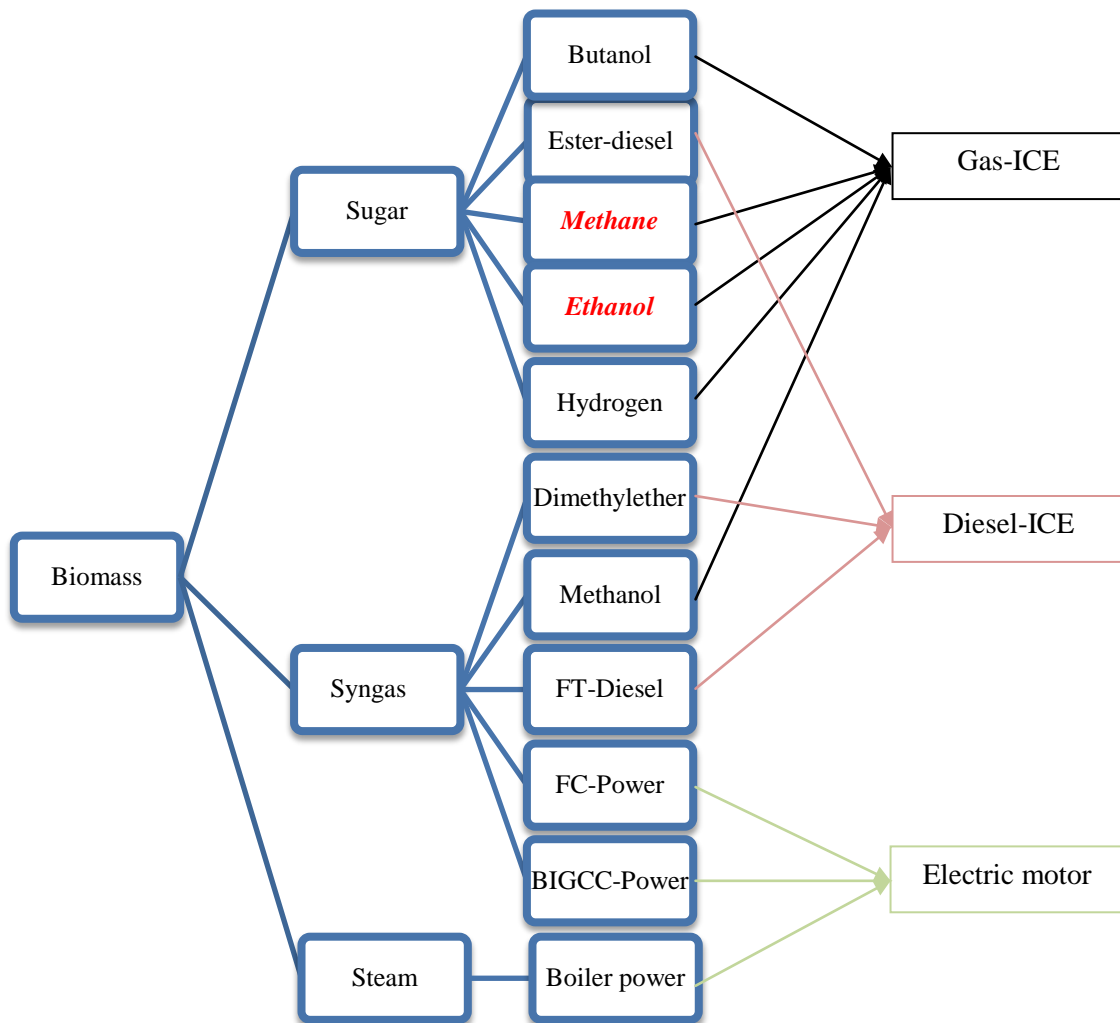


Figure 1.3.1. Kinds of biofuel obtained from biomass. (Based on: Huang & Zhang, 2011b)

1.4. Ethanol and Methane can be Produced from Biomass

There are different techniques to obtain bioenergy as we can see in Figure 1.4.1. Their usage and economic, environmental and social characteristics are different depending upon technique, location and farming practices. (FAO, 2008)

It is possible to produce ethanol from biomass, to be exact from lignocellulose. This means, the possibility to generate energy from a renewable source in a sustainable way, and consequently reduce the fossil fuel use in the transport sector, with its related benefits, less greenhouse gases emissions and reduced fossil fuel dependence. As well, their distribution is easy around the entire world. Although, this trade has to cope with several barriers, such as, tariffs, taxes, which have to be decreased to establish a competitive market (IEA, 2011).

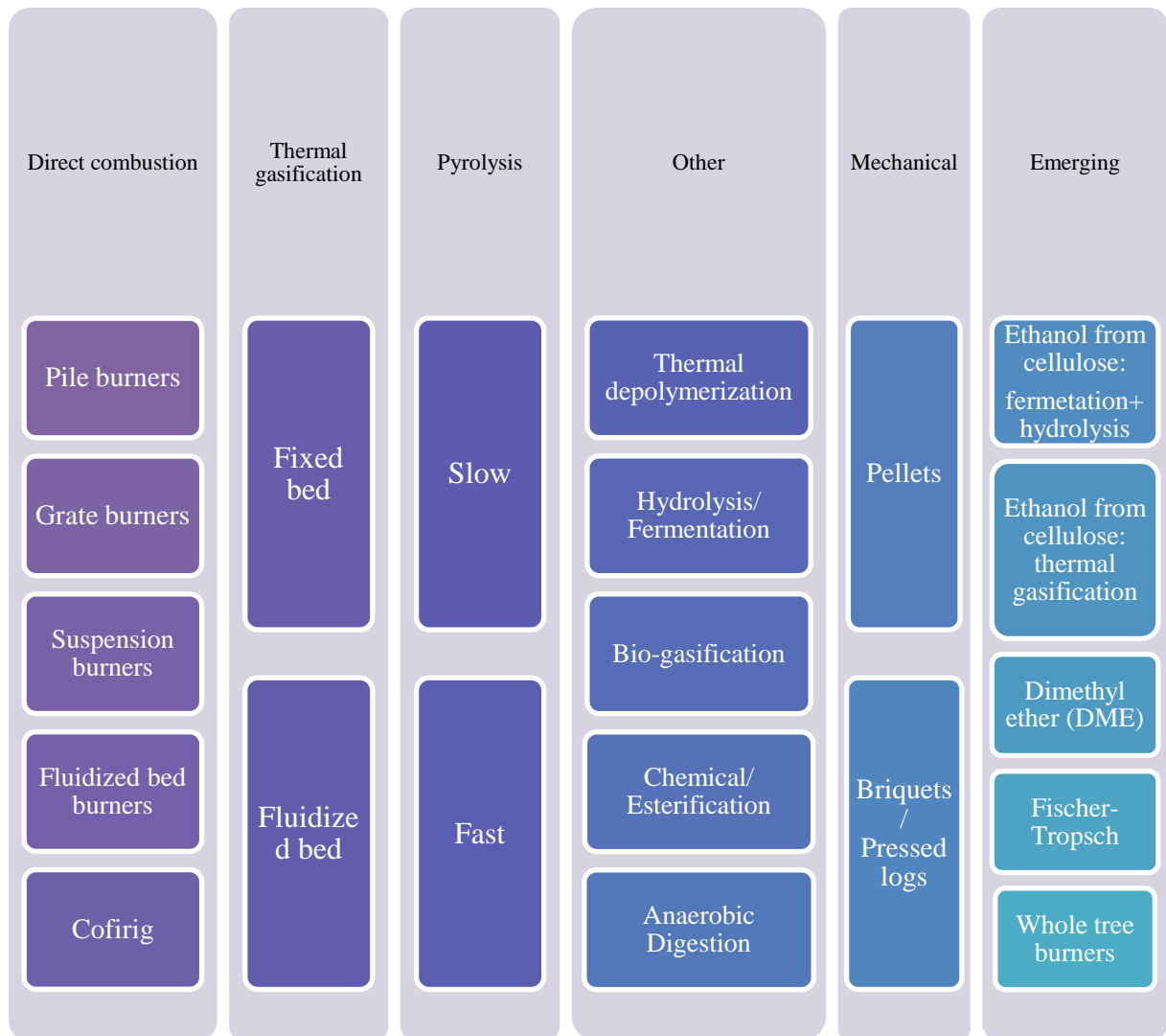


Figure 1.4.1. Bioenergy technologies. (Based on. Ladanai & Vinterbäck, website of Northeast Regional Biomass Program (NRBP), <http://www.nrbp.org/bioenergy/technology/index.htm>)

1.5. Competition between Food and Fuels.

Biomass resources can stem from different sources, such as forest biomass, agriculture biomass, waste biomass and energy crops. Depending on the kind of source, there are two types of biofuels. When the biomass resource is agriculture crops (food), such as sugar, maize and oil crops, they are called first-generation biofuels, while second-generation biofuels are produced from fibrous material, cellulose, hemicelluloses and lignin (Ladanai & Vinterbäck, 2009).

The main problem to use first-generation biofuels is the dispute between food and biofuel. Currently, there is a competition for land, water and other resources between agricultural and biomass crops (Pimentel et al., 2009)

Nowadays, bioethanol is the largest biofuel. Its raw materials are different, but over 80% being from corn kernels and sugarcane, it means, first generation biofuel (Ladanai & Vinterbäck, 2009). Although, its input is lower in the transport area (Lynd, 2010; Lynd et al., 2008)

The first generation biofuel use brings several issues. First of all, the competition between food and energy, since both of them use the same raw material and land (IEA Bioenergy, 2009). Although they compete for the land, there are several solutions, such as, using residues and organic waste, second generation biofuel for ethanol production, controlling biomass energy husbandry expansion with regulations which promote bioenergy crop move into degraded land, abandoned area, surplus land, marginal land (Field et al., 2007; Tilman et al., 2006; Hoogwijk et al., 2005; Hoogwijk et al., 2003). The main issue is the necessity to identify the land for a sustainable production (IEA, 2010), and to have policy support (Croezen et al., 2010). Secondly, first generation biofuels show limited roles in the future transport fuel mix, except sugar cane (IEA, 2010). Perennial crops have more benefits than annual crops, such as; less input and maintenance are required. Thirdly, high energy input is required for farming, i.e., fossil fuel consumption and CO₂ emissions increase. Finally, they have others environmental impacts, such as, eutrophication and acidification (e.g., Cherubini et al. 2009; Weiss et al., 2007, Zah et al., 2007, Tilman et al., 2002). Due to these drawbacks, first generation biofuel use and their benefits are unclear. Critic tolls have been increased in the last years (IEA, 2008). On the other hand, second generation biofuel popularity is increasing. Many studies show their high efficiency in the land and biosource use (IEA, 2010; Campbell et al., 2009; Ohlrogge et al., 2009). In addition, required land might be poor quality (Ladanai & Vinterbäck, 2010), although it exists some restriction in primary and conservation forest, due to economic, social and environmental reasons (FAO, 2005). Integrated Food and Energy Systems are developing, helping to retain the soil quality, reducing the controversial issue between food and fuel, thus providing some benefits to farmers, for instance, efficient use of residues, diversification and access to energy (IEA, 2011).

Several discussions about the impact and causes of food price crisis have been carried out in the last years ((Doornbosch & Steenblik 2007). Biofuels were accused of being one of the main factors of 2007-2008 food price increase (Ninni, 2010). Nevertheless when the causes of the crisis were studied, they showed biofuels were not the main cause of the world food price crisis (Dewbre et al., 2008). Food price increased significantly in the last years, on account of several factors, such as, deficient harvests linked to extreme weather events, food stocks decreased, soaring fuel and energy prices and production of biofuels subsidies (FAO, 2009 b).

Food price increase depends more on trade barriers, policies and limitations of marketing infrastructure than on lack of land (de Fraiture et al. 2008, Hellegers et al., 2008). New food policies are unique, based on international and national food security, ensuring to have enough food, at the right time, in the right place (Marsden, 2010).

Developing countries are the most affected areas by food price crisis (FAO, 2009 a). Although biofuel production has also some profits in rural areas, they help to increase the input and employment in these areas, it means, poverty alleviation. (Best, 2006)

1.6. Lignocellulosic Biomass.

Lignocellulose is arguable the best raw material for biofuel production, since lignocellulosic is renewable, abundant, available and cheap (Cloete & Malherbe, 2002). There are several types of lignocellulosic biofuel production (Figure 1.6.1)

Biofuels manufactured from lignocellulose can avoid many issues linked to first generation biofuels. Moreover, their production offers some benefits, such as, consuming waste residues, using abandoned land, restoring degraded and contaminated soils, decreasing erosion and land degradation, increasing soil fertility and soil carbon stocks i.e., improving the quality of agricultural land (IEA, 2011). Thereby, second generation biofuels might promote rural development in developing countries and improving their economy (IEA, 2010).

Lignocellulosic biomass may be used to produce a wide range of biofuels, such as, cellulosic ethanol (Farrell et al.,2006; Shaw et al., 2008) , butanol (Atsumi et al., 2008; Zhang et al.,2008), electricity (Campbell et al., 2009; Logan, 2009), bioalkanes (Schirmer et al.,2010), fatty acid esters (Kalscheuer et al., 2006; Steen et al.,2010; Huang & Zhang, 2011a),methane (Dererie et al.,2011),hydrogen (Cortright et al., 2002; Zhang et al., 2007; Chou et al., 2008; Ye et al., 2009), hydrocarbons (Serrano & Dumesic, 2011; Wang et al., 2011) and waxes (Steen et al.,2010).

Cellulose, hemicelluloses and lignin are lignocellulosic constituents (Cloete & Malherbe, 2002). A main problem is the resistance of lignocellulose to be degraded by enzymes. This resistance is different depending on the species, genetics and types of cells. Increasing the amount of soluble polysaccharides from the cell while the cell wall crystallinity decreases will increase the enzymatic accessibility to the cellulose (e.g., Sivakumar et al., 2010). This can be accomplished by pretreatment methods. Due to this, ethanol commercialization is more difficult. (Cloete & Malherbe, 2002).

For producing ethanol from lignocellulose, several stages are carried out: pretreatment, enzymatic saccharification or chemical hydrolysis, ethanol fermentation and distillation (Dererie, 2010). There are different techniques to produce ethanol, where they do not use all the stages; for instance, pretreatment can be missing .However, steam pretreatment favors cellulose hydrolysis with minimal use of chemicals. Ethanol fermentation produces high amount of residues, mainly pentoses and lignin, since pentose fermenting microorganisms are not yet commercially available. Anaerobic digestion of the ethanol fermentation residue could be a good alternative to obtain high

yields, increasing biofuel production, since it produces biogas, as well as enriching the nutrients in the digestion residue. It might be possible to dry the digestion residue with waste steam from pretreatment and distillation and using it as fertilizer. Due to the high drying temperature pathogen and toxicity issues can be avoided (Trobro et al., 2011).

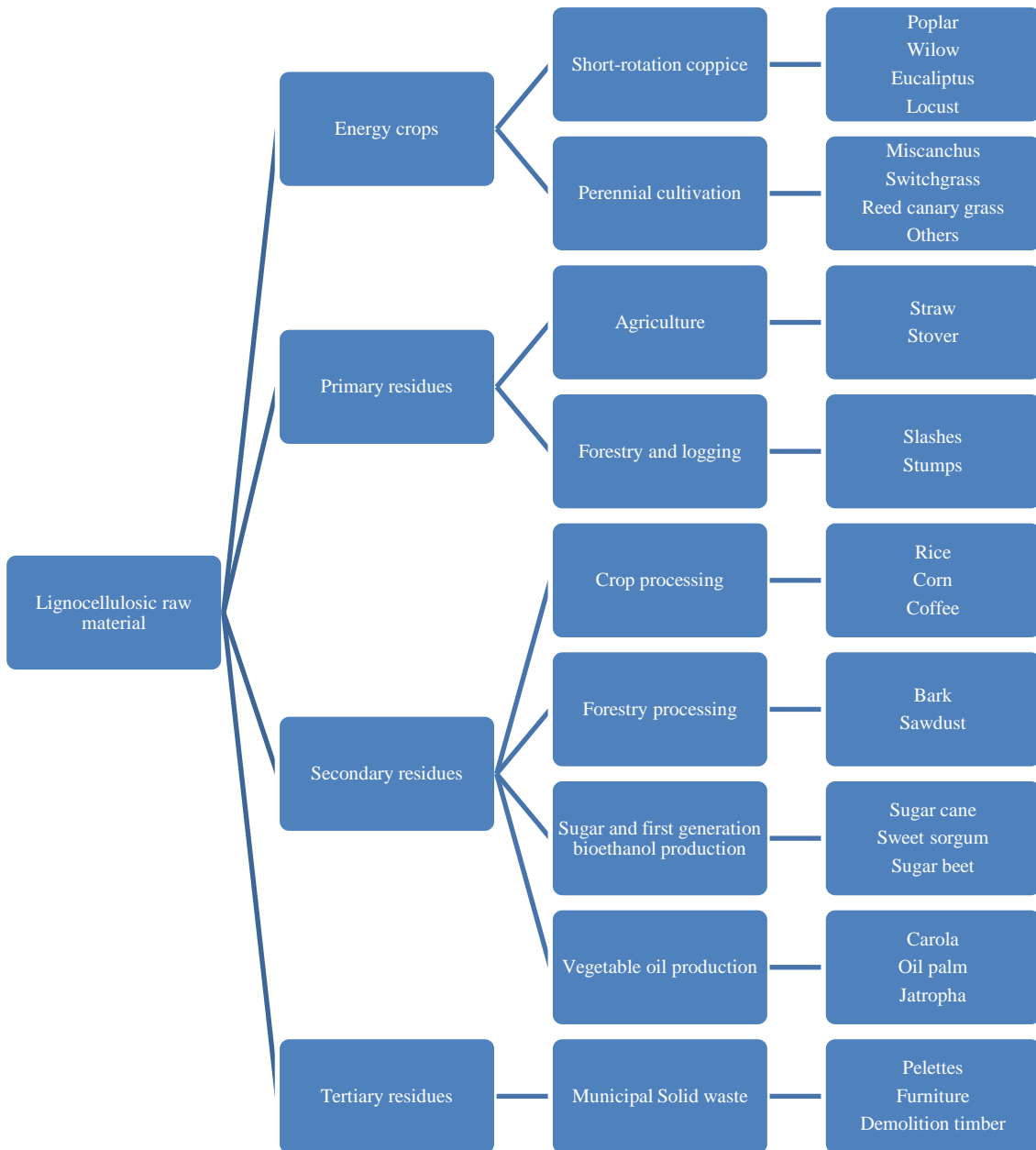


Figure 1.6.1. Lignocellulosic raw material for biofuel production. (Based on: Ladanai & Vinterbäck, 2010; IEA 2007; Rosillo-Calle et al., 2006; Faaij et al., 1997; Bassam, 1998)

Pretreatment is generally the most expensive process step. It increases ethanol production yield because it helps the degradation of lignocellulose and reduces the degree of crystallinity which promotes enzymatic action. It is possible to distinguish different pretreatments depending on the technique: mechanical, thermal, chemical and biological. The use of one technique or another will depend on composition of lignocellulose, energy requirement, amount of residues and their costs (Dererie, 2010).

- **Mechanical Pretreatment**
To decrease degree of polymerization and crystallinity and increase surface area, it cuts lignocellulose into tinier pieces.
Advantages: Inhibitors are not produced, thereby increasing ethanol yield.
Disadvantages: High energy is required for cutting the raw material (Dererie, 2010).
- **Thermal Pretreatment**
Lignocellulose is heated to 150-180 °C, solubilizing the hemicelluloses first and then partly the lignin. Temperatures over 250°C must be avoid because pyrolysis reaction might start (Dererie, 2010).
Disadvantages: Inhibitors on enzymatic reactions are produced (Dererie, 2010).
 - **Steam pretreatment**
Steam explosion is carried out, by increasing the temperature and the pressure in a short time, 5-15 minutes using steam, followed by rapid pressure decrease. It is common to impregnate the raw material with sulfuric acid, although there are several studies about steam pretreatment without sulfuric acid to promote chemical-free pretreatment. Principal issue is the production of furfural and phenolic compounds which inhibit ethanol and methane production (Dererie, 2010).
 - **Liquid hot water pretreatment**
Hemicelluloses is solubilized with hot water instead steam. Inhibitors formation might be avoided, keeping pH in the range of 4-7, although it reduces cellulose hydrolysis yields. Due to higher water input, the amount of soluble hemicelluloses and lignin are low (Dererie, 2010).
- **Acid Pretreatment**
It hydrolyses the xylan part of hemicellulose; the other part is quite stable in acidic environment. Solubilized lignin is condensated and precipitated quickly, reducing ethanol and methane production yields. The production of inhibitors and volatile products increases loss of fermentable carbon, decreasing ethanol production (Dererie, 2010).
- **Alkaline Pretreatment**
Solvation and saponification is carried out, producing delignification. Due to this, enzymes and bacteria accessibility are increased. The main problem is the condensation and precipitation of solubilized lignin, which causes inhibitors production and carbon losses (Dererie, 2010).

Ethanol fermentation is easy for hexoses, whereas it is more difficult with pentoses. The fermentation is generally completed in 24 hours. The ethanol can act as an inhibitor to fermenting organisms thereby limiting the amount of fermentable sugars that could be added. In some cases, it is better with simultaneous saccharification and fermentation (SSF), where cellulose enzyme and fermenting microbes work together. Enzymatic saccharification produce sugars and fermentative organisms transform sugar into ethanol thereby avoiding inhibition effects. Yield can be higher with SSF and costs are lower due to it can be possible to use less expensive enzymes to liquify hemicellulose and cellulose (Dererie, 2010).

Distillation is the next step. Its aim is to separate ethanol, from the stillage. Usually, two stripper columns and one rectification column are distillation stage (Sassner et al., 2008).

High amount of biomass waste are produced in ethanol fermentation with lignocellulosic material. There are many methods to treat this stillage, and to obtain other co-products. Some of them are anaerobic digestion, membrane filtration and direct application to land (Wingren et al., 2008). A subsequent anaerobic biogas digestion of the stillage seems to be an excellent option, since its energy demand is lower and it also produces methane (Wingren et al., 2008). Several researches show higher yield if it combines ethanol production with anaerobic digestion, but also the production of enriched nutrient fertilizer (Dererie et al., 2011).

Anaerobic digestion is next step after distillation. Organic compounds are converted to methane and carbon dioxide, through different microbial processes: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Figure 1.6.2 shows the microbial processes in biogas digestion (Dererie, 2010).

1. Hydrolysis: Complex compounds such as cellulose are converted into soluble organic compounds which are easier absorbed by microbes.
2. Acidogenesis: These compounds are absorbed and degraded by fermentative microbes, producing alcohols and volatile acids.
3. Acetogenesis: The acetate-forming bacteria transform alcohols and volatile acids into hydrogen gas and acetate or acetic acid.
4. Methanogenesis: Methane and carbon dioxide are produced in the last stage. Two kinds of bacteria performance in methanogenesis: Acetotrophic, which transforms acetate into methane and carbon dioxide, whereas the other group, hydrogenotrophic produces methane using hydrogen as electron donor and carbon dioxide as electron acceptor, its key function is to maintain low pressure of hydrogen.

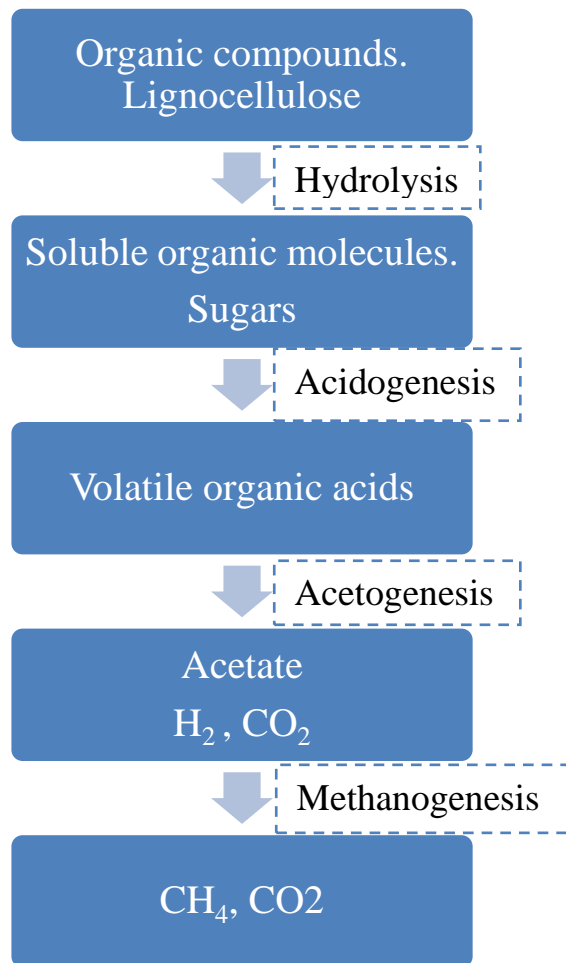


Figure 1.6.2. Anaerobic digestion stages (Based on: Dererie, 2010)

It is common to use only one reactor where all the stages will be carried out, thus facilitating biomass processing and even avoiding inhibitor production. The rate of production is affected by different parameters such as temperature, alkalinity, pH, solid and hydraulic retention times (Dererie, 2010).

It is not necessary that all the steps in co-production of ethanol and biogas is carried out. It is possible to obtain biogas without prior ethanol fermentation, however several researches show higher energy yield if ethanol and biogas production are carried out sequentially, 28%- 34 % more of biomass can be converted into biofuel energy compared to biogas digestion alone (Dererie 2010). Besides, the digestion process is faster after ethanol fermentation compared to direct digestion, implying that ethanol fermentation and saccharification helps lignocellulose degradation and promotes enzymatic and bacterial action. Because fermentation process is faster than digestion a faster biogas digestion should give a more constant mass flow through the process (Dererie et al., 2011).

There are some obstacles which prevents the large scale commercialization of second generation (lignocellulose based) biofuels, such as, polymer stability, refinement of

pentoses sugars, expensive pretreatments to hydrolyze sugars, availability of lignocellulose, the biofuel production cost and nutrient recycling feasibility (Trobroy et al., 2011).

Several studies about ethanol production costs show that main costs are for feedstock and capital. Although, raw material cost are unclear, since the yield depends on the chosen species. Likewise, it is hard to precise the optimal enzymatic dosage due to its costs are uncertain (Sassner et al., 2008).

In order to be economical competitive, specific research and development issues will need to be carried out. Micro-organism and enzymes yields must be improved, and pentoses should be used for fermentation and as co-products and the lignin should be used as a feedstock for chemicals and materials (IEA, 2011).

1.7. Bioenergy Combines can reduce investment and production costs.

Undoubtedly, biofuels have to be sustainable not only environmentally, but also socially and economically, it means they have to become competitive with fossil fuels. One key to compete against fossil fuels resides is the politic support which would guarantee biofuel production in a competitive way (IEA, 2011).

The main cost, as mentioned above, is raw material in first generation biofuels (40%-70% of total production costs) and in second generation biofuels, the main factors are capital cost (35%-50% of total costs) and raw material (25%-40%). Reduced these costs are vital to deal with fossil fuels (IEA, 2011).

One problem to decrease feedstock costs is that they depend on oil prices, agricultural commodity prices and other factors, whose behavior are difficult to predict (IEA, 2011).

Capital investments depend on financing, interest rates, raw material availability for location of the plant and the production process. Uncertainty in market prices for biomass, biofuels, utilities and residues can delay major investments in production capacity (Trobroy et al., 2011). Several strategies might be taken into account in order to reduce the capital costs and to be economically acceptable. One of them, and this report is based on it, is the co-location with existing biofuel plants, power plants and other industrial facilities. Furthermore co-products use could be more efficient (IEA, 2011).

In this report, the co-location with Combined Heat and Power Plant (CHP Plant) is investigated, a so-called bioenergy-combine. Second generation biofuel production linked with a CHP require a chemical free and simple processes in order not to generate large amount of waste. Many synergies are offered with this integration, such as; use

low pressure steam to dry material, access to cheap high pressure steam (20 bar), facilitated biofuel distribution, and distribution the residual material as fertilizer (Trobro et al., 2011).

1.8. CHP and Biofuel Production.

There are several benefits with a biofuel production in connection with a CHP, as is mentioned above. CHP plants are also known as cogeneration Plant.

Combined heat and power (CHP) produces simultaneously electricity and heat from a unique fuel source, such as: biogas, biomass, coal, natural gas, oil or waste heat. It is an “Integrated energy system”. Depending on the needs it might be modified. CHP supplies onsite generation of electrical power, waste-heat recovery for different process, such as: heating, cooling, dehumidification and a perfect integration system for a wide range of technologies, thermodynamic process and fuel types into existing infrastructure (EPA,2008).

CHP systems are mainly a gas turbine or engine with a heat recovery unit and a steam boiler with a steam turbine. The high steam requirement in ethanol production leads to use of the second type as the best choice. Solid fuels are used, such as, coal, biomass or waste products.

Steam, generally superheated, is generated in the boiler, through the burning of biomass, waste or coal. Nowadays the numbers of CHP that are using biomass or waste as fuel are increasing, implying less GHG emissions and more environmentally friendly production. Superheated steam pass by the turbines and generator, producing electricity. This electricity usually goes to public electricity network. The rest of steam still has enough heating value to warm up the water which will be provide to the consumers via the district heating network. It might be possible to add “summer”-cooler to improve the yield of the CHP, since in summer the demand of heat is minimal. Figure 1.8.1 shows the CHP system.

To integrate the biofuel production with CHP, first of all it is necessary that biofuel production demands are supplied by the CHP characteristics, such as, steam and temperature, i.e., if it is possible to provide the amount of steam at the pressure required to produce ethanol. Secondly, how and where the feedstock will go inside the system. And finally checking if it is available economically, i.e. electric losses are not too high.

Several studies show the compatibility of these two industries (Trobro, 2011). The main bottleneck is that ethanol production requires high pressure 20 bar saturated steam for the steam explosion pretreatment. Key issues are if the CHP produces enough amount of saturated steam and if the steam can be extracted without complications.

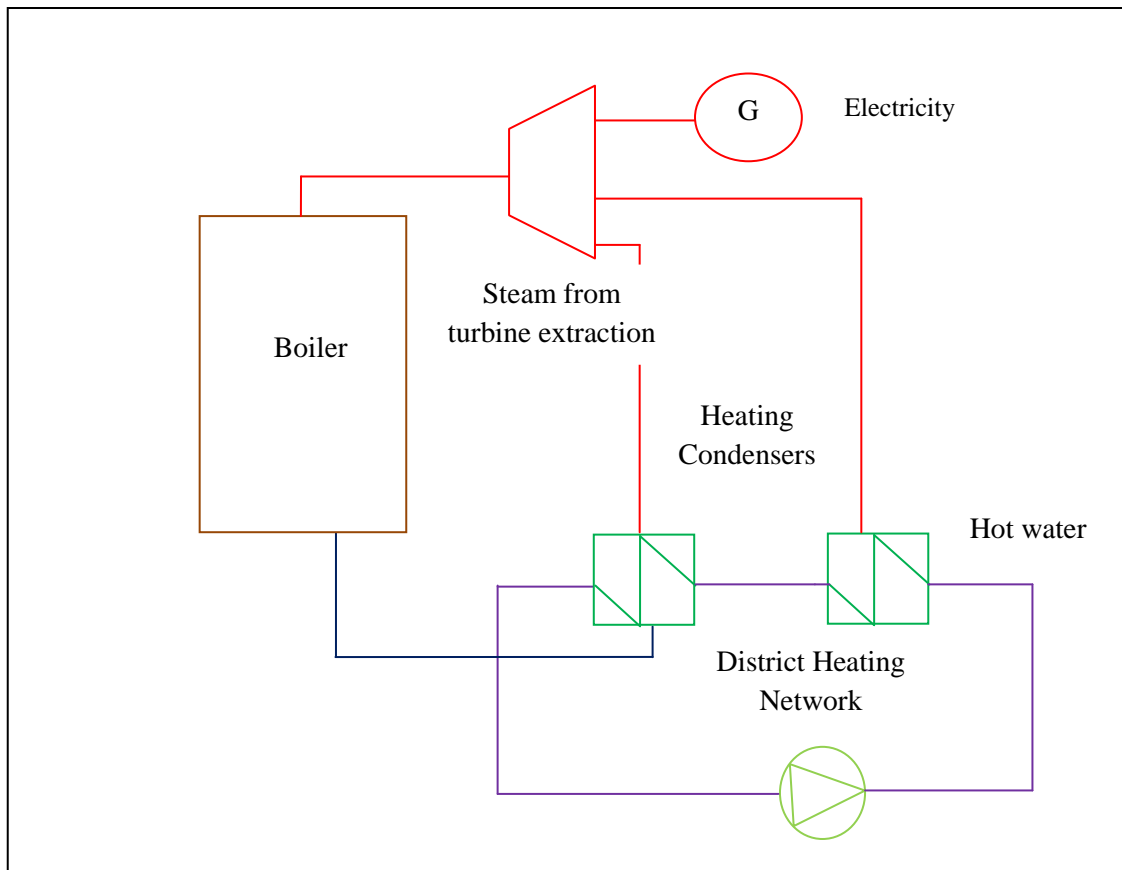


Figure 1.8.1. CHP system

Swedish CHPs produce electricity and low pressure steam for district heating. Some modifications are required in the turbine in order to take out 20 bar steam for biofuel production. To compensate for the reduction in electricity generation, CHP might be run all the year round, mainly in summertime when the district heating production is minim, and there is a surplus of steam (Trobro et al., 2011).

2. METHODS

2.1. CHP and Biofuel Production.

Figure 2.1.1 presents a possibility to integrate biofuel production in a CHP. Number **1** is the **boiler**, where the fuel, biomass or waste, is combusted, producing overheated steam, which pass by **turbine 2** producing electric energy. After the turbine, the pressure of steam is decreased to 20 bar saturated steam. This steam flow is divided in two. One goes to the next **turbine** (number **4**) where its pressure will be reduced again, reaching 1-5 bars. Next step will be **condenser** (number **5**), producing heating for district heating. The other steam flow will be used for the **ethanol and biogas production** (number **3**). As mentioned above, overall energy yields are better if it combines ethanol production and biogas anaerobic digestion. It is also necessary to use lignocellulose as raw material for sustainable production. It should be possible to recycle the steam in the different stages of the biofuel production, saving energy and costs. Steam remaining from ethanol production is used for the district heating network. Its pressure should be between 1-5 bars.

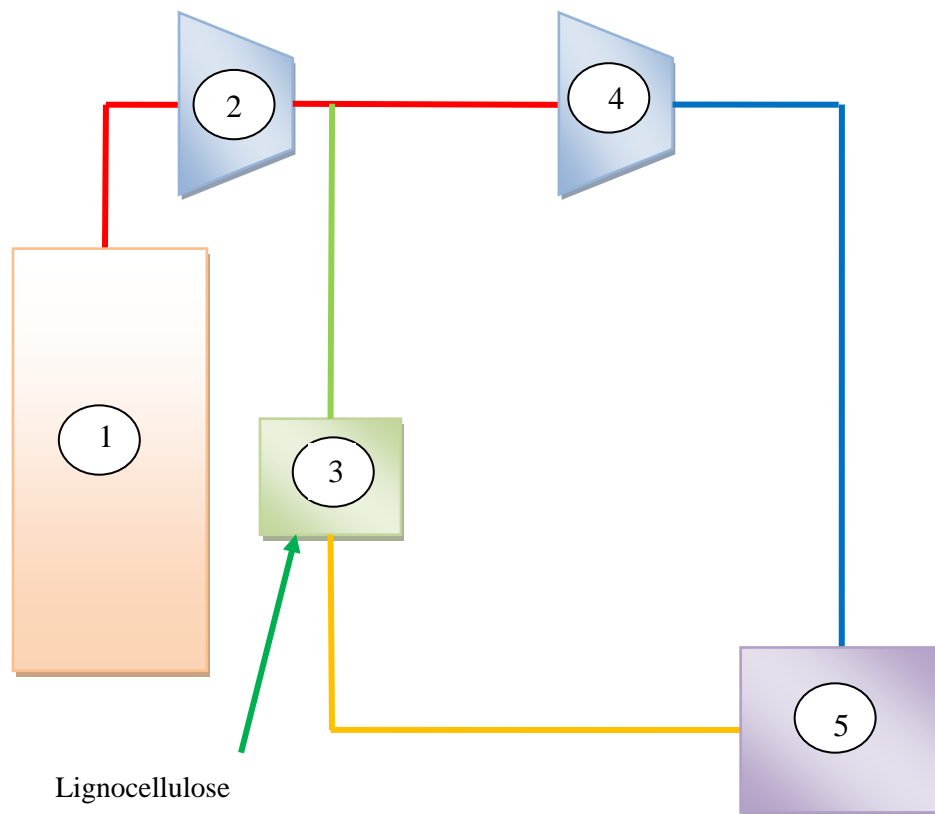


Figure 2.1.1 Bioethanol production integrate in CHP

2.2 Heat Engine Cycle efficiency. Carnot Cycle

The Carnot cycle describes an ideal theoretical heat engine cycle which is the most efficient. In practice, one only reaches the half of this thermal efficiency. The thermal efficiency is very important to a power plant, but not only that, there are others factors as important as the efficiency, such as the size of the plant, machines and operating and capital costs.

Carnot cycle is based on the first and second Law of Thermodynamics that states that “energy is conserved” and “entropy in a closed system increases spontaneously”. The two statements can be combined to “no heat engine can be more efficient than a reversible heat engine working between the same temperature limits”.

$$\eta = \frac{-\sum W}{Q_1} = \frac{\sum Q}{Q_1}$$

Where:

- η = cycle efficiency
- W =Net work output
- Q_1 =Gross heat supplied
- ΣQ = Net heat supplied

In the Carnot cycle all the heat is supplied while the system has a constant temperature, and the heat later ejected is ejected at a lower constant temperature. The two isothermal processes combined with two adiabatic processes constitute the cycle. As the processes are reversible, the adiabatic processes are isentropic, as well. It does not depend on the substance used.

Processes which are carried out in the Carnot Cycle:

- A-B: isothermal heat supply.
- B-C: isentropic expansion from T_H to T_C .
- C-D: isothermal heat rejection.
- D-A: isentropic compression from T_C to T_H .

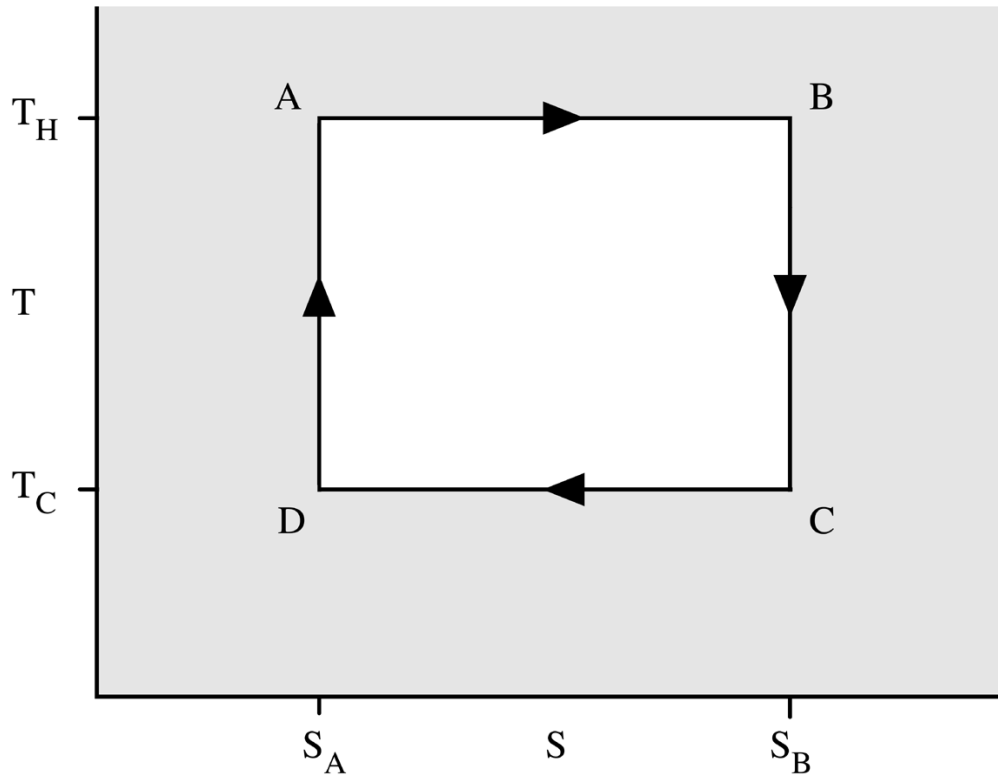


Figure 2.2.1. Carnot Cycle represented on T-S (Temperature-Entropy) (by PAR from Wikipedia)

The heat engine cycle efficiency is given by the network output divided by the gross heat supplied at the higher temperature. In Carnot cycle the gross heat supplied is Q_1 , where Q_1 is the area $ABS_B S_A A$ as figure 2.2.2 shows. And ΣQ is the area ABCDA.

$$Q_1 = \text{area } ABS_B S_A A = T_H(S_B - S_A)$$

$$\Sigma Q = \text{area } ABCDA = (T_H - T_C)(S_B - S_A)$$

Hence the Carnot cycle efficiency will be:

$$\eta_{Carnot} = \frac{(T_H - T_C)(S_B - S_A)}{T_H(S_B - S_A)} = \frac{T_H - T_C}{T_H}$$

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}$$

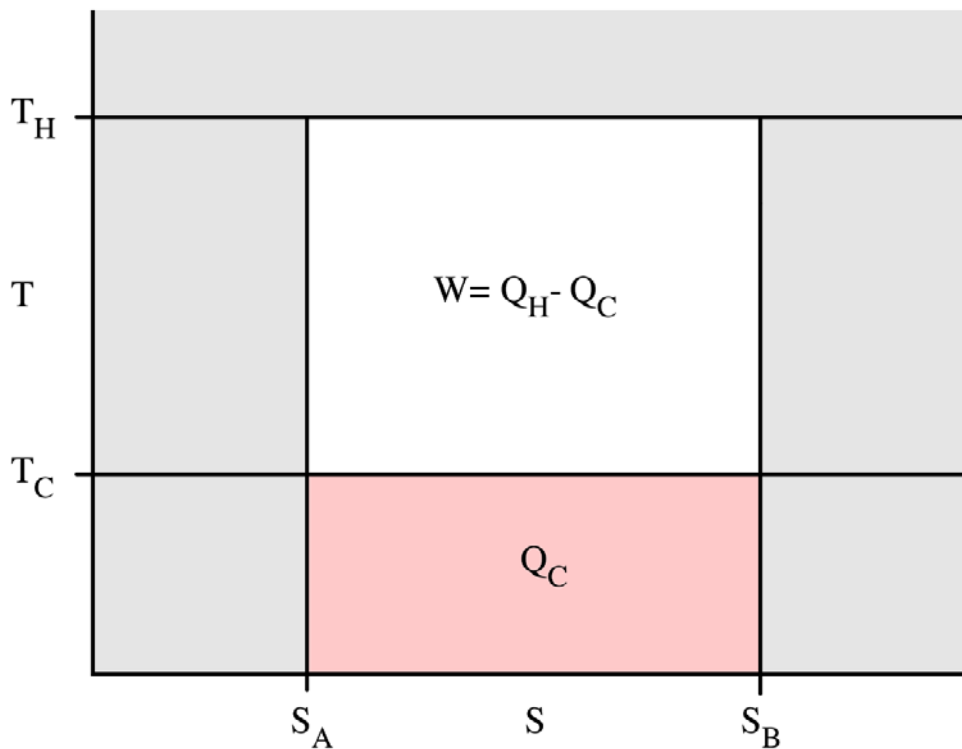


Figure 2.2.2. Carnot cycle efficiency (Author: Eric Duminil from Wikipedia)

The efficiency will be higher if T_H is much higher than T_C , $\eta_{Carnot} \approx 1$. However a system in practice operates between similar temperatures, obtaining a thermal efficiency about 30%, due to losses, since the processes are irreversible in practice.

The main issue is the lack of one system which can receive and reject the Carnot cycle at a constant temperature; only wet vapour can behave on this way. Even though, it is the most efficiency cycle, it is not used in steam plants. Steam plants are based on Rankine cycle which will be discussed later.

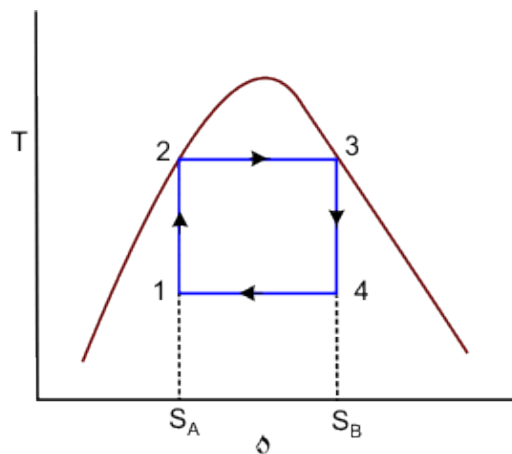


Figure 2.2.3 Wet vapour Carnot cycle. T-S diagram (http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT-KANPUR/Basic_Thermodynamics/lecture27/27_3.htm)

2.3 Steam Cycles. Rankine Cycle

As mentioned before, Carnot cycle is the most efficient cycle, in theory. However there are some difficulties. Considered the figure 2.2.3, at point 1 the steam is wet at T_c , but it is hard to stop the condensation at point 1 and immediately compress the steam until reaching T_H , point 2. It is better that it completes the compression, as in figure 2.3.1. The new fluid is water at point 1, instead of steam, which will be pumped to boiler pressure, point 2. In this way, the compression is brought off more efficiency and the equipment used is less expensive, since the pump used has smaller dimension than if it pumped steam. At point 2 the water does not reach the saturation temperature, it is necessary to provide heat until it reaches T_H . This is a constant pressure process but not isothermal. This cycle is called Rankine cycle. It is more suitable for steam systems than Carnot cycle, although Carnot is more efficient.

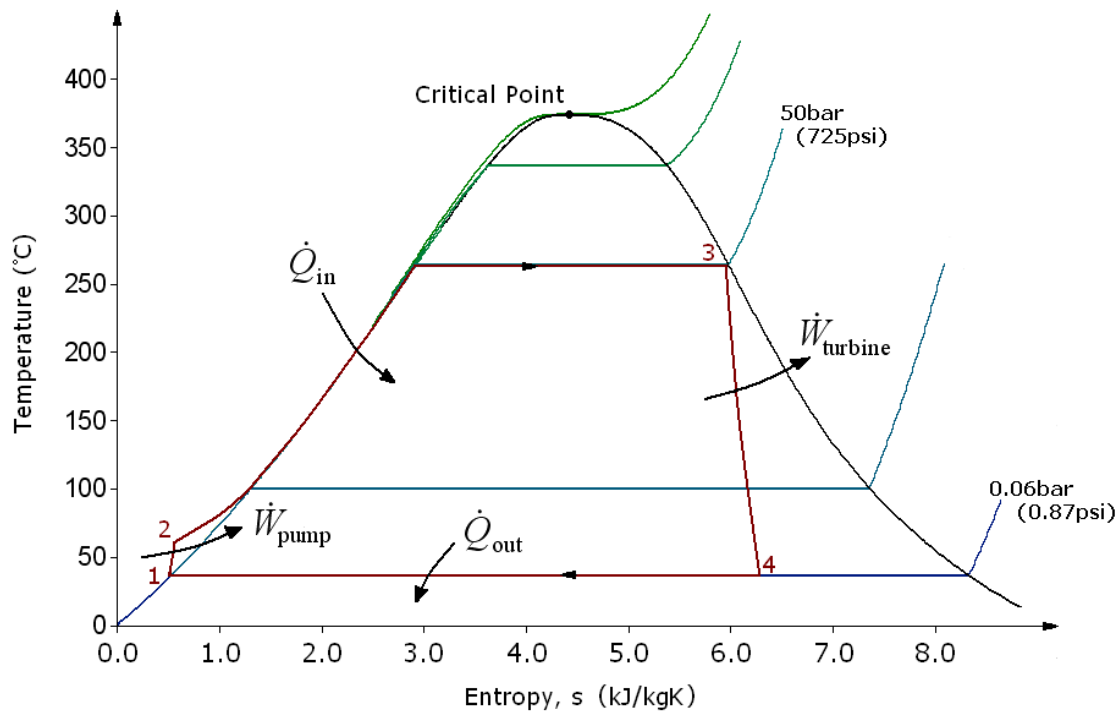


Figure 2.3.1. Rankine cycle. T-S diagram (Author: Andrew.Ainsworth from Wikipedia).

In the steam plant, the water is pumped until saturated temperature in a boiler which supplies the extra heat necessary to reach T_H . Then, the steam goes into the turbine, producing electricity. The next step is the condenser, where the steam will condensate to water. Here the steady-flow energy equation is used to analyze the steam flow.

$$Q + W = dh$$

Boiler:

$$Q_{23} + W_{23} = h_3 - h_2$$

$$W=0$$

$$Q_{in} = h_3 - h_2$$

Turbine:

$$Q_{34} + W_{34} = h_4 - h_3$$

The expansion is

- Adiabatic: $Q = 0$
- Isentropic: $s_3 = s_4$

$$+W_{34} = h_4 - h_3$$

As well, Work output

$$-W_{34} = h_3 - h_4$$

Condenser:

$$W=0$$

$$Q_{41} = h_1 - h_4$$

Heat rejected, so;

$$-Q_{41} = h_4 - h_1$$

Pump:

$$Q_{12} + W_{12} = h_2 - h_1$$

The compression is:

- Isentropic: $s_1 = s_2$
- Adiabatic: $Q=0$

$$+W_{12} = h_2 - h_1$$

So, Network input,

$$\sum W = W_{34} + W_{12}$$

W_{12} is almost neglected, if we compare with W_{34}

$$\sum W = W_{34}$$

Or it also possible to show as network output

$$-\sum W = -(W_{34} + W_{12}) = (h_3 - h_4) - (h_2 - h_1)$$

Heat supplied in the boiler = $h_3 - h_2$

Rankine efficiency,

$$\eta_R = \frac{\text{net work output}}{\text{heat supplied in the boiler}}$$

$$\eta_R = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

$$\eta_R = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_1) - (h_2 - h_1)}$$

W_{12} is neglected

$$\eta_R = \frac{(h_3 - h_4)}{(h_3 - h_1)}$$

The efficiency ratio of a cycle is the ratio of the actual efficiency to the ideal efficiency which is Rankine cycle efficiency in steam cycle.

$$\text{Efficiency ratio} = \frac{\text{cycle efficiency}}{\text{Rankine efficiency}}$$

In practice it is much easier to inject heat in a gas at the same pressure than at the same temperature. For this reason it is better to use Rankine cycle instead of Carnot cycle, since the heat supply is at constant temperature in this cycle. Carnot cycle also shows a low work ratio, although it is the most efficient. The work ratio of a cycle is the ratio of the network output to the gross work output. On p - v diagram (Figure 2.3.3), network output, 12341 area, is much more smaller than the gross work output 12V₃V₁1 area where V₁ is the volume in point 1 and V₃ is the volume in point 3, i.e. the work ratio of Carnot cycle will be lower value than in Rankine cycle. For these reasons Rankine cycle is used in steam plants instead of Carnot cycle, although it is more efficient in theory.

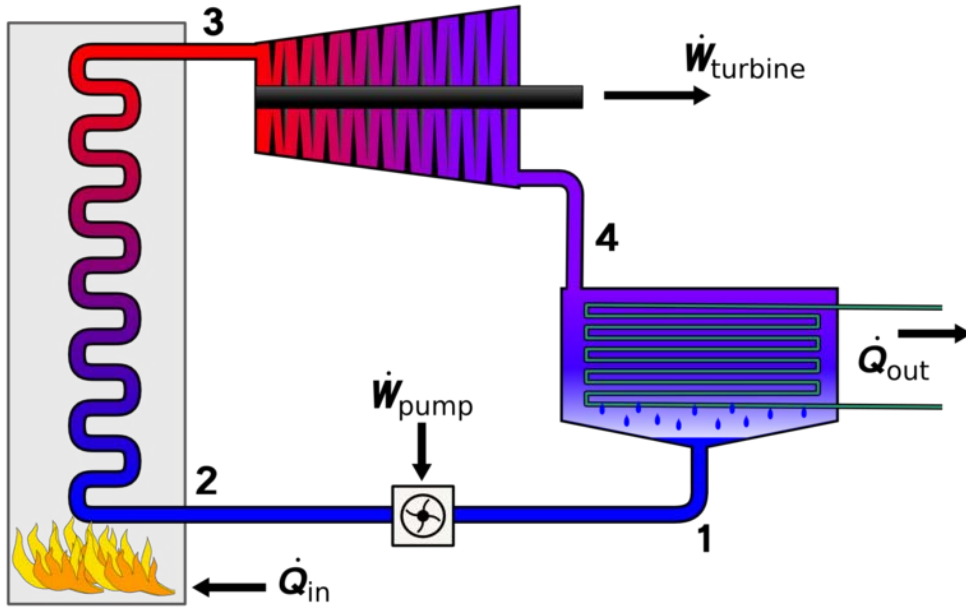


Figure 2.3.2 Steam plant. (Author: Andrew.Ainsworth from Wikipedia.)

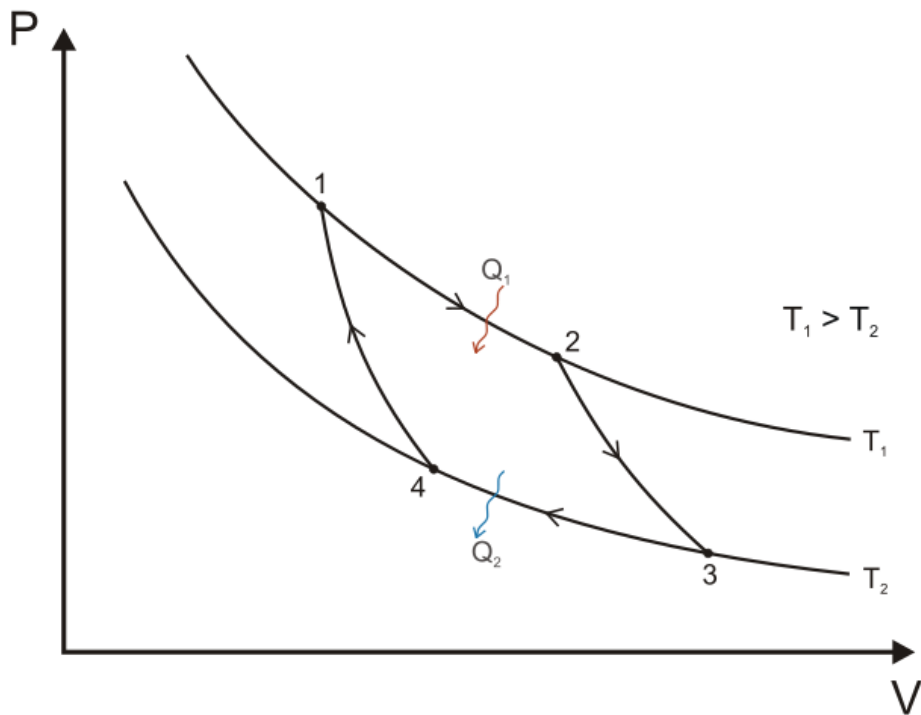


Figure 2.3.3. Carnot cycle on a p-v diagram (Author: Keta from Wikipedia).

2.4 Mass and Energy Balance

The main idea is to integrate the ethanol production with the CHP Plant, in order to be more competitive in an economic way, reducing investment and operating costs and using surplus of steam.

The figure 2.4.1 shows how the installations might look like.

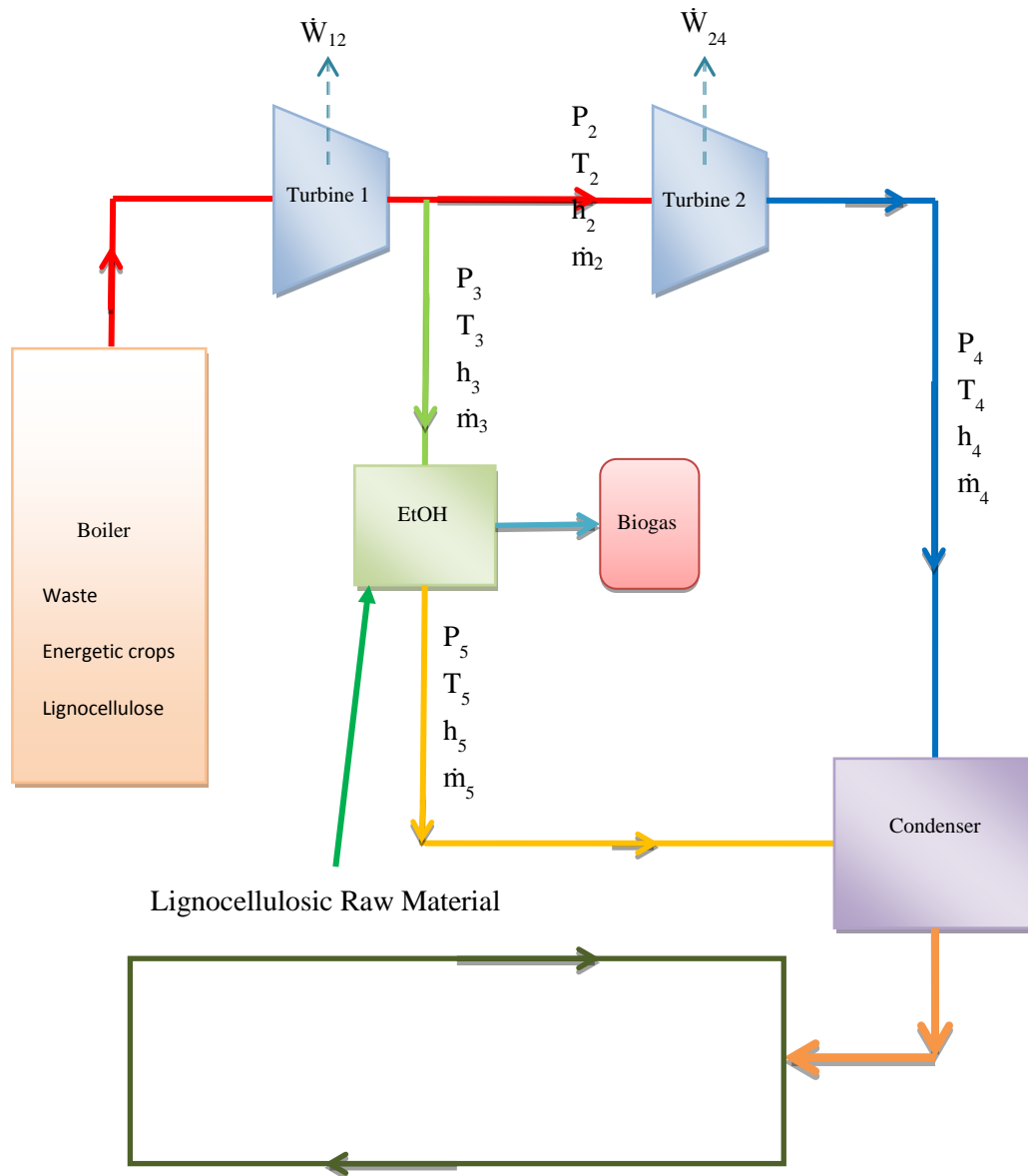


Figure 2.4.1. Ethanol and methane co-production integrated in CHP.

Where:

- P= Pressure (bar)
- T= Temperature (°C)

- h = Enthalpy (kJ/Kg)
- \dot{m} = Steam flow (ton/h)

Our objective is to calculate the amount of steam necessary for ethanol and methane production, and if it is feasible in a CHP Plant. Hence P_3 , T_3 , h_3 and \dot{m}_3 has to be calculated

Firstly, we calculated the steam necessary for pretreatment. To that end we assumed that the Power of the Turbine 1 was 13, 3 GWh/year, it is about 1, 67 MW and the steam supply by the turbine 1 was saturated steam at 20 bars. To calculate \dot{m} we used the formula: $P = h \cdot \dot{m}$

Where:

- P = Turbine Power (kW)
- h = Enthalpy (kJ/Kg)
- \dot{m} = Steam flow (ton/h)

The value of enthalpy was obtained from “Table. Properties of saturated steam”. So the enthalpy of saturated steam at 20bar is 2798, 3 kJ/Kg. Knowing these values is easy to calculate \dot{m}_3 .

Our first wrong assumption was that $\dot{m}_2 = \dot{m}_3$, obtaining a huge ethanol production, rendering it impossible to provide the necessary amount of feedstock biomass. Finally, we thought more reasonable to assume $\dot{m}_2 = 25\dot{m}_3$.

Next step was to calculate the amount of ethanol that it produced with \dot{m}_3 . We assumed that the energy requirement in the pretreatment was 7MJ/L EtOH for oat straw, obtaining the number of kg of steam necessary to produce 1kg EtOH. \dot{m}_3 was calculated before, so it is possible to know how much kg of ethanol is produced at a specific power.

According to the mass balances in the co-production of ethanol and methane using oat straw in Dererie et al., 2011 the ethanol production yield is 15%, i.e., it produces 15 Kg ethanol per 100 Kg of lignocellulose. Therefore, the amount of lignocellulosic feedstock was calculated with this yield and the amount of ethanol was obtained as before. Once amount of raw material was calculated, the amount of CH_4 production was worked out assuming that the production yield was 9%as in Debebe et al., 2011.

Electricity losses were also estimated in order to check the feasibility of the process. To do this, \dot{W}_{24} was calculated in two different scenarios, first scenario with bioethanol production, figure 2.4.1 and the second scenario without it, figure 2.4.2. To calculate \dot{W}_{24} it was used the next formula:

$$\dot{W}_{HC} = \eta \cdot \dot{q}_H = \frac{T_H - T_C}{T_H} \cdot \dot{q}_H$$

In our case,

$$\dot{W}_{24} = \frac{T_2 - T_4}{T_2} \cdot \dot{q}_2 = \frac{T_2 - T_4}{T_2} \cdot \dot{m}_2 \cdot h_2$$

Where:

- \dot{W}_{24} = Turbine₂ work flow (MW)
- η = Energy efficiency (%)
- T_2 = Temperature before Turbine (K)
- T_4 = Temperature after Turbine (K)
- \dot{q}_2 = Heat flow (kJ/s)
- \dot{m}_2 = Steam mass flow (Kg/s)
- h_2 = Enthalpy (kJ/Kg)

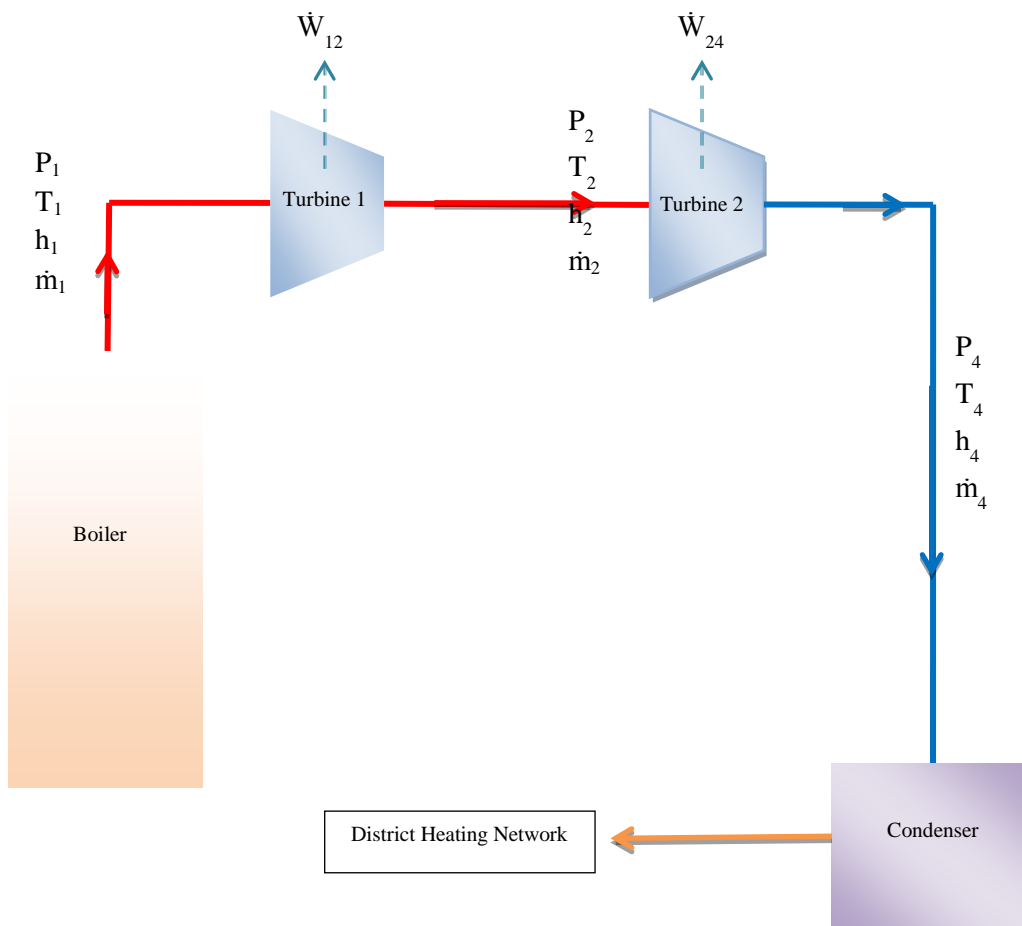


Figure 2.4.2. CHP without ethanol production.

The losses will be the difference between \dot{W}_{24} without ethanol production and \dot{W}_{24} with ethanol production. In scenario 1, with ethanol production, $\dot{m}_2 = \dot{m}_1 - \dot{m}_3$, and in scenario 2, $\dot{m}_2 = \dot{m}_1$. So the difference will be in \dot{m}_3 , the higher value of \dot{m}_3 the higher electric energy losses.

We assumed that $\dot{m}_2 = \dot{m}_4$, i.e., no mass will be accumulated in the equipment, to simplify the calculations. And also, \dot{m}_4 is not only steam, but also water; it was checked with Mollier-diagram which compares specific entropy with specific enthalpy at specific temperature and pressure.

I had the opportunity to visit the CHP in Uppsala owned by Vattenfall, the 14th of March. I went with my supervisor Stefan Trobro. There we meet the production manager, Hans Blomfeldt and an operator of the plant. We obtained some feedback on our calculations.

After our visit to Vattenfall, some of our assumptions about steam pressures and temperatures were clarified. Looking at our data and focusing on the waste incinerator Block 5, we decided to modify our system and increasing the amount of raw material, since the steam delivered from the waste incinerator is were regarded enough to provide the steam requirements. So we did some changes such as, the turbine number 1 elimination (figure 2.4.3). \dot{m}_1 was instead adapted to the capacity of Block 5, so it was no longer necessary to assume that $\dot{m}_2 = 25\dot{m}_3$. The power in turbine 2 was now derived from the mass flow $\dot{m}_2 = \dot{m}_1 - \dot{m}_3$,

The amount of steam necessary for the distillation stage was estimated, following the data of Wingren et al. Using this paper as a reference, and in our case fermentation plus anaerobic digestion, extra primary steam for distillation is not necessary but instead secondary steam from turbine 2 or the pretreatment can be used. The steam required for distillation is low pressure steam, 1-4 bar, i.e., it is enough with steam supplied for the turbine at 20 bar (Wingren et al., 2008).

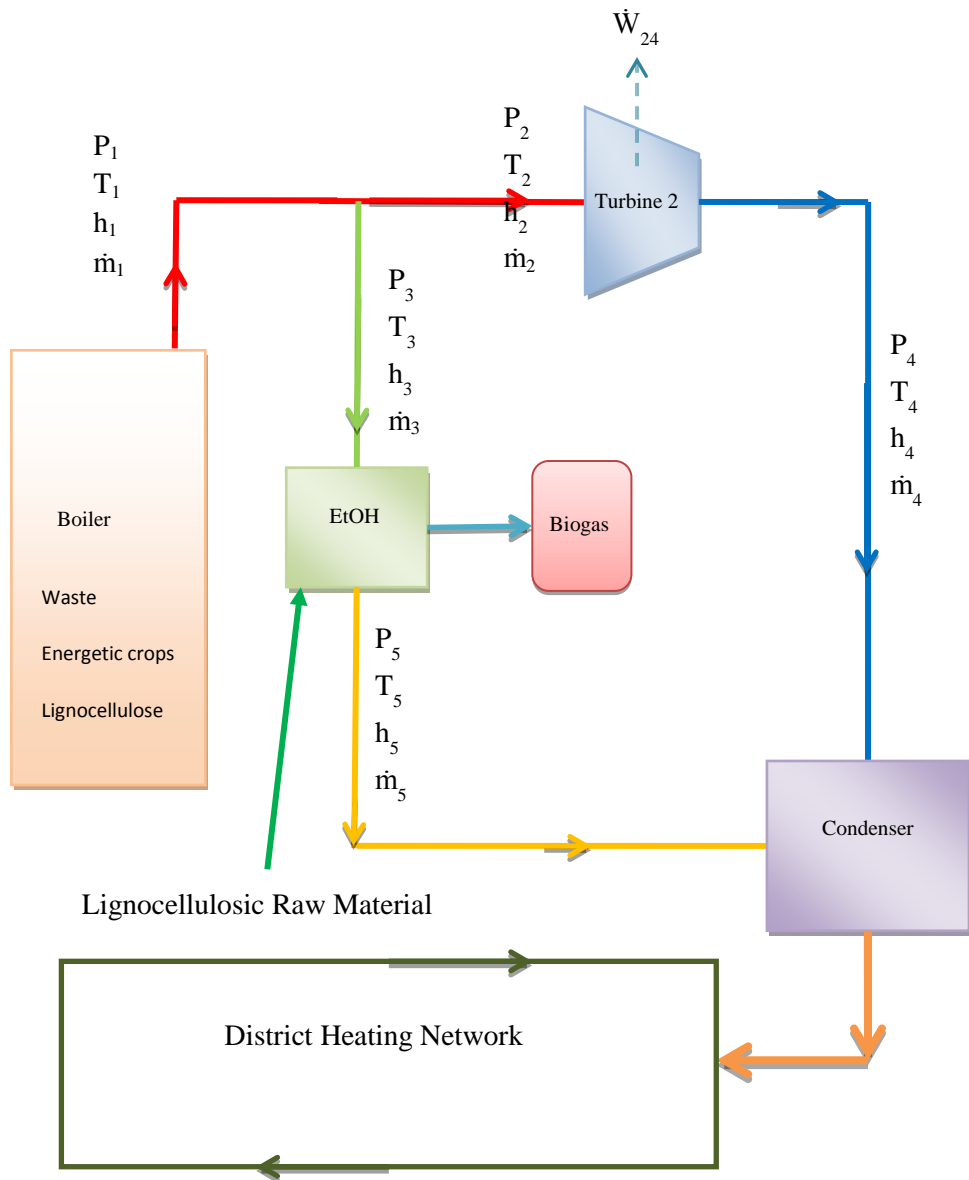


Figure 2.4.3. Ethanol and methane co-production integrated in Waste incinerator.

3. RESULTS AND DISCUSSION

The bioenergy combine system was modified after the visit to the CHP in Uppsala owned by Vattenfall. A short summary of the visit follows below.

First, we were talking about the Plant and its mechanical characteristics. The Plant contains a big boiler which usually operates mainly in winter time and when the demand of heating is very high. This boiler can use wood-pellets for fuel and can generate high-pressure overheated steam and electricity in several steam turbines. The site also contains waste incineration CHP's, called block 2, 3, 4 and 5. These typically operate all through the year. Block 5 can produce 20 bar saturated 212 °C steam from the boiler and it is possible to extract this steam before it passes through the steam turbine. Block 5 therefore seems suitable for steam delivery to a bioenergy combine.

I then made a short summary about the concept of coproduction of ethanol and methane integrated with a CHP plant and its requirements, such as pressure and amount of steam, temperature and amount of lignocellulose. Some of our assumptions about steam flow, pressure, temperature, condensation and overheating were clarified and validated.

The Vattenfall representatives commented on the presentation and found the bioenergy combine concept interesting and would in principle welcome the possibility of an additional demand for block 5 20 bar steam in the summertime. They pointed out that future work would have to clarify that the space requirements of the biofuel production is compatible to the layout of the plant. We were then invited to a guided tour of the plant. The visit enabled the bioenergy combine system to be improved and we are grateful for this opportunity and would like to thank Vattenfall, Uppsala.

After the visit we started to recalculate our data based on block 5 as the CHP part of the bioenergy combine. With the formulas described previously we were able to estimate the steam requirement for pretreatment and distillation and also the production of ethanol and methane.

With our first assumption that turbine power would be around 1, 67 MW, it was necessary to use 4, 5 ton/h of raw material. After the Vattenfall visit, and checking that it was suitable, we decided to increase the amount of raw material, describing two scenarios:

Scenario 1: 4, 5 ton. Oat straw+ 8 ton. Norway Spruce.

Scenario 2: 4, 5 ton. Oat straw+ 8 ton. Salix.

3.1. Pretreatment, Ethanol and Methane Production.

The next tables show the steam mass flow. Ethanol production yields were taken from the paper “Techno-economic evaluation of bioethanol production from three different lignocellulosic materials” (Sassner et al., 2008), as well the energy required for Spruce. We assumed that Salix has the same energy required than Spruce. However the energy required for oat straw was assumed to be 7 MJ/L EtOH. It is assumed that CH₄ production yield for Spruce and Salix is the same than Oat Straw (Dererie et al., 2011).

EtOH and methane production were calculated multiplying raw material and η production. Energy obtained was determinate multiplying High Heating Value (HHV) and ethanol or methane production. And finally the steam required (ton/hour) was:

$$\dot{m} = \frac{\text{Energy required} \cdot \text{Production ethanol}}{\text{Enthalpy} \cdot \text{Density}}$$

The steam requirement, ethanol and methane production and energy obtained will be the sum of the steam needed in Oat Straw plus Spruce in scenario 1, and the sum of Oat Straw plus Salix for scenario 2 (Table 3.1.2)

Table 3.1.1 Steam mass flow and energy balance in pretreatment for different species

<i>Table 3.1.</i>		Oat Straw	Spruce	Salix
Raw Material (ton/hour)		4,5	8	8
Ethanol Production	Density(g/ml):	0,789	0,789	0,789
	HHV(MJ/Kg):	29	29	29
	η Production (%):	15	23	19
	Energy required(MJ/L EtOH):	7	6,05	6,05
	Steam required(kg/Kg EtOH):	3,17	2,74	2,74
	Steam required(ton/h):	2,14	5,05	4,13
	EtOH (Kg/h):	675,0	1 843,1	1508,6
Energy flow obtained(MJ/s)		5,44	14,85	12,15
Methane Production	η Production (%):	9	9	9
	CH₄ (Kg/h):	405	720	720
	HHV(MJ/Kg):	55,5	55,5	55,5
	Energy flow obtained(MJ/s)	6,24	11,10	11,10

Table 3.1.2. Steam mass flow and energy balance in pretreatment for two scenarios.

Table 3.2	Steam required (ton/h)	EtOH (ton/h)	CH ₄ (ton/h)	Biofuel energy obtained (MJ/s)
Oat Straw+ Norway Spruce	7,19	2,52	1,125	37,63
Oat Straw+ Salix	6,27	2,18	1,125	34,93

According with the table 3.1.2, more energy is obtained in scenario 1, with Oat Straw and Norway Spruce, although the consumption of steam is higher as well. To determine what it is better is necessary to calculate the energy losses in turbine 2. Methane production is assumed to give the same yields as oat straw (Dererie, 2011) and is the same for both scenarios, so it cannot be take into consideration in order to determine which scenario is better.

Technical conditions are described in Tables 3.1.3 and 3.1.4 for the two scenarios. The different points are based on Figure 2.4.3. Part of the pressures and temperatures can theoretically be provided in the Vattenfall, waste incinerator number 5 in Uppsala. Our study is focused on the technical requirement for the ethanol production in a CHP, for this reason, points 2 and 3 are the most important to know their values. We started with the point 3. Enthalpy and steam mass flow were already known. Next step was to calculate the power needed in order to deliver the steam required, through the next formula: $P_3 = h_3 \cdot \dot{m}_3$. All the parameters for point 3 and 1 were known. $\dot{m}_2 = \dot{m}_1 - \dot{m}_3$, P_2 whether max and min, was determined with the same equation as P_3 : $P_2 = h_2 \cdot \dot{m}_2$. It was also assumed that mass flow in point number 4 is only steam, although it is not relevant for the calculations. They are not constant values, we use max. and min. because the operation of CHP produce different amount of electricity and heat depending on costumers demand. Point 5 parameters should be similar as point 4 parameters, for this reason we assumed that the parameters would be the same in point 4 as point 5. These values are quite interesting in order to know the technical requirements for the ethanol production in a CHP. I have to annotate that for the pretreatment is also necessary to use low pressure steam, although this steam might be taken after the turbine for instance. It is the high pressure steam the limiting factor.

Table 3.1.3. Pressure (P), Temperature (T), enthalpy (h), mass flow (m) and Power needed to produce steam required, in scenario 1.

Oat Straw+ Norway Spruce	1 min.	1 max.	2min	2 max.	3	4 min.	4 max.	5 min.	5 max.
P(bar.)	20	20	20	20	20	1	4	1	3
T(°C)	212,38	212,38	212,38	212,38	212,38	99,61	143,63	99,61	133,52
h(KJ/Kg)	2798,3	2798,3	2798,3	2798,3	2798,3	2674,9	2737,6	2674,9	2724,9
\dot{m} (Kg/s)	5,56	27,78	3,56	25,78	2,00				
\dot{m} (ton/h)	20,00	100,00	12,81	92,81	7,19				
Power (GWh/year)	124,37	621,84	79,66	577,13	44,71				
Power (MW)	15,55	77,73	9,96	72,14	5,59				

Table 3.1.4. Pressure, Temperature, enthalpy, mass flow and Power needed to produce required steam, in scenario2.

Oat Straw+ Salix	1 min.	1 max.	2min	2 max.	3	4 min.	4 max.	5 min.	5 max.
P (bar.)	20	20	20	20	20	1	4	1	3
T(°C)	212,38	212,38	212,38	212,38	212,38	99,61	143,63	99,61	133,52
h(KJ/Kg)	2798,3	2798,3	2798,3	2798,3	2798,3	2674,9	2737,6	2674,9	2724,9
ṁ (Kg/s)	5,56	27,78	3,81	26,04	1,74				
ṁ (ton/h)	20,00	100,00	13,73	93,73	6,27				
Power (GWh/year)	124,37	621,84	85,38	582,85	38,99				
Power(MW)	15,55	77,73	10,67	72,86	4,87				

Comparing the results, scenario 1 requires more energy than scenario 2 due to the demand of steam (\dot{m}) is bigger in scenario 1 than in 2, since Spruce has higher yield in ethanol production than Salix. The steam requirement of pretreatment is independent of ethanol yield while a steam requirement of distillation depends on the amount of ethanol. The different steam requirements in scenario 1-2 can therefore reflect the assumption in table 3.1.1.

Energy balance with and without ethanol production is compared in Work flow terms (MW) in the next tables for the scenarios. \dot{W}_{24} was calculated with the next equation:

$$\dot{W}_{24} = \frac{T_2 - T_4}{T_2} \cdot \dot{q}_2 = \frac{T_2 - T_4}{T_2} \cdot \dot{m}_2 \cdot h_2$$

taking the minimum values from point 2 and maximum for point 4, being the worst case $\dot{W}_{24 \text{ min}}$, and $\dot{W}_{24 \text{ max}}$ was calculated taking the maximum values from point 2 and minimum in point 4, being the best case. Electric losses are in percentage. They are defined as the difference between 1 and the ratio \dot{W} with ethanol production and \dot{W} without ethanol production.

$$\text{Electric losses}(\%) = 1 - \frac{\dot{W}_{\text{with EtOH production}}}{\dot{W}_{\text{without EtOH production}}}$$

Table 3.1.5. Energy balance scenario 1.

Oat Straw+ Norway Spruce	$\dot{W}_{24 \text{ min}}$	$\dot{W}_{24 \text{ max}}$
With EtOH Production (MW)	1,4	16,8
Without EtOH Production (MW)	2,20	18,06
Electric losses (%)	36	7

Table 3.1.6. Energy balance scenario 2(MW)

Oat Straw+ Salix	$\dot{W}_{24 \text{ min}}$	$\dot{W}_{24 \text{ max}}$
With EtOH Production (MW)	1,51	16,93
Without EtOH Production(MW)	2,20	18,06
Electric losses (%)	31	6

The electric losses are lower in the best case ($\dot{W}_{24 \text{ min}}$ Straw + Salix) only 6%, although the losses are very high in the worst case, reaching 36% ($\dot{W}_{24 \text{ max}}$ Straw + Spruce). There are fewer losses in the scenario 2 than in scenario 1 although the difference is small and might reflect out underlying assumptions. These results are relevant, since they show that the electric losses if CHP is running a full capacity are low. However, if the CHP is running with the minimum capacity and the low pressure required is the high pressure case of 4 bar, the losses are bigger, almost 40%. This topic should be studied more deeply and check whether the pressure in point 4 is 1 or 4 bar in practice. Actually it might be possible that steam in point 4 is not at 4 bar. In that case, additional low pressure steam would have to be provided to carry out the distillation.

The main goal of our study is to investigate if it is feasible to co-produce ethanol and methane integrated with a CHP plant in Sweden. To that end, Swedish total potential was estimated. It is assumed that Sweden has the capacity of 20-50 CHP like the waste incinerator number 5 in Uppsala. Work hours per year were 8000h/year.

It is quite interesting to calculate as well the biofuel production in terms of TWh/year, in order to check if Swedish biofuel demand would be supplied. To that end, it is necessary to multiply ethanol production (ton/year) and HHV (MJ/kg) and divided by 3600s/hour (Figure 3.1.9) We can compare the data obtained with the current biofuel consumption in the transportation sector ~3, 5 TWh/year The Swedish fossil fuel (petrol and diesel) demand is ~83 TWh/year (Energiläget 2011) for the internal transport sector, so currently only ~3% of the total energy (96 TWh, Energiläget 2011) used in the transport sector comes from ethanol and methane. If we focus on Table 3.1.9. we observe that the ethanol and methane production in the worst case would be increased by a factor of two and more than a factor of three in the best case. That means, some fossil fuel would be replaced, but the ethanol and methane production would not be enough to replace all the fossil fuel consumption in the Swedish transport sector. In the best case, it could be possible to reduce the fossil fuel consumption with ~14% in Sweden. This data is interesting in order to study how the amount of fossil fuel can be replaced.

Table 3.1.7. Biofuel production from a block 5 type waste incinerator CHP.

Block number 5		Oat Straw + Spruce	Oat Straw + Salix
Ethanol Production	Ton./h	2,52	2,18
	Ton./year	20160	17440
	TWh/year	0,1624	0,140489
Methane Production	Ton./h	1,125	1,125
	Ton./year	9000	9000
	TWh/year	0,0725	0,0725

Table 3.1.8. Swedish Ethanol Production Potential

Swedish Potential		Oat Straw + Spruce	Oat Straw + Salix
Ethanol Production (ton/year)	20	403200	348800
	50	1008000	872000
Methane Production (ton/year)	20	180000	180000
	50	450000	450000

Table 3.1.9 Swedish Ethanol Production Potential (TWh/year)

Swedish Potential		Oat Straw + Spruce	Oat Straw + Salix
Ethanol Production (TWh/year)	20	3,25	2,81
	50	8,12	7,02
Methane Production (TWh/year)	20	1,45	1,45
	50	3,625	3,625

3.2. Distillation.

Not so much information is available about the steam required in distillation. Our results are based on Wingren et al. paper which is detailed distillation process for softwood. We also assumed these data for Straw and Salix. The higher steam requirements for straw (Dererie, 2011) because of lower ethanol concentration are ignored here, partly because the biofuel combine will have abundant low pressure steam after the steam turbine.

The steam needed in distillation is low pressure steam between 4 and 1 bar (Wingren et al., 2008). As in the pretreatment, the steam required is lower in scenario 2 than 1, although the different in (Kg steam/Kg EtOH) is not so high.

According with Wingren, there is the possibility to recycle the steam, i.e., replace the 20 bar primary steam for distillation with secondary steam. Furthermore, there is a surplus of steam with subsequently fermentation and anaerobic digestion process. Although in

our case the steam required in distillation will be a little bit higher than the table 3.2.1 shows, because in their study the ethanol concentration in the stillage is higher than in our case (Dererie et al., 2011). The heat requirements for AD, i.e. reactor tank heating and residue drying is assumed also to be possible using secondary steam.

Table 3.2.1. Distillation Steam Required.

	Oat+Spruce	Oat+Salix
	Fermentation and AD	Fermentation and AD
Data from Wingren paper:		
Energy required (MW):	11,3	11,3
Ethanol production(kg/s):	1,65	1,65
Energy required (MJ/kg EtOH):	6,84	6,84
Our case:		
EtOH(kg/h)	2 518,1	2 183,6
Power required (MW):	4,79	4,15
Energy required (MJ/kg EtOH):	2,97	2,58
Steam required (kg steam/kg EtOH)	p=1bar	1,11
	p=4bar	1,08
Steam required (ton steam/h)	p=1bar	2,8
	p=4bar	2,73

The power required (MW) was calculated multiplying EtOH Production (kg/h) with Energy required (MJ/kg EtOH) according with Wingren paper. To obtain the steam required for the distillation, first is necessary to determine the energy demand in the form steam primary, according with Wingren 38,8 Mw are 19 MJ/L, so 4,79 MW will be 2,34 MJ/L = 2,97MJ/kg EtOH if we multiply by ethanol density. The steam required (kg steam/kg EtOH) will be the energy divide by the enthalpy, in our case it is saturated steam at 1 bar pressure in the worst case with $h=2674,9$ kJ/kg, and steam at 4 bar in the best case with $h= 2737,6$ kJ/kg. Finally, this value is multiplied by EtOH production, obtaining tones of steam demand per hour.

The difference between the amount of steam need at 1 bar pressure and at 4 bar pressure is practically neglected. It is bigger the difference between Oat Straw and Spruce, as in the pretreatment. The reason is the highest production of ethanol which is produced with Spruce as raw material.

4. CONCLUSION AND FUTURE STUDIES

Currently, ethanol is the largest biofuel used in transportation sector. So if it is produced in a sustainable way and if it comes from wood material could be the best solution to replace fossil fuel. It is necessary to invest more in the biofuels field. The main bottleneck is the huge investment cost for the build-up of production capacity. To avoid these huge costs, we can integrate ethanol production in a CHP.

This report shows that it is compatible in mass flow and energy balance terms to integrate ethanol production in a CHP Plant, particularly in a waste incinerator Block 5 type unit. On my point of view, the perfect combination would be ethanol and methane production in a waste incinerator, like Block 5.

Showing in this paper that the steam systems seem technically compatible, I consider that ethanol and methane production integrated in CHP is a good alternative in order to decrease the fuel consumption and to achieve the 20,20,20 target.

The technical demands are supplied. The amount of steam provided by the boiler at 20 bar is enough for supplying steam demands in pretreatment and post turbine steam should be enough for the distillation. And the electric losses are low, in the best case with high primary steam production. The steam required in distillation is low pressure, for this reason the combination between ethanol production and waste incinerator is feasible, there is not extra high pressure steam demand. However if the demand of low pressure steam due to distillation and also pretreatment is not supplied, extra high pressure steam will be needed. Even there is the possibility to recycle the steam delivered in the pretreatment, and use it in other steps, such as distillation. In some case, as in ethanol fermentation followed with anaerobic digestion, it might be produced with surplus of steam.

The integration could be possible with only ethanol production integrated into the CHP, but I think that it is better if the ethanol fermented stillage is treated, obtaining other co-products and it might be possible for fertilizer production as well. As far as I concerned, anaerobic digestion is one of the best alternative to treat the stillage, because of its low energy demand, low cost, and the methane production as a co-product.

In my opinion, the best alternative in Sweden, it is the production of ethanol and methane in a CHP from Oat Straw and Norway Spruce, because the availability of Norway Spruce wood is higher than Salix and the energy balance shows better results with Norway Spruce than with Salix, the profit should be higher. Although the energy demand is also higher in Spruce than in Salix, so it should be further studied in economic terms.

Sweden has the potential to produce high amounts of ethanol per year, reducing its fossil fuel consumption in transportation sector. Sweden have enough CHP's that might

be integrated with ethanol and methane production, obtaining almost 14% of the annual Swedish fuel demand.

It would be interesting to conduct an economic assessment about ethanol production integrated in CHP, describing the facilities which would be necessary to build, the cost of the materials, the changes in the CHP infrastructure which would be effected. It could be an important research to investigate what the real Swedish potential is, how much biofuel it could be possible to produce if in all CHP's are integrated with ethanol production, how much Spruce are available, and if it is better to use another kind of wood with high ethanol production yield. Looking for solutions to avoid adding low pressure steam if the demand was not supplied, if it is possible and feasible to have the CHP running with high capacity. In my opinion, there are a lot of things to do, but they are working in the right way. Perhaps, it is necessary more subsidies from the government to drive their establishment and development.

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