Potential Energy Crops and Their Utilization Technologies in Ostrobothnia

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ABSTRAKT

Det finns ett ökande behov att ersätta fossila bränslen med miljövänligare alternativ för att minska mängden växthusgaser som förorsakas av användningen av fossila bränslen. Detta betyder att användningen av förnyelsebara energikällor måste öka. Ett möjligt sätt att uppnå detta är att odla biomassa som kan användas som råmaterial för att tillverka olika bränslen eller användas i olika former för att producera elektricitet och fjärrvärme. Biomassan som odlas måste vara av en art som tål de varierande förhållanden i Finland, måste ha hög avkastning per hektar och måste relativt lätt kunna konverteras till bränsle av något slag. Österbotten har valts som exempelområde eftersom det finns många företag i regionen som är aktiva inom energisektorn och det torde därför finnas kunskap för att på ett så effektivt som möjligt sätt kunna utnyttja biomassan.

Syftet med detta arbete är att undersöka vilka växter som är lämpliga för de finska klimatförhållanden, deras avkastning, olika förbehandlingstekniker samt vidarebehandling av biomassan till användbara bränslen. De olika slutprodukterna som kan erhållas presenteras också.

Genom att använda data från källorna i teoridelen framställdes ett Excel kalkylblad som användes för att beräkna värden som användes för att jämföra mängden energi som skulle kunna tas tillvara från förbränning av fast biomassa och från förbränning av biogasen som bildats om biomassan hade omvandlats till biogas genom anaerob rötning.

Resultaten från beräkningarna visar att för vissa växter är anaerob rötning och förbränning av den producerade biogasen är ett bättre alternativ med tanke på energimängden. Beroende på om biomassan ska förbrännas eller rötas anaerobt bör olika växter odlas. Om förbränning är den valda omvandlingsmetoden bör Miskantus odlas medan om biomassan skall anaerobt rötas är hampa det bästa alternativet.

För att göra resultaten mera jämförelsebara med varandra borde förbehandlingens inverkan tas i beaktande: hur den påverkar mängden biomassa som finns kvar för vidare behandling, hur förbehandling påverkar biomassans kvalitet och energin som kan tas tillvara. I detta arbete har förbehandlingens inverka på biomassan inte tagits i beaktande utan fokus ha lagts på biomassornas avkastning och energimängd. Därför kan energimängderna som fås ur växterna vara högre än de är i verkligheten.

Nyckelord: biomassapotential, energigröda, förbehandling, förbränning, förgasning, rötning

ABSTRACT

There is an ever increasing need to replace fossil fuels with less polluting and more environmentally friendly alternatives. This means that the usage of renewable energy source must increase. One such energy source could be biomass grown specifically for the purpose of using it as an energy source or as a raw material which is used to produce various fuels. The type of biomass grown needs to be able to survive in Finnish climate conditions, has to have a high yield per hectare and needs to able to be converted to fuel easily. Ostrobothnia on the west coast of Finland was chosen as the area where to grow biomass since there are many companies that are involved in the energy sector and therefore the know-how on how to best utilize the biomass should exist in the region.

The purpose of this work is to investigate suitable plants for growth in the Finnish climate, their yield, different pretreatment technologies as well as further refinement of the biomass into a useable fuel. The different end-products will also be discussed briefly.

First, a literature review was performed to find data on different biomasses grown in Finnish conditions or conditions similar to those in Finland. An Excel file was then used to input and calculate different data in order to determine which plants are the most promising in terms of biomass and energy yield when utilized.

The results indicate that anaerobic digestion of some of the biomasses and combustion of the resulting gas is more energy efficient than combustion of the biomass. Depending on whether the biomass is to be combusted or anaerobically digested, different biomasses need to be grown. If combustion is the preferred method of heat and power generation then based on the calculations Miscanthus should be cultivated. If, however, the biomass is to be anaerobically digested, then hemp would be the ideal plant to grow.

To make the results more comparable and realistic the effect of pretreatment needs to be taken into account: how it affects the amount biomass that is available for further use after it has been pretreated, how pretreatment affects the quality of the biomass and subsequent energy yields. The effect of any pretreatment of the biomass has not been taken into account in this work since more focus was put on finding suitable plants and their energy yields. Therefore, the amounts of energy achieved may be somewhat higher than what would be achievable in reality.

Key words: biomass potential, energy crops, pretreatment, combustion, gasification, digestion

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LIST OF SYMBOLS AND ABBREVIATIONS

AD	Anno Domini
ASBR	Anaerobic sequencing batch reactor
$Ca(OH_2)$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CaS	Calcium sulfide
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CSTR	Continuously stirred reactor
DFB	Dark fermentative bacteria
$Fe(OH)_3$	Iron oxide-hydroxide
Fe_2O_3	Iron oxide
FT	Fischer-Tropsch
g/Nm^3	Grams per normal cubic meter
H_2	Hydrogen
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
HCl	Hydrogen chloride
HHV	Higher heating value
HRT	Hydraulic retention time
kW_e	Kilowatt equivalent
LHV	Lower heating value
LHW	Liquid hot water
mL	Milliliter
MPa	Megapascal
MW_e	Megawatt equivalent
MW_{th}	Megawatt thermal
NO_X	Nitrous oxides
PFB	Photo fermentative bacteria
RCG	Reed canary grass
SCW	Super critical water

SCWG	Super critical water gasification
SO_X	Sulfur-oxides
VS	Volatile solids
Wt-%	Weight percent
ZnO	Zinc oxide

1 INTRODUCTION

There is a growing need to replace fossil fuels with greener, more environmentally friendly alternatives. There are many different alternatives for this depending on the intended end product. The European Commission (2020) proposed as part of the European Green Deal that by 2030, the European Union would have achieved the goals of reducing greenhouse gas emissions by at least 40% compared to 1990. The renewable energy share in the union is to be at least 32% and the energy efficiency must improve by at least 32.5%.

Since the European Union is pushing for higher shares of renewable energy sources, there needs to be a way to meet these demands. In response to this, the Finnish government has put forward lofty goals for how to reduce greenhouse gas emissions and states in the report titled Finland’s Integrated Energy and Climate Plan (Ministry of Economic Affairs and Employment, Ministry of the Environment, Ministry of Agriculture and Forestry, Ministry of Transport and Communications, Ministry of Finance, 2019): “The Government will work to ensure that Finland is carbon neutral by 2035 and carbon negative soon after that. We will do this by accelerating emissions reduction measures and strengthening carbon sinks. […] Electricity and heat production in Finland must be made nearly emissions-free by the end of the 2030s while also taking into account the perspectives of security of supply.” A possible solution to this would be growing biomass to be used as a raw material source for various end uses, such as transportation fuel, combined heat and power (CHP) or domestic use.

There are many benefits to using renewable energy sources, as it is a way of guaranteeing a safe, sustainable and easily accessible energy economy. Renewable energy emits in general far lower amounts of pollutants than fossil fuels. Burning of fossil fuels releases pollutants, such as carbon, nitrogen and sulfur dioxide, and contributes to climate change. Access to fossil fuels is also restricted, since they are buried underground or under the ocean floor. Locating and extracting the fossil fuels is also becoming more difficult and expensive and will continue to become more so as usage of fossil fuels increases. The price of oil is especially volatile and dependent on many factors. An increase in price can also have far-reaching consequences, such as the oil crisis during the 1970’s (Gopalakrishnan, et al., 2019).

Belyakov (2019) states that there are several reasons as to why biomass is an attractive source of energy. A key reason is that biomass is renewable and domestically available in many countries and sulfur oxide emissions are lower for biomass, since it naturally contains less sulfur than fossil fuels. Depending on climate and region, a large variety of crops that could allow for combinations with energy and food production could be grown. Biomass also has the potential to provide energy and energy-intensive products such as liquid, gaseous or solid fuels, chemicals and chemical feedstock as well as lumber, paper and other finished products and goods.

The purpose of this work is to investigate suitable plants for growth in the Finnish climate, their yield, different pretreatment technologies as well as further refinement of the biomass into a useable fuel. The amount of heat and power that could be produced from the energy crops or fuels derived from them is also investigated to see which crops should be grown based on the amount of energy obtained from them. The different end-products will also be discussed briefly. In this work, the region of Ostrobothnia on the west coast of Finland is used as the region where to grow the biomass. There are many companies working within the energy sector in the region. Thus, there should be know-how concerning how to most effectively utilize the biomass for energy production.

2 LITERATURE REVIEW

The following chapters will present different energy crops that can be grown in Finland as well as pretreatment options, methods for extracting energy from the biomass and different end products that can be achieved by using biomass as raw material.

2.1 Energy Crops

The following chapters will present different energy crops that can be grown in Finnish climate conditions. Focus has been placed on sources that involve growing energy crops in Finnish and Swedish climate conditions.

2.1.1 Straw

The straw of cereals such as barley, wheat, rye and oat that is left in the fields to decay after harvesting could be used as solid fuel or be gasified. Straw and wood-based fuels share some properties, for example, their elementary composition is quite similar. Both fuels also contain high volumes of volatile matters and, when combusted, burn with a tall flame which requires a large burning space. Unlike wood, however, straw has a low density, 30-40 kg/m^3 when loose and around 100-150 kg/m^3 when baled. Straw has a high ash content, low energy density and low ash melting temperature. The ash melting temperature varies greatly between cereal species, so combustion of straw requires a boiler grate which works with both melted and unmelted ash. If straw is to be combusted, a moisture content of 20% or less is recommended (Alakangas, et al., 2016).

The chemical composition of straw varies between species and is also affected by factors such as the age of the plant and cultivation conditions such as weather, soil type and fertilization. The time of harvesting also affects the composition of the biomass. If the straw is harvested early, so called yellow straw, the chlorine content can be four times higher than if it is harvested late (grey straw) (Alakangas, et al., 2016). Grey straw is straw that has been left in the field for some time after harvest and has been exposed to considerable amounts of rain after harvest. Minimizing the amount of chlorine in the straw is important in order to avoid corrosion in the boiler and pipes (Skøtt, 2011).

Table 1 Data for straw in Finnish climate conditions

Straw			Source
Average yield	t/ha/a	2	(Seppälä, et al., 2008)
Moisture content	%	17-25	(Alakangas, et al., 2016)
HHV	MJ/kg	18-19	(Parvez, Lewis & Afzal, 2021)
Ash content	%	4-12	(Parvez, Lewis & Afzal, 2021)

2.1.2 Willow

Willow is mostly grown for use as fuel in combined heat and power generation in plantations that are made up of closely planted fast-growing species of willow. There are around 300 different species of willow that grow in the Northern hemisphere, but only a few of these are suitable for use as short rotation crops. Crossbreeding between different willow species has been done since the 1970's to produce a hybrid that would be suitable for this kind of cultivation (Gustafsson, Larsson & Nordh, 2007). Characteristic for different willow species is their fast growth, high resprouting capacity (the ability to grow new shoots from the stump after harvesting), short breeding cycle, high genetic diversity, few pest problems, and most importantly, the potential for large biomass production. Willow plantations are typically managed as short rotation coppice, meaning that there are multiple harvests and regrowths from the same stump. Willow has so far been used mostly as solid fuel for heat and power generation but may in the future become a source for liquid and gaseous fuels as well (Nordborg, et al., 2018). According to Gustafsson, Larsson & Nordh (2007), willow can be planted close to its end user and in this way contribute to a local sustainable energy supply. A well-managed willow plantation can achieve 8-10 tons dry matter of willow chips per hectare per year, which equates to the energy contents of 4-5 m^3 of oil. Beside from their role as a fuel supply, willow plantations also serve the purpose of taking up nutrients from municipal wastes such as sewage sludge, sewage water, run-off water from landfills and ash from powerplants. The plants can also help with cleaning soil that has too high levels of heavy metals Gustafsson, Larsson & Nordh, 2007).

Sowing of willow is done in spring or early summer, usually between

April and June, and it is harvested in winter between November and April when the plant has stopped growing and the leaves have fallen off. Harvesting is done in intervals of 3-4 years and the overall lifespan of a plantation is 25 years or more. This means that the plantation can be harvested 5-6 times in its lifespan. After that the stumps can be removed and the area used for growing willows can return to normal agricultural use.

As other crops willow needs good care to grow well. The most important step to assure a good return on the crops is to make sure the establishment of the crops is done properly. Weeding is therefore important, as is fertilizing (Gustafsson, Larsson & Nordh, 2007).

According to Gustafsson, Larsson & Nordh (2007), the recommended pH-value of the soil for a willow plantation should be between 5.5 and 7.5. Clay-based earths are suitable for growing willow. With regard to field size, 5 hectares or greater is recommended. Preparation of the field is of utmost importance in order to get rid of couch grass and the best way to achieve this is by ploughing the field a year before willow is to be planted and treat the field with glyphosate-based herbicide during the summer. During autumn the field is to be plowed and if there are still weeds growing in the field during spring, then the field can be re-treated with more herbicide. Before sowing can start the field needs to be harrowed just like with other crops. It is recommended that the depth to which the field be harrowed is between 6-10 cm. To be noted is also that removal of stones from the field is important to avoid damage to the harvesting equipment.

The willows to be planted are one year old and are prepared in winter and are kept at -4 °C in a cold-room until the time that planting can begin in spring. A few days before planting begins the seedlings are taken out of the cold-room. It is important to keep the seedlings in a cool and shaded place during planting. Planting of the seedlings is done as previously stated between April and June., However, the earlier one is able to plant the seedlings, the greater their chance of good establishment and growth during the first year. Planting is done with a machine that cuts the seedlings to a smaller size, around 18 cm long and then plants them. They are then stuck down into the field so that only 1-2 centimeters are above ground, this helps prevent drying of the seedling. The total amount of seedlings planted per hectare are around 13 000. Because of this it is important to have a clear plan of how to plant the willows.

During the establishment phase weeding is of the utmost importance. Weeds compete with the willows for nutrition, water and light and if left unattended leads to the weakening of the willows and thus them growing slower. Before the seedlings start to sprout, preferably within a week of planting, it is recommended to spray the field with some kind of herbicide that prevents weed seeds from growing. As the effect of the herbicide subsides mechanical weed removal may be used. If the weeding has been successful during planting, there is no further need for chemical or mechanical weeding. A year after planting the willows will have developed a greater root system and are developing many new sprouts and thus shadowing the weeds. In the winter after planting, the willow sprouts are cut to facilitate the growth of a thicker clump.

Once the willows have established, fertilizing is needed, and it is mostly nitrogen that is needed. The amount of nitrogen needed varies with the age of the willows and the development of the sprouts. In older plantations the amount of nitrogen needed is less due to dead leaves giving of nitrogen (Gustafsson, Larsson & Nordh, 2007).

Harvesting is done when the willows exceed 25 tons dry matter per hectare or when the stem diameter of the thickest sprouts exceeds 6 cm, this usually occurs when the willows are 3-4 years old. Harvesting is done in winter when the leaves have fallen (Gustafsson, Larsson & Nordh, 2007).

There are a few things that can damage the willows. According to Gustafsson, Larsson & Nordh (2007), the most common source of damage to the willows are: frost, leaf beetles, fungi of the Melampsora family and to some minor extent being eaten by animals during the establishment-phase.

Table 2 Data for willow in Finnish climate conditions

Willow			Source
Average yield	t/ha/a	4.22	Based on (Tahvanainen & Rytkönen, 1999)
Moisture content	%	51-53	(Alakangas, et al., 2016)
HHV	MJ/kg	18.92	(Szyszlak-Barglowicz, Zając& Piekarski, 2012)
Ash content	%	1.3	(Parvez, Lewis & Afzal, 2021)

Figure 1 Salix (Swedish University of Agricultural Sciences, 2020).

2.1.3 Poplar

The *Populus* (poplar) genus includes between 40 and 100 species and 100 cultivars grown in the Northern hemisphere. According to (Nordborg, et al., 2018), characteristics for poplar species are fast growth, high survival rates and large production potential, and intensively managed poplar plantations have some of the highest growth rates in the world. Poplar cultivars are grown from cuttings, just like willow, which makes setting up a poplar plantation easy. Poplars usually require soil with a high moisture content, although there are species and hybrids that have different requirements for moisture. Poplars grown as short rotation wood crop have strict requirements regarding water, soil and weather. To ensure high productivity, a long growing period from June to September with an average temperature of 17 °C is required. The soil pH requirement for poplar is commonly between 5.5 and 7.5 but is dependent on species (Stolarski & Krzyżaniak, 2017).

Poplar is planted using cuttings that are about 20 cm long. These are obtained from parental plantations from 1 or 2-year-old shoots in winter. The cuttings are planted in early spring, as early as possible, and can stick 2-3 cm above ground or be level with the soil surface. The number of cuttings planted per hectare are 6600 to 10 000, though this depends on planting density. Poplar plantations can also be set up using live poplar stakes ranging from 1.3 to 2.5 meters in length and these are also obtained from 1 or 2-year-old shoots. The live stakes are planted to a depth between

0.4 and 0.6 meters with the rest of the stake sticking out. This method, however, decreases the planting density to 1100-1600 poplars per hectare.

The yield of poplar depends on species, soil type, weather conditions, harvest rotation, fertilization and other agricultural procedures. In Europe, the yields have been in the range of 1.6 to 1.9 tons dry matter per hectare per year. Depending on species, the poplar trees are harvested in rotations of 3-12 years (Stolarski & Krzyżaniak, 2017). Nordborg et al. (2018) claim that Swedish poplar plantations yield between 3 and 10 tons dry matter per hectare a year when measured from the ground to the top bud and including bark but excluding branches.

Table 3 Data for poplar in Finnish climate conditions

Poplar			Source
Average yield	t/ha/a	9.53	Based on (Johansson & Karačić, 2011)
Moisture content	%	45-60	(Nuamah, et al., 2012)
HHV	MJ/kg	18.79	(Telmo & Lousada, 2011)
Ash content	%	2.6	(McKendry, 2002)

2.1.4 Hemp

In their report, Malvisalo and Luotola, (2020), state that growing hemp has a long history in Finland, possibly dating back as far as 3000-5000 years ago. Hemp has traditionally been grown for its fibers and used as raw material for clothes, other textiles and ropes. Hemp seeds have also been used as food or animal feed. Growing hemp became common in Finland between 500 and 800 AD and became even more popular in the 1400 and 1500’s and reached its peak in 1700 and 1800’s when hemp was grown throughout the country. In the 20th century, growing hemp became less popular and was mostly grown in the middle and eastern parts of Finland. During the 1990’s, growing hemp became the subject of renewed interest and resulted in a new strain of oil hemp called Finola. As of 2017 the total area that was used to grow hemp in Finland was 540 hectares.

The entire hemp plant can be utilized as fuel; for the most part it is used in pellet and briquette form, but the plant can be burned as is in powerplants instead of peat. Hemp can also be used to make biogas and ethanol production from hemp is under investigation. Hemp is an excellent energy crop; its attributes are equal to or exceeds other common energy crops. Compared to other conventional fuels, combustion of hemp produces low sulfur emissions (Malvisalo & Luotola, 2020).

Studies show that during growth, hemp binds carbon dioxide much more effectively than trees and other commercial agricultural plants. A ton of stems can bind up to 1.63 tons of carbon dioxide and the leaves and roots bind 0.3 tons which returns to the soil as nutrients improving soil quality. This means, depending on the harvest, that 8-16 tons of carbon dioxide per hectare is bound in Finnish growth conditions. In comparison, forests bind between 2 and 5 tons per hectare depending on calculation methods (Malvisalo & Luotola, 2020).

Growing hemp as a preceding crop improves the harvest of subsequent crops and reduces the number of weeds, thus decreasing the need of herbicides. The root system has also been shown to improve the composition of the earth. Hemp is a good rotation or preceding crop that can be utilized as weed prevention or to absorb heavy metals from the earth. Studies have shown that hemp binds heavy metals to its leaves. Once the plant has grown to maturity, the heavy metals are removed when the plant is harvested (Malvisalo & Luotola, 2020).

In their report, Malvisalo and Luotola (2020), claim that the best types of soil for growing hemp are the ones that are a combination of earth and fine sand and clayey soil containing organic matter. The field where hemp is to be grown cannot be too dry or too wet, as hemp is quite sensitive to both conditions. With regard to soil pH-level, it needs to be at least 5.6 but for optimal growth of the plant 6.0-7.0 is recommended. Hemp can be sown using the same equipment that is used for cereals and should be done in May when the soil temperature is between 5 and 10 °C. the seeds should be sown to a depth between one and two centimeters. There is no need for herbicides; once hemp har started to grow, it will efficiently cast shadows on the weeds. In Finland, there are no known vermin that affect hemp but during rainy summers sclerotinia disease and grey mold may appear.

The fertilizer needs for hemp are nitrogen 80-150 kg/ha, potassium 60-100 kg/ha and phosphor 20-30 kg/ha. Manure is also a very good fertilizer; due to the long growth time of hemp the plant has time to utilize the nutrients efficiently. Though hemp may need plenty of nutrients, it does not deplete the soil of them as its deep root system makes the soil airier and lifts up nutrients for the next rotation of crops. The water demand of hemp is quite high during its growth season, 300-400 millimeters. It is at its greatest during July, when hemp grows at its fastest (Malvisalo & Luotola, 2020).

Prade et al. (2011) found two different harvesting periods depending on the end-use of the hemp: as feedstock for anaerobic digestion or combustion of the plant. If biogas is the desired end product harvesting of the hemp should be done between September and October and according to their findings an average yield of 14.4 t/ha are to be expected. The average moisture content of hemp which is to be digested was 69%. If the hemp is to be combusted, harvesting should be done between February and April and the harvests resulted in, on average, 9.9 t/ha. The average moisture content of hemp harvested in this time period was 29%. According to Malvisalo & Luotola (2020) hemp that is to be used as fuel can be harvested in autumn using a regular combine harvester, assuming that the plants are not too high. Harvest should be commenced when around 70% of the seeds have ripened. The strain of hemp grown in Finland for use as fuel produces 600-900 kg of seeds per hectare.

Table 4 Data for hemp in Finnish climate conditions

Hemp			Source
Average yield	t/ha/a	9.9—14.4	(Prade, et al., 2011)
Moisture content	%	30-75	(Prade, et al., 2011)
HHV	MJ/kg	19.1	(Prade, et al., 2011)
Ash content	%	1.5-8.5	(Parvez, Lewis & Afzal, 2021)

Figure 2 Industrial hemp plant (Parvez, et al., 2021)

2.1.5 Reed Canary Grass

Reed canary grass is indigenous to Finland. It is a perennial grass which has a high biomass yield. In its natural state it grows by the sea and lakes, on road verges and ditches. Reed canary grass grows in tussocks around one square meter or more and spreads easily. Harvests from the more promising varieties have been in excess of 10 tons per hectare dry matter. Fuel properties of reed canary grass are affected by the soil and growth site as well as the cultivar, fertilization and the time of harvest (Alakangas, et al., 2016). Furthermore, according to Jensen et al. (2018), reed canary grass is inexpensive to establish and fits existing farming practices, providing low risks and flexibility to farmers. Reed canary grass is also able to produce harvested biomass from late summer to early spring, producing biomass earlier than any other energy grass. It also tolerates a wide variety of management practices and as such has many usages: silage or hay production, pulp and paper, bedding or straw for livestock, soil conservation or as a source of biomass for energy conversion.

Reed canary grass is a tolerant grass capable of handling many stresses such as flooding, drought, grazing and freezing. For these reasons, it can be found growing in many different areas besides those mentioned by Alakangas et al. (2016); forest margins, pastures, and disturbed zones. Therefore, it offers great potential as a bioenergy crop, especially on marginal land, since it can grow well in both dry and wet areas. Wet soil is not a problem for reed canary grass, it grows extremely well in it. Aside from being tolerant of wet soils, it is also quite capable of growing in a wide pH-range of 4.9-8.2 (Jensen, et al., 2018).

Biomass from reed canary grass can be used in many energy conversion processes such as pyrolysis, combustion, anaerobic digestion and cellulosic ethanol production. Production and harvesting are affected by the intended end use of RCG. For example, when used for biogas production or forage, the crop needs to be harvested green. If used for biomass, delaying the harvest until spring is recommended, as the nutrient requirements of the succeeding crop are minimized. Lower moisture content as well as lower contents of ash, chloride, and potassium are a result of harvesting RCG later.

The establishment costs of RCG are low due to the fact that it can be established from seeds. Several days at a cool temperature are required for the seeds to germinate. Depending on the intended end use of RCG, different seeding rates are used, for forage production a seeding rate of 6-9 kg per hectare are recommended, whereas rates of 11-20 kg per hectare are recommended for bioenergy purposes. Sowing can take place in spring or autumn; higher yields have been reported from seeds sown between May and June than in September. After sowing, the field is usually rolled to conserve moisture in the seedbed and broadleaf herbicide is applied (Jensen, et al., 2018). Based on research done by Lewandowski & Schmidt (2006), RCG seems to react positively to nitrogen fertilization. Their research showed no inversion point for RCG yield when increasing amounts of nitrogen fertilizer were added.

Harvesting of RCG can be done with regular conventional agricultural machinery regardless of end-use scenario. Mowing and baling is the common method of harvesting RCG that is to be combusted, however, harvest losses can be great. Combinations of machinery can be used to minimize losses, such as the use of disc mowers without conditioners, followed by swashing with a rotary rake, reduced harvest losses compared to the use of mowers with conditioners. Dry matter yield decreases with cutting height, and cutting below 3.8 cm, which can be viewed as a maximum cutting height, may expose the crop to winter injury. Based on Jensen, et al. 2018, RCG harvests seem to vary between 12 and 21.5 tons dry matter per hectare.

Table 5 Data for reed canary grass in Finnish climate conditions

Reed Canary Grass			Source
Average yield	t/ha/a	9-10	(Lehtomäki, Viinikainen & Rintala, 2008)
Moisture content	%	10-60	(Jensen, et al., 2018)
HHV	MJ/kg	17.64	(Boateng, Jung & Adler, 2006)
Average ash content	%	3.0-8.5	(Parvez, Lewis & Afzal, 2021)

2.1.6 Miscanthus

Miscanthus is an East Asian perennial rhizomatous grass. Experiments have shown that it has a high biomass yield and have confirmed its outstanding low-temperature C4 photosynthesis. Today, it is a leading perennial energy grass in Europe due to the previously mentioned attributes. It was introduced to Europe from Japan by Danish plant collector Axel Olsen in the 1930’s (Lewandowski, et al., 2018).

The plant contains a high amount of holocellulose (cellulose and hemicellulose) and this makes it an excellent multipurpose feedstock for conversion to many different materials and for different uses in energy production systems. Diverse and promising hybrids of Miscanthus are currently being evaluated in different climate and soil types, including marginal lands, which are less suitable for food production. Aside from being used as fuel Miscanthus can be used for making paper, as animal bedding and as building material (Lewandowski, et al., 2018).

Miscanthus tends to propagate by rhizomes instead of seeds. The methods of planting miscanthus are direct planting of rhizomes, plugs of plants produced from rhizome cutting, nodes produced in modules, micropropagation and seeds. Currently, there are programs that are trying to produce viable seeds, as it is anticipated that the most effective way to scale up miscanthus production is to utilize seed-based establishment. Using seeds has the advantages of higher propagation rates, lower cost, farmers gaining quicker access to novel genotypes and phytosanitary safety. In colder climates, the establishment rate and reliability with plant plugs have been greatly improved by using mulch films that were originally produced for corn production (Lewandowski, et al., 2018).

Figure 3 Miscanthus rhizomes (Grace, 2021).

According to (Lewandowski, et al., 2018), Miscanthus offers a number of beneficial environmental aspects, one of which is the low requirement of herbicides for weed management and crop protection chemicals. Effective weed control is, however, important during the first year in order to avoid negative impacts on the establishment success of Miscanthus. Mechanical weeding can be done in the first year between the Miscanthus rows and, once the crop is well enrooted, the entire field. Most of the herbicides that are available for Miscanthus have been available for a few years and mostly originate from corn production. Once Miscanthus has established itself, it competes well with weeds, due to its rapid growth causing it to shade the ground beneath it.

With regard to nutrients, Miscanthus is a resource-efficient crop that efficiently recycles its nutrients. Fertilization recommendations vary greatly depending on nutrient offtake and soil conditions at the growth site. In their book, Lewandowski et al. (2018) quoted multiple results from experiments indicating that Miscanthus does not respond to nitrogen fertilization in a significant way.

Harvesting Miscanthus can be a labor- and fuel-intensive process depending on the chosen method of harvesting. The harvesting procedure affects the production cost, harvest yield and the overall environmental performance of the entire production chain. Self-propelled forage harvesters can be used for making Miscanthus chips in early spring (February-April) when the moisture content is below 20%. Miscanthus can also be harvested through mowing and baling. This harvest method has some advantages despite the additional operation: the harvester cuts the plants faster and uses less fuel than a chipper. If the Miscanthus is not dry enough, it can be left in the field to be aired and then baled for long-term storage. When compared to Miscanthus chips, bales have a higher density (150 kg/m^3 for chips, compared to 350 kg/m^3 for bales) and as such they are easier to transport.

Miscanthus can be combusted to produce heat, electricity, or combined heat and electricity. When used for heating purposes, it is used for direct firing of thermal power stations, in small-scale biomass burners and currently a new market is being developed for heating boilers using Miscanthus pellets. The suitability of Miscanthus biomass for combustion has some limitations due to its high chloride and potassium contents when compared to wood biomass. Miscanthus has a low ash melting temperature due to its high potassium content and the high levels of chloride may damage the boilers through formation of corrosive compounds. Ways for getting around the low ash melting temperature are using a fluidized bed for combustion and water-cooling the boiler grates. Harvest time plays a large part in the amount of inorganics that are present in Miscanthus-based biomass. In temperate climates, March has been found to be the optimal harvest time to provide biomass with low levels of moisture, chloride, potassium and ash (Lewandowski, et al., 2018).

Table 6 Data for miscanthus in Finnish climate conditions

Miscanthus			Source
Average yield	t/ha/a	8.7-13.7	(Clifton-Brown, Stampfl & Jones, 2004)
Moisture content	%	16	(Clifton-Brown, Stampfl & Jones, 2004)
HHV	MJ/kg	17.84	(Szyszlak-Barglowicz, Zając& Piekarski, 2012)
Ash content	%	2-7	(Parvez, Lewis & Afzal, 2021)

Figure 4 Miscanthus (Grace, 2021).

2.2 Biomass Composition

Lignocellulosic biomass is the largest source of renewable organic matter. All plants that have been mentioned in this work fall into this category. There are three major polymers that make up lignocellulosic biomass: cellulose, hemicellulose and lignin. In addition to these, lignocellulosic biomass also contains inorganic minerals, proteins and extractives (Mussatto & Dragone, 2016).

Cellulose is made up of a linear polymer chain that appears in an organized fibrous structure and is the main structural constituent of the cell wall of plants. Intra- and intermolecular hydrogen bonds in the structure of cellulose result in the creation of a rigid microfibril network that gathers together to constitute fibrils and then cellulose fibers. These aggregates of cellulose molecules appear as both amorphous and crystalline forms. The crystalline regions are more resistant to hydrolyzation than the amorphous regions and render the cellulose insoluble in most solvents by preventing chemical and enzymatic degradation. Cellulose becomes soluble at higher temperatures when the hydrogen bonds of the crystalline structure start to break down. It is also possible to dissolve cellulose in concentrated acids, but this causes degradation of the polymer by hydrolyzation (Mussatto & Dragone, 2016;

Peral, 2016).

Hemicelluloses are the second most common polymer of lignocellulosic biomass and are amorphous in structure. They are made up of a group of polysaccharides that bind to cellulose microfibrils by hydrogen bonds and to lignin by covalent linkages. Hemicelluloses are more thermally sensitive than cellulose and are easily hydrolyzed. At low temperatures, hemicellulose is insoluble in water, but its hydrolysis is possible at temperatures lower than those required for hydrolysis of cellulose. The solubility of hemicellulose in water can be improved by using acids or alkali.

Lignin is the third most abundant polymer in lignocellulosic biomass and is the most complex polymer in nature. It is an amorphous polymer. It can be found in cell walls of plants granting structural support, resistance to impact, compression, bending, impermeability and resistance against microbial attack and oxidative stress. It also plays an important part in the transport of water, nutrients, and metabolites in the plant cell. Depending on biomass, the composition of lignin varies greatly; lignin in hardwood has a different composition than that of lignin in soft wood or grass (Mussatto & Dragone, 2016; Peral, 2016).

2.3 Pretreatment

Pretreatment of lignocellulosic biomass is an essential step in in the conversion from feedstock to end product. The purpose of pretreating the biomass is to make the cellulose more accessible to enzymes so that hydrolysis can occur rapidly with high yields. The aim of pretreatment is to remove hemicellulose and lignin, reduce the crystallinity of cellulose and increase the porosity of the biomass. A good pretreatment of the feedstock must avoid the loss or degradation of carbohydrates and the formation of inhibitors to the following hydrolysis and fermentation processes. A good pretreatment should also promote the formation of sugars. The choice of pretreatment depends on for example, how the biomass components of cellulose, hemicellulose, and lignin are to be utilized (Mussatto & Dragone, 2016; Peral, 2016).Various physical, chemical and physiochemical pretreatment methods are presented below.

2.3.1 Physical Pretreatment

There are many physical pretreatment options for biomass. Peral (2016) lists the physical pretreatment options as follows: mechanical comminution, extrusion, liquid hot water, pyrolysis and torrefaction, freezing and irradiating. Some are more novel than others and are not in widespread use and will not be considered in this work. The lesser used methods are freezing of the biomass and irradiating the biomass and will not be covered.

Mechanical comminution

The aim of mechanical pretreatment is to improve the digestibility of biomass. This is done by cutting, shredding, chipping, milling or grinding to reduce the size of the biomass particles, increase the surface area, increase the pore size of the particles and the number of contact points. The starting materials are commonly pre-sized during harvesting or preconditioning by chipping, forage cutting or shredding to sizes between 10 and 50 mm. This is the minimum pretreatment required before biomass processing. The size of the biomass can further be reduced by grinding or milling by using hammers, knives, vibratory ball mills, balls, discs, colloids, and extruders to further reduce the size to 0.2-2 mm. Chipping of the biomass helps reduce limitations to heat and mass transfer. Milling and grinding are more effective at reducing the size of biomass particles and cellulose crystallinity. If maximum reduction of cellulose crystallinity is desired, usage of a vibratory ball miller is recommended over the use of a ball miller. Disk milling is a superior way compared to hammer milling in enhancing the hydrolysis of biomass. Factors that affect the digestibility of biomass are the kind of biomass used, duration and type of milling.

Mechanical pretreatment does have some drawbacks in terms of energy demand. The desired size of the biomass particles and the characteristics of the biomass determine the energy requirements for mechanical comminution. These are often very high. The energy requirements are affected by the initial moisture content in the biomass and composition of the biomass. The high energy demand makes mechanical comminution less attractive as an option for pretreating biomass. Combining chemical or biological treatments before mechanical pretreatment has shown that a reduction in process energy usage is possible (Peral, 2016).

Extrusion Pretreatment

With extrusion pretreatment the biomass is exposed to heating, mixing and shearing and suffering chemical and physical modification in the process. The softened surface regions of the biomass are removed by the shear forces in the extrusion process and exposing the interior to thermal and/or chemical action thus improving cellulose conversion. Screw speed, extruder temperature, feedstock particle size and moisture content are factors that affect the energy requirement. The main benefits of extrusion pretreatment are moderate temperatures, short residence time and the lack of inhibitor formation, rapid mixing, the feasibility for scale-up and the possibilities for continuous operation (Peral, 2016).

Liquid Hot Water Pretreatment

Liquid hot water pretreatments are known by many names: hydrothermolysis, hydrothermal pretreatment, autohydrolysis, solvolysis or steam pretreatment. LHW pretreatment changes the structure of the biomass by having hydro ions react with it and hydrolyzing hemicellulose and removing some of the lignin, making cellulose more accessible for further hydrolyzation while also avoiding the formation of fermentation inhibitors which occurs at higher temperatures.

Maintaining a pH-level between 4 and 7 is important, because at these levels the dissolved hemicellulose exists mostly in oligomeric form and the formation of degradation products that further catalyze the hydrolysis of cellulosic materials is minimized. Depending on biomass feedstock, the temperature of the pretreatment process can vary from 140 to 230 °C. At high temperatures, sugar degradation may increase significantly and between 40 and 60% of the biomass can be dissolved in the process, removing 4-22% cellulose, 35-60% lignin and most of the hemicellulose.

Water pretreatment is an interesting alternative to biomass treatment for many reasons, including, lacking the need of catalysts, resulting in an environmentally safe process. The cost of pretreatment reactors can be kept low, because there is a low risk of corrosion when using water pretreatment instead of acid pretreatment. The entire process is simplified because of lower temperatures and the minimization of degradation products means there is no need for neutralization or a final washing step, because the pretreatment solvent used is water. Also, as a consequence, there is no acid recycling or sludge handling. From an economic standpoint, the low cost of the solvent is an advantage for large-scale applications. The greatest disadvantage with LHW is related to downstream processing: the concentration of product is lower than with other pretreatment options. This way of pretreatment has high energy requirements due to the volumes of water involved in the process (Peral, 2016).

Pyrolysis and Torrefaction

Pyrolysis is a thermal pretreatment method where biomass is heated in an inert atmosphere at temperatures between 350 and 650 °C and is usually used to improve the energy density of biomass-based fuels. The nonoxidizing atmosphere is usually provide by nitrogen gas. Process conditions for torrefaction are similar, however, the temperatures are lower: 200-300 °C. As a result, torrefaction is occasionally called mild pyrolysis. Besides temperature, time is also an important factor in determining the performance of thermal pretreatment, as the length of thermal pretreatment can vary from a few minutes to hours.

At temperatures above 300 °C, cellulose decomposes to gaseous products and char. Decomposition is slower at lower temperatures and the resulting products are less volatile. Hemicellulose is almost completely depleted under severe conditions and cellulose is largely oxidized. The most difficult component to degrade is lignin and as such its removal is very low during torrefaction conditions. Following thermal pretreatment, the properties of biomass are greatly improved. The main benefits of thermal pretreatment are the more uniform properties of biomass, resulting in better grindability, reactivity, higher energy density and lower moisture content (Peral, 2016).

Dayton and Foust (2020) state that pyrolysis is an option for producing liquid transportation fuels; the end product does, however, depend on factors such as temperature, pressure and residence time. Flash (fast) pyrolysis optimizes liquid products which are known as bio-oils. They are a mixture of multiple components derived mostly from the fragmentation and depolymerization reactions of cellulose, hemicellulose and lignin.

2.3.2 Chemical Pretreatments

Some chemical pretreatment options are presented in the following chapters.

Acid Hydrolysis

Treatment of lignocellulosic biomass with strong acids such as HCl and H_2SO_4 are good options in promoting the hydrolyzation of cellulose. By using strong acids there is no need to use enzymes to reach acid hydrolysis and obtain fermentable sugars. Using acids as a pretreatment option has benefits such as flexibility in feedstock choice, mild temperature operation conditions and high monomeric sugar yield. These positive aspects are however overshadowed by the fact that acids are corrosive, toxic and hazardous making this pretreatment option very expensive.

One of the most commonly used acid-based pretreatment options is dilute acid pretreatment due to its high efficiency. Almost all of the hemicellulose is removed and recovered by using dilute acid pretreatment, leaving the cellulose more accessible to further hydrolysis. This pretreatment is especially suitable for treating biomass with a low lignin content as the removal of lignin is insignificant as the lignin is retained in solid matter. Sulfuric acid is commonly used due its effectivity and low cost. However, acids such as nitric acid, hydrochloric acid and phosphoric acid are also used. Organic acids such as fumaric and maleic acid can also be used if inorganic acids cannot be used. Acid treatments can be divided into two types: low temperature and batch process that can be used for high-solids loading at temperatures below 160 °C or high temperature and continuous flow process for low-solid loadings with temperatures exceeding 160 °C.

There are some downsides to using dilute acids: the formation of fermentation inhibiting compounds that have to be neutralized, adding cost and possible waste disposal issues depending on the neutralization method chosen. Also, expensive alloys are needed for constructing the reactor due to the high temperatures involved and the corrosive nature of acids. Maintenance costs are also high with this kind of pretreatment system. Acid recovery costs are also a disadvantage because they are high, this is however a necessity to keep the process economically feasible. The expensive treatment costs and environmental problems caused by waste streams have led to the of other pretreatment options (Peral, 2016).

Alkaline Hydrolysis

Some bases are also suitable for pretreatment of lignocellulosic biomass. Suitable pretreatment agents are potassium, sodium and calcium hydroxides. Often lime (calcium hydroxide) or sodium hydroxide is used. The biomass is soaked in the solution and mixed at a mild temperature for some time. Compared to other pretreatment technologies alkali pretreatment is carried out at lower temperatures and pressures and can even be carried out in ambient conditions but doing so requires a very long processing time ranging from hours to days instead of minutes. The alkaline agent disrupts the lignin structure and breaks the links between lignin and other carbohydrates. The reactivity of the remaining polysaccharides is increased with the removal of lignin. Adding nitrogen or air to the mixture greatly improves the removal of lignin. Condensation of lignin is prevented by the low severity of this process, resulting in high lignin solubility if biomass with a low lignin content is used. The mild conditions of alkaline pretreatment mean that there is very little degradation of the sugars to other compounds such as organic acids. When compared to acid pretreatments, there is less sugar degradation (Peral, 2016).

According to Dayton and Foust (2020), using ammonia in a process called ammonia fiber expansion can also be used as an alkaline pretreatment option. Biomass is soaked in liquid ammonia at high pressure and moderate temperature. The ammonia causes the lignocellulosic biomass to swell, it alters the lignin structure and depolymerizes the cellulose. By rapidly decreasing the pressure, the ammonia is released, the fibers are disrupted and a substrate with much higher porosity is left. This high porosity enhances the efficiency of enzymatic hydrolysis to give high sugar recovery. Since ammonia vaporizes at lower pressure recovery of it is simple. A drawback to using ammonia as a pretreatment option is that effectiveness is decreased for biomass with high lignin content.

When using the alkaline pretreatment methods presented by Peral (2016) a neutralizing step is needed before enzymatic hydrolysis. The neutralizing step causes salts to be formed and need to be removed or recycled.

When using lime pretreatment slurrying the lime with water is necessary. The slurry is then sprayed on the biomass and the biomass is then stored or heated for a period of time. This can take a very long time, so an alternate method is to perform this kind of pretreatment in a closed reactor where temperature and flow can be controlled. The lime involved can be recycled. Alkaline pretreatment is most effective when the feedstock consists of biomass with low lignin content (Peral, 2016).

Organosolv Pretreatment

Pretreating lignocellulosic biomass with organosolvents involves the use organic or aqueous solvent mixtures with inorganic acid catalysts such as HCl or H_2SO_4. Salicylic, acetylsalicylic or oxalic acids are organic acids that can also be used as catalysts. Common solvents are ethanol, methanol, acetone and ethylene glycol. Organosolv pretreatment is usually carried out at temperatures up to 200 °C and high pressure.

The solvent hydrolyses lignin and lignin-carbohydrate bonds. Lignin is removed to a great extent; hemicellulose is almost completely solubilized, and cellulose remains in solid form. Using organic acids in pretreatment accelerates the delignification process and hydrolysis of cellulose and dissolution of lignin via the dissociation of hydrogen ions. In this case, adding a catalyst at high temperatures is not needed. A large part of soluble carbohydrates is further broken to byproducts that are inhibitory to fermentation.

There are many benefits of using organosolv pretreatment. One benefit is that organic solvents are able to separate three fractions: dry lignin, an aqueous hemicellulose stream and a relatively very pure cellulose fraction. Using this pretreatment option also makes it possible to produce high-quality sulfur-free lignin with high purity, which can then be processed into specialty chemicals. Using organosolvents is the only physiochemical pretreatment method for pretreating lignocellulosic material with a high lignin content. Reduction of the feedstock size is not required to achieve satisfactory cellulose conversion making this pretreatment option less energy intensive.

Disadvantages when using organosolv pretreatment are the use of flammable organic solvents at high temperatures, operating the process requires containment vessels. Due to explosion hazards and health, environmental and safety concerns, no leaks can be tolerated. In order to reduce costs, the solvents need to be recovered from the reactor, evaporated, condensed and recycled. Doing so is necessary because the solvent may inhibit the growth of microorganisms, subsequent hydrolysis and anaerobic digestion or fermentation. This pretreatment option is more costly than other pretreatment options due to the catalysts and chemicals involved (Peral, 2016).

2.3.3 Physicochemical Pretreatments

Steam Explosion

The most common physiochemical pretreatment method is steam explosion. The biomass feedstock is treated with saturated high-pressure steam followed by rapid decompression. Consequently, an explosive reaction takes place resulting in lignin matrix disruption and hemicellulose degradation. The crystallinity of cellulose may decrease, and substrate surface may increase, improving cellulose digestibility. Biomass that has been physically pretreated (ground, chipped or raw preconditioned) is treated with high pressure steam at temperatures between 160 and 260 °C and pressures of 0.7-4.8 MPa. To promote hemicellulose hydrolysis the pressure is held from a few seconds to minutes before the biomass is exposed to ambient pressure. Resulting from the treatment, hemicellulose is hydrolyzed by acetic acid generated in the process and solubilized in the liquid phase, lignin becomes depolymerized and the cellulose in the solid fraction becomes more accessible, increasing the digestibility of the feedstock. The results are dependent on temperature, residence time, moisture content and particle size. Adding acids or alkali can help improve the results.

Benefits of this pretreatment option are the possibility to use feedstock with coarse particle size, thus removing the need for preconditioning it to be suitable for this process, the lower energy input for pumping and mixing of substance after steam explosion pretreatment. There are also no chemicals involved, which makes this an environmentally safe process. This also has the added benefit of cutting costs related to recycling. The sugars formed in this process have a high degree of recoverability because of their low dilution. The soluble carbohydrate-rich stream can be easily removed and used to make high value-added products.

Downsides of using steam explosion pretreatment are the generation of fermentation and enzyme inhibitors during the pretreatment and their removal adds extra costs to this process. Another negative aspect is the incomplete destruction of the lignin-carbohydrate matrix, resulting in the possibility that components precipitate or condensate. An efficient isolation of lignin and cellulose components must be carried out, depending on the subsequent product lignin may need to be removed completely. Pretreatment of biomass feedstock with steam explosion requires high amounts of energy and also involves elevated running costs (Peral, 2016).

2.4 THERMAL CONVERSION OF BIOMASS

Direct Combustion

When combusting biomass the heat released can be used to produce electricity via the Rankine cycle. Depending on the condition and combustion properties of the fuel, different firing parameters and furnace designs can be selected to ensure optimal uptime or efficiency (Mandø, 2013). Bajpai (2020) states that combusting biomass is the simplest way to obtain heat and is an extensively used method, because technologies used for fossil fuels can be implemented in biomass combustion as well. It is possible to increase the overall efficiency of the combustion process by producing district heat in conjunction with power. This is known as a combined heat and power (CHP) plant and can reach efficiencies of up to 90% for cogeneration (Mandø, 2013).

Mandø (2013) presents three wood fuels: wood chips, wood pellets and torrefied wood. Woodchips which are not dried prior to combustion contain large amounts of moisture. Moisture evaporates as the chips are burnt, but the energy required to evaporate the moisture in the fuel cannot typically be recovered. Maintaining combustion of fuels with a moisture content of 55 wt-% or more is difficult, and the water content of the fuel also impacts on the heating value of a fuel: More moisture in the fuel equals a lower heating value for it. The amount of water in the fuel also affects the combustion time and thereby extends the residence time in the furnace.

Wood pellets, basically dried wood with a moisture content below 10%, have a significantly higher heating value than woodchips. The moisture content in wood pellets cannot usually be lowered beyond 10%, since they will absorb moisture from the atmosphere. Wood pellets should be stored indoors to avoid the absorption of moisture into the pellets. This is a slight disadvantage when wood pellets are used to replace coal, as coal can be stored outside since it contains very little moisture and does not absorb much moisture either. It is important to monitor the moisture content and temperature of the wood pellets during storage, as these can indicate the onset of bio-decomposition.

Torrefaction of wood is done to evaporate moisture and lighter volatiles from the fuel. This is an upgrade when compared to pelletization of the wood. During torrefaction hydroxyl groups, which are responsible for absorbing moisture, are removed from the fuel with the result that torrefied wood can be stored outside and will not absorb moisture, just like coal.

The content of volatile matter is significantly higher in biomass than in coal. The volatiles are also released at a lower temperature and more rapidly than coal, resulting in biomass having a lower ignition temperature. When designing the air supply special attention is needed to ensure that the amount of oxygen supplied to the combustion process is sufficient, since the volatile matter is released faster, and insufficient oxygen may delay combustion. The volatiles are released as gas when heat is applied and combust when they mix with oxygen. The gaseous volatiles are combusted quickly when compared to the combustion of charcoal and a high ratio of volatiles in the furnace decreases the residence time of the fuel. The remaining charcoal will be reduced to ash during burnout (Mandø, 2013).

Emissions

Pollutants and other waste products from combustion are a major concern for power generation by biomass firing. In order to meet government legislation regarding emissions, extensive flue-gas cleaning is required. The pollutants formed when biomass is combusted are similar to those formed during combustion of coal and include particle matter, hydrocarbons, carbon monoxide, NO_X and SO_X. There are many different technologies available for reducing emissions. The amount of fine particles in the flue gas can be reduced by using electrostatic precipitators and bag filters. Dry and wet scrubbers can be used to clean SO_X from flue gases and if a fluidized bed is used for biomass combustion, adding dolomite or limestone can help to reduce SO_X emissions. Emissions resulting from incomplete combustion can be reduced by managing the air-to-fuel ratio and by designing the reactor so that residence time and temperature are optimal for complete combustion. Boilers for biomass combustion are often based on boiler designs for coal combustion and some problems may arise as a result of this, due to differing combustion patterns of biomass. This may lead to incomplete combustion and poor operating conditions in general. Suspension firing of biomass in particular is a case where changes to combustion patterns are to be expected due to the larger particle size of biomass, different composition of biomass compared to coal and more extreme particle morphology of the biomass particles.

One of the biggest concerns with combustion systems in general, regardless of fuel, is the emission of NO_X gasses. NO_X can be formed in many ways: fuel NO_X originates from the nitrogen bound in the fuel, thermal NO_X is formed as a result of high temperature reactions between gaseous oxygen and nitrogen and prompt NO_X forms following a reaction between gaseous hydrocarbon radicals and nitrogen. NO_X emissions depend on both fuel and firing conditions. In general, biomass fuels contain less nitrogen than fossil fuels, which helps to reduce NO_X emissions. Nitrogen content in the fuel naturally varies from one type of biomass to another.

If the fuel of choice is based on straw or grasses, which contain chlorine, acidic gasses such as HCl need to be taken into consideration. Not only are they corrosive to the combustion system but they are also corrosive air pollutants. Large chlorine and other halogen fractions are also promoters of furans and dioxins.

When using biomass as fuel for combustion the release of CO_2 is less of a concern due to the short circulation time from when the fuel is burnt to when the gas is reabsorbed by plants. This is the main reason why biofuels are considered CO_2 neutral (Mandø, 2013).

Fouling

Deposition of ash particles and condensing gasses on the heating surfaces of a boiler is called fouling. Deposition on the heating surfaces inside the boiler is called slag. Heat transfer rates will diminish as a result of fouling and depending on the composition of the deposit, may also cause significant corrosion on the heating surfaces. In extreme cases sever slag build-up may lead to boiler damage if pieces of slag break off and fall to the bottom of the boiler. Fouling is typically dealt with by using soot blowers which regularly clean the heating surfaces using water. Fouling is not a problem for the furnace wall heating surfaces in a fluidized bed due to the abrasion of the bed material but fouling of convection passes still occur. Compared to coal, biomass has a different chemical composition and this effects the rate of deposition and composition of the deposition which may be much more detrimental to the performance of the boiler when compared to a coal-fired plant. Wood and wood-derived fuels do not cause notable fouling problems which has led to their widespread use as a substitute for coal. Herbaceous fuels, on the other hand, cause deposition problems at moderate to high temperatures due to their high amounts of alkali metals, silica and chlorine (Mandø, 2013).

Agglomeration

When ash melts and sticks together agglomeration occurs, causing de-fluidization in fluidized bed boilers and transport problems in grate-fired boilers. Melting of phosphorous and potassium salts are what cause agglomeration and it is also promoted by the presence of calcium and silica in the biomass. Especially in fluidized-bed boilers agglomeration is a very serious problem which has to be dealt with to avoid down-time. There are different strategies for dealing with the agglomeration problem: pre-treatment of the fuel, coating the sand particles to prevent them from reacting with silica, using alternative bed materials and using additives to prevent the formation of salts. Additives which are typically used are: limestone, dolomite, kaolin and magnesite. Usage of these materials has however given rise to new problems such as higher attrition and entrainment rates, chemical stability and plugging of air nozzles and windbox. These problems make the new materials less attractive to use than sand. (Mandø, 2013)

Corrosion

Corrosion problems are mostly caused by the buildup of corrosive species such as metal chlorides on the heating surfaces inside the boiler. In addition to acting as a barrier for heat transfer, fouling of the heating surfaces may destroy the boiler. The composition of the deposit, heating surface material and the temperature of both the deposit material and the heating surface will impact the severity of corrosion. Biomass combustion causes extensive fouling of heating surfaces. Grasses, straws and other herbaceous plants contain high levels of alkalis, which are potentially corrosive elements when deposited on heating surfaces. As previously mentioned, temperature is a factor in corrosion; if the temperature rises above the melting point of chlorides, the corrosion process may be accelerated to a great extent (Mandø, 2013).

2.5 THERMOCHEMICAL TREATMENT OF BIOMASS

Biomass can be used to produce many different end-products, but the focus of this section is on the use of biomass as a fuel without treatment and using biomass to produce fuels. According to Belyakov (2019), the major ways in which biomass can be prepared for use as fuel or raw material are: preparation of solid fuel through pelletization, chipping, and sorting and separation. Gasification, pyrolysis or anaerobic digestion are also possible preparation and treatment options depending on the desired end product.

Gasification

A gasifying agent, such as air, carbon dioxide, steam or mixtures of these, is used to partially oxidize biomass at high temperatures (600-1000 °C). This forms a gas called synthesis gas, syn gas for short, which is a mixture of combustible gases such as carbon dioxide, methane, and hydrogen. The resulting gas can be used for many purposes, for example as boiler fuel, as an energy source and as raw material from which to produce hydrogen as well as used in the production of methanol and ethanol. (Belyakov, 2019; dos Santos & Pereira, 2021).

Regardless of the type of gasifier used, the main steps in gasification of biomass are: drying of the biomass particles, pyrolysis, or devolatilization, of the biomass in order to remove the volatile compounds that make up 70-86% of the dry biomass, partial oxidation of pyrolysis gases and possible char and finally gasification, also called reduction, of char (Roddy & Manson-Whitton, 2012; Richardson, et al., 2015).

Pereira and Martins (2017) have divided the gasifier into four zones where these steps occur and explained more in detail what happens in each of them. In the drying zone, the temperature is between 100 and 200 °C to evaporate the moisture from the biomass. The biomass particles are not altered chemically by the drying process. The moisture content affects the operation of the gasifier as well as the composition of the syn gas. The type of gasifier used limits the moisture content of the biomass. Pyrolysis starts to occur at 250-600 °C and is the thermal decomposition of the biomass without oxygen or air taking part in the process. As a result, different organic and inorganic gases are released. When the fuel starts pyrolyzing the water vapor, tar and different non-condensable gases are separated from the solid part producing the residual carbon consisting of ash and char. About 80-95% of the original mass in the liquid-phase products, such as water, oils, tar and various gas-phase products, comprising non-condensable gases, are converted during pyrolysis, leaving 5-20% of char. The make-up of the gaseous and solid products during the pyrolysis step is correlated with the weight loss of the feedstock and is dependent of factors such as fuel particle size, temperature, heat rate and the residence time of the gaseous components. Pyrolysis can be divided into two stages: primary and secondary. In the primary stage, the chemical bonds are broken due to the temperature increase, releasing condensable and non-condensable gases and char. In secondary pyrolysis, the volatiles are cracked a second time and form non-condensable gases and char. If these remain in the feedstock for long enough, additional char and gases may be formed when the oil vapors are cracked. However, if removed quickly from the reaction area the oil vapor can escape into the gas phase before being cracked and can be condensed outside to bio-oil or tar. In the reduction stage, the reactions take place without oxygen because it takes place in the combustion process. The reduction reactions are endothermic and take place between 800 and 1000 °C. In the reduction zone char reacts with the hot gases and is converted into a gaseous product. It is at this stage where the combustible gases are formed; charcoal and hydrogen are combined with carbon to form methane and carbon monoxide is formed from carbon dioxide. The combustion zone of the gasifier is established by oxygen input into the reactor. The char and volatiles that were formed at the pyrolysis stage are partially oxidized leading to a rapid increase in temperature exceeding 1100 °C. The combustion reactions are swift and mainly produce water vapor and carbon dioxide. The heat caused by combustion is used in the drying and pyrolysis zones (Pereira & Martins, 2017).

The composition of the resulting gas depends on many parameters such as the temperature of the pyrolysis stage, residence time, pressure and the feedstock. After these steps comes the proper gasification process which, by utilizing higher temperatures, cracks the tars and hydrocarbons in the pyrolysis gas stream and char is partially oxidized. Carbon is converted to carbon monoxide and hydrogen in a reaction called the water gas reaction, which utilizes the water vapor from the original biomass to react with the carbon (Roddy & Manson-Whitton, 2012; Richardson, et al., 2015).

Gasification Technologies

A wide range of gasifiers have been developed around the world, each tailored to different feedstock materials, different requirements for syngas and different scales. Three basic types of gasifier design are used, depending on circumstances, and their main differences are mainly: from where the biomass is fed into the gasifier, how it is moved around (via gas flow or through gravity), operating temperature (especially whether it is above or below the char/ash melting point), operating pressure and the oxidant used (air, steam or oxygen) (Roddy & Manson-Whitton, 2012).

In a fixed bed gasifier, the fuel bed needs to have good permeability due to the fact that gas flows relatively slowly through it. This means that crushed or pulverized feedstock is to be avoided and lumpier feedstock should be utilized. When biomass is used as feedstock, air is most commonly used as the oxidant although oxygen can also be used. There are two main types of fixed bed gasifiers, updraft and downdraft. Fuel is added from the top in both gasifiers. In an updraft gasifier the oxidant is added from the bottom and the resulting syngas exits from the top of the gasifier. With this setup the biomass and gases move in opposite directions resulting in some of the falling char burns and provides heat. The downdraft gasifier reverses this by having the oxidant be inserted from the top or the side and the resulting syngas exits through the bottom of the gasifier. The biomass and gases move in the same direction in this case. As the biomass falls some of it is burnt resulting in the formation of a hot charcoal bed. Due to their relative simplicity both of these reactors are suitable for smaller scale facilities. Due to high charcoal burnout and good internal heat exchange updraft gasifiers have high thermal efficiency. They can also accommodate feedstock with higher moisture content since the upwards gas flow dries the biomass from its entry point. Syngas produced this way has a relatively low temperature meaning that it is suited for gas clean-up units. Furthermore, the power range for which an updraft gasifier can be configured is wide; from 10 kW_e to over 30 MW_e. A major disadvantage with updraft gasifiers is the fact that the tarry gas from the pyrolysis zone has to pass out in the syngas, and as such produce many times more tar than downdraft gasifiers, 100 g Nm^{-3}compared to 1 g Nm^{-3} for a downdraft gasifier (Roddy & Manson-Whitton, 2012).

This low tar generation is the major advantage of downdraft gasifiers. The disadvantages of downdraft gasifiers when compared to upwards gasifiers are higher particulate carryover, slightly lower gasifier efficiency (which is due to the relatively high temperature of the exiting gases), scale-size limitations, and tighter feedstock quality constraints in terms of moisture content and particle size. This leads to it often being necessary to briquette or pelletize the biomass. Configuration of the gasifiers throat is critical to ensure tar destruction. This has the effect of constraining the maximum size of the gasifier to around 8-10 MW_{th} (and often smaller than this) (Roddy & Manson-Whitton, 2012).

Unsteady operation or periods of part-load operation may lead to excessive tar formation. Before restarting a fixed bed gasifier care needs to be taken to ensure that all combustible gases have been vented. Other common problems with this type of gasifier are high temperature corrosion and fuel blockages. Flow maldistribution may cause the syngas to be nonuniform (Roddy & Manson-Whitton, 2012).

The fluidized bed was invented in 1926 by Winkler for large-scale coal gasification. Crushed solid fuel particles of biomass are used suspended together with a much larger mass of a fine inert bed material (this can be dolomite, silica sand or even the ash from the burnt biomass) in high gas flow. New particles are fed and mixed with particles already undergoing gasification. The four stages; drying, devolatilization, gasification and combustion are not stratified as in a fixed bed gasifier but occur simultaneously. The temperature in the gasifier is relatively low at around 900 °C or less, which means that reactive feedstocks can be used. Some fluidized gasifiers have been designed to be used while pressurized. Since high volumes of gas are required for fluidizing the fuel particles these types of gasifiers are commonly air-blown, although oxygen-blown gasifiers do exist. The tar levels for fluidized bed gasifiers are usually between those of up- and downdraft gasifiers, around 10 g Nm^{-3}. An external heat source is needed at start-up to bring the sand up to temperature. During normal operation a part of the biomass is combusted in a controlled flow of oxidant in order to maintain the bed temperature. Thanks to the intensive mixing in the bed resulting in good heat exchange and high reaction rates, the size of fluidized bed gasifiers is more compact. Since they are able to operate at lower temperatures fluidized bed gasifiers are more resistant to biomass feedstocks that have ash with a lower melting temperature or highly corrosive ash. Incomplete carbon burnout is a drawback that is caused by the range of residence times of individual particles (Roddy & Manson-Whitton, 2012).

In bubbling fluidized bed gasifiers biomass is fed from the side while air, steam or oxygen is being blown upward through the bed at a flow rate that is just enough to keep the biomass agitated. Pyrolysis in this kind of gasifier is faster than in fixed bed gasifiers due to better mixing. The temperature in bubbling fluidized bed gasifiers is, according to Pereira and Martins (2017), between 800 and 1000 °C. The gasifier can be operated under atmospheric pressure or pressurized. If the reactor is designed with a larger head space above the bubbling bed the result of this design choice is a lower level of tar in the resulting syngas. As a result of particle attrition in the fluidized bed the level of particulates can be high. A cyclone is used at the syngas exit to catch particles of char and ash. Bubbling bed fluidizers have been run on many types of biomass feedstock and have proven to be quite tolerant of moisture content and particle size variation because of the mixing quality. Bed agglomeration is one of the main risks with bubbling fluidized bed gasifiers. This can occur if biomass feedstocks with too low an ash melting temperature are used (Roddy & Manson-Whitton, 2012).

When using a circulating fluidized bed, the biomass is fed in from the side. The velocity of the oxidant is higher in order to keep the biomass feedstock suspended with the particulates being returned to the fluidized bed via a cyclone and siphon. This type of gasifier can be operated pressurized if the syngas usage downstream requires pressure. The higher velocity of the oxidant leads to high particle concentrations as a result of particle attrition. An important design element to be noted is that the gasifier needs to be erosion tolerant due to the high velocity of the particles in the gasifier. A circulating bed fluidizer can easily switch between feedstocks as long as the particle size is below 20 mm. Bed material and ash are separated by the cyclone and returned to the reactor. Circulating bed fluidizer are particularly suitable for gasification of biomass when the size of the particles is hard to control; smaller particles are gasified in their first pass into the reactor while larger particles remain behind until they are sufficiently consumed to be carried over to the external recycle loop. Carbon burnout is better with this kind of gasifier than in bubbling fluid bed gasifiers (Roddy & Manson-Whitton, 2012).

The dual fluidized bed utilizes two separate but linked circulating bed fluidizers for combustion and gasification. Biomass is fed to the gasifier and converted into syngas and char by using steam as oxidant. Suspended sand and char drop into the combustor where the char is burnt in air. The velocity of the air needs to be sufficient enough to keep the heated sand particles suspended and drive them through the cyclone. The hot particles are returned to the gasifier by the cyclone while releasing syngas. Using steam as oxidant not only boosts the hydrogen content of the resulting syngas but also increases its methane content. The main advantage of using a dual fluidized bed gasifier is the ability to optimize combustion and gasification separately., and the ability to produce syngas with a relatively low amount of nitrogen by using air instead of oxygen during combustion (Roddy & Manson-Whitton, 2012).

Characteristic of an entrained flow gasifier is that the biomass particles and gas flow in the same direction rapidly with a very short residence time in the reactor. This type of gasifier can also be used with slurries or atomized liquid feedstocks. This type of gasifier is the most common technology used for gasifying coal and has been in use since the 1950's. As the processing temperature of this type of reactor is high, they discharge their ash as fused and molten slag. The slag that is formed works as a heat and corrosion layer on the inner walls of the reactor. A suitable flux, for example limestone, is added to control the viscosity of the liquid slag. Oxygen is the most commonly used oxidant in this kind of gasifier. Because biomass cannot be slurried, the use of entrained flow gasifiers is quite uncommon when biomass is the feedstock of choice. (Roddy & Manson-Whitton, 2012).

Supercritical water gasification is a promising new technology that can be used to convert wet biomass, water content over 70%, into a methane and hydrogen rich syngas. The operating parameters of a supercritical water gasifier are a temperature in excess of 374 °C, and a pressure over 22 MPa (the supercritical condition for water) (Pereira & Martins, 2017). At these conditions water has unique properties, being something like a gas and liquid. This means that the physical-chemical properties of supercritical water are partially that of a liquid and partially that of a gas. Under supercritical conditions physical-chemical properties such as viscosity, density, ion product and dielectric constant are different from those of water in gas or liquid phase. The density of SCW is in between that of liquid water and gaseous water. Viscosity of SCW is low and implies higher diffusion coefficient values of water which allows for higher reaction rates. The dielectric constant of SCW is low, close to that of many nonpolar solvents. This means that SCW is a good solvent for nonpolar organic compounds and is capable of solubilizing undesirable gasification products such as tar. The ability to solve polar inorganic compounds decreases significantly which may lead to fouling problems in the reactor due to precipitation of these salts. A variety of biomasses, including lignocellulosic biomass and forest residue have been successfully gasified in supercritical water gasifiers. The biomass is almost completely gasified under supercritical conditions and the cleavage products are dissolved in the supercritical water minimizing the formation of coke and char. During supercritical water gasification the main component of biomass, cellulose, is hydrolyzed at temperatures above 200 °C resulting in the formation of fructose, glucose and oligomers. This stage has high productivity and is swift. Thereafter acids, phenols, furfural and other intermediates are formed from soluble carbohydrates. They are then decomposed into hydrogen, methane, carbon monoxide and carbon dioxide. (Pereira & Martins, 2017). The usage of catalysts improves the efficiency of supercritical water gasification. The reaction rate can be increased, and the temperature decreased. By decreasing the reaction temperature, the equipment and operating costs of SCWG are decreased. Catalysts also increase the hydrogen yield and conversion rate of the biomass (Heidenreich, Müller & Foscolo, 2016).

2.6 BIOCHEMICAL CONVERSION

Converting biomass to energy through biochemical processes is the most well-known and tested method, even at an industrial level. Biological conversion methods can be divided into two methods: anaerobic digestion and fermentation (Tursi & Olivito, 2021).

2.6.1 Anaerobic Digestion

Anaerobic digestion is a multi-step biochemical reaction that uses several types of microorganisms that do not require oxygen to live. The product of this reaction is biogas, which is mostly comprised of methane and carbon dioxide. Complex organic matter, such as proteins, fats and carbohydrates, are broken down by specialized microorganisms into molecules with a smaller atomic mass, which are soluble in water, such as amino and fatty acids and sugars. The end product of this process is biogas: mostly methane and carbon dioxide. This entire process can be broken down into four steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Kirk & Gould, 2020).

The first step in anaerobic digestion is hydrolysis. Biomass is generally comprised of very large organic polymers, proteins, carbohydrates and fats, and it is through hydrolysis that these polymers are broken down into smaller molecules such as amino acids, fatty acids and simple sugars. Some of the products of hydrolysis, including acetate and hydrogen can be utilized later by the methanogens later in the digestion process. The majority of these large molecules must, however, be further broken down in the next step, acidogenesis, so that they can be utilized in the creation of methane (Kirk & Gould, 2020).

Acidogenesis, or fermentation, is the step in which acidogenic microorganisms further break down the biomass products following hydrolysis. The acidogenic bacteria create an acidic environment in the digester while also producing hydrogen, ammonia, carbon dioxide and hydrogen sulfide. Aside from these, other products formed during this step are volatile fatty acids, carbonic acids, alcohols and small amounts of other by-products. While acidogenic bacteria further breaks down the organic matter, it is still unusable and too large for methane production. The next step in breaking down the organic matter is acetogenesis. (Kirk & Gould, 2020)

Many of the products created in the acidogenesis step are catabolized by acetogens and form acetic acid, hydrogen and carbon dioxide which are then used by methanogens to create methane. (Kirk & Gould, 2020)

In the final step of anaerobic digestion; methanogenesis, the methanogens create methane from the final products of acetogenesis, as well as from some of the intermediate products from hydrolysis and acidogenesis (Kirk & Gould, 2020).

2.6.2 Fermentation

Fermentation can be divided into two categories, photo and dark fermentation. These methods ae mostly used to produce hydrogen from biomass. Vaishali and Debabrata (2018), state that suitable biomass feedstocks for fermentation are ones based on sugar-rich plants such as Miscanthus. Before use in fermentative processes some pretreatment of the feedstock is needed in order to remove lignin and saccharification of the crystalline cellulose present in lignocellulosic crops. Lignocellulosic biomass may be in abundance, but the aforementioned steps increase the operational costs and limits the usage of it as feedstock.

Dark Fermentation

According to Antonopoulou et al. (2011), dark fermentation is a fermentation process that is carried out under anaerobic conditions in the absence of light. This process is directly related to the acidogenic step in anaerobic digestion. A wide variety of bacteria, such as facultative or obligate anaerobes, are able to convert organic matter to carbon dioxide, hydrogen and metabolites; volatile fatty acids (Wukovits & Schnitzhofer, 2009). Dark fermentation is an effective and viable method, because it is carried out at ambient pressure and temperature (Antonopoulou, et al., 2011).

The energy conversion efficiency of dark fermentation is rather low, due to solvents and volatile organic acids being obtained as co-products and remaining in the effluent of the reactor as unused sources of carbon. Increases to the conversion efficiency can be done by degrading the coproducts in a consecutive step to generate more hydrogen via photo fermentation or methane via anaerobic digestion (Wukovits

& Schnitzhofer, 2009).

Process conditions have a large effect on the production of hydrogen. Factors such as hydraulic retention time, pH and the partial pressure of hydrogen all influence the metabolic balance. Hydrogenase enzyme activity is sensitive to pH to the extent that the mediums pH affects the specific production rate and hydrogen yield, as well as the types of organic acid formed. Temperature affects the metabolic activity and growth rate of the bacteria and an increase in temperature increases hydrogen production. Production rates and hydrogen yields of thermophilic bacteria (which grow at temperatures exceeding 60 °C) often show higher values compared to mesophilic bacteria (bacteria which grow at ambient temperatures). Under carefully chosen conditions thermophilic bacteria produce 83-100% of the maximum theoretical output of hydrogen (Wukovits & Schnitzhofer, 2009).

Hallenbeck, Lazaro & Sagır (2019), state that there are several limiting factors with regards to dark fermentation. Hydrogen yield and production rate being much lower than the theoretical maximum is a drawback. To improve hydrogen yields a secondary system should be added since dark fermentation alone cannot utilize all compounds in the feedstock resulting in alcohols and organic acids going unused unless a secondary system is added that can make use of the remaining products. The second step could be a methanogenic reactor for the production of methane or a photo fermentative system for hydrogen production.

Photo Fermentation

Photo fermentation converts organic matter into biohydrogen and carbon dioxide, just like dark fermentation. The major difference compared to dark fermentation is that photo fermentation requires light to happen. Photo fermentation is used to convert short-chain organic acids to hydrogen by utilizing purple nonsulfur bacteria. Photo fermentation uses photoheterotrophic bacteria, the bacteria evolve hydrogen catalyzed by nitrogenase under nitrogen-deficient conditions using simple organic acids and light. There are a few reasons why photo fermentation is an attractive way of producing hydrogen, the first being that there is no oxygen involved in photo fermentation so there is no inhibition to hydrogen production caused by oxygen. Other reasons are the high theoretical conversion yield and the ability to use light of a wide spectrum to decompose organic acids to hydrogen and carbon dioxide (Wukovits & Schnitzhofer, 2009).

The major disadvantage of this way of fermentation is, however, the need for a large surface area with which to collect sufficient light energy. This is due to the low photochemical efficiency of the photo fermentative process. The need for light in this process also leads to a day-night cycle which means that hydrogen production is not continuous. Reactor design is also something of a technological challenge since the reactor needs to offer optimal surface-to-volume ratio and an even distribution of light within the reactor (Wukovits & Schnitzhofer, 2009).

Combined Biological Treatment Processes

Since these conversion processes are inefficient by themselves, Wukovits and Schnitzhofer (2009), suggest a combination of the previously mentioned biological processes to improve efficiency. They presented two combinations: dark fermentation combined with anaerobic digestion and dark fermentation combined with photo fermentation.

Combining dark fermentation with anaerobic digestion of the volatile organic acids and solvent coproducts would produce hydrogen and methane. If hydrogen is the desired product, a reforming step could be included to convert the produced methane into hydrogen.

Dark fermentation combined with photo fermentation would allow for the conversion of feedstock containing carbohydrates to hydrogen and carbon dioxide that would otherwise not be achievable due to thermodynamic limitations (Wukovits & Schnitzhofer, 2009). Hallenbeck, Lazaro & Sagır (2019), suggest that by growing dark fermentative bacteria (DFB) and photo fermentative bacteria (PFB) in the same reactor simultaneously the hydrogen yield can be improved. This would work by using the organic acids formed by DFB as substrate for the PFB resulting in complete substrate utilization and thus improving hydrogen yield. The use of this kind of co-culture could also lead to a decrease in the total reactor volume, a reduction in fermentation time and lowering the costs of operating the reactor due to a simpler operation process.

2.7 REFINEMENT AND FINAL PRODUCTS

The previously mentioned treatment methods can, as discussed in the chapters before, produce a variety of products that can be used as such or be further refined and utilized.

2.7.1 Syngas

Synthesis gas is, as previously stated, manufactured through the gasification of biomass and can be combusted as boiler fuel or utilized as raw material in the production of hydrogen gas, methanol and ethanol.

Refining the syn gas is often done with the Fischer-Tropsch process which is, briefly described, the production of liquid hydrocarbons from carbon monoxide and hydrogen by using transition metal catalysts. Before further refinement, the synthesis gas has to be cleaned of contaminants to avoid problems downstream in the process, namely catalyst poisoning. Common contaminants to be removed are tars, particulates and acidic gases such as sulfur. Tars are problematic since some synthesis applications, such as chemical or fuel production, require the syngas to be cooled. When the gas is cooled the tars start to condense on the cool surfaces and may lead to plugging, fouling of pipes or the formation of small aerosol droplets. Tars can also affect the reforming catalyst used by deactivating it. Overall process efficiency may also decrease due to tars having a high energy content. Tars are not a problem if the syngas is going to be directly used for combustion. Tar removal is often done by cooling the syngas and physically removing the condensed tar by using wet scrubbers or electrostatic precipitators. Catalytic and thermal methods for tar removal are also employed and may involve the recirculation of tars back into the gasifier where they are broken down to form gas and energy. (Evans & Smith, 2012)

Particulates are solid particles of ash in the gas stream which can potentially damage equipment downstream. Removal of particulates is also often needed to comply with emission regulations. Particulates are often removed by using either barrier or cyclonic filters. Cyclonic filters are used to remove the bulk of particulate materials from the gas stream. They are used in the first removal step in gasifier systems and can handle gases of varying temperature ranges. Removal of tars and alkali metals is also a possible use case for this type of filter. Barrier filters are made up of a range of porous materials which allow gas to pass through and may either be rigid, bag or packed bed constructions. When gas passes over the barrier, particulate materials are blocked and cannot go through the barrier. Barrier filters are most commonly used for removing smaller diameter particulates and are used after cyclonic filters. Barrier filters are not suitable for use with wet sticky materials such as tars, since they tend to block this type of filter. Finer particulates can be cleaned up using electrostatic filters and wet scrubbers (Evans & Smith, 2012).

2.7.2 Biogas

Biogas is formed during anaerobic digestion and is a mixture of carbon dioxide and methane. Anaerobic digestion was originally used as a method of waste treatment but can also be used to produce biogas and biohydrogen from energy crops (Stamatelatou, Antonopoulou & Michailides, 2014). There are many uses for biogas; it can be burnt to produce heat, generate electricity, and used as fuel for vehicles. The most common use case for biogas is to combust it in CHP plants. To improve the quality of biogas it has to be upgraded to ensure that it meets the requirements of the gas appliances where it is to be used. Upgrading the biogas improves its quality and heating value. Upgrading the biogas usually involves removing CO_2, water, H_2S and trace gasses from the biogas. Removal of CO_2 is done utilizing either physical or chemical technologies. Most commonly, carbon dioxide is removed through either absorption or adsorption. In absorption processes it is possible to remove both CO_2 and H_2S simultaneously. The most common solvent used for countercurrent scrubbing of pre-compressed biogas is water. CO_2 and H_2S are released in a flash tank after pressure scrubbing is completed, and the pressure is reduced, and the temperature increased in the tank. Almost complete absorption can be achieved if $Ca(OH_2)$ solutions are used to remove both CO_2 and H_2S. This results in the formation of the insoluble $CaCO_3$ and CaS. Another way of removing CO_2 and H_2S from the biogas is to use organic solvents or alkali amines, since the gases are more soluble in the chemicals than the methane in the biogas. This method makes low pressure operation possible; the chemical, however, needs to be regenerated with steam. Carbon dioxide can also be removed by using pressure swing adsorption on solids such as activated carbon. Using molecular sieves is also possible. High temperature and pressure are generally required to achieve adsorption. This process does require dry biogas, making water vapor removal a necessary step if this method is to be utilized. Removal of carbon dioxide is also possible by cooling the biogas at elevated pressure to at least -78 °C; at this temperature, CO_2 becomes a liquid and can removed. This method is costly and, therefore, it is only in limited use (Borja & Rincón, 2017).

Water is removed from the biogas by means of physical or chemical technologies: adsorption, absorption or condensation. Design of the pipework is also a common method to condense the water, refrigeration is another method. Silica gel or aluminum oxide can be used for adsorption of water. Absorption of water can be done with glycol or hygroscopic salts (Borja & Rincón, 2017).

According to Borja & Rincón (2017), sulfur removal from biogas can be done by chemical precipitation, adsorption, absorption or membrane separation. The common adsorption module for sulfur removal is based on two parallel adsorbent modules packed with activated carbon or Fe_2O_3, $Fe(OH)_3$or ZnO. This method of chemical adsorption has become popular due to its simplicity, high efficiency and fast oxidation kinetics. Microorganisms of the Thiobacillus family can also be used to remove sulfides from biogas. The microorganisms oxidize them to mainly elementary sulfur and some sulfates. The simplest method of desulfurization is to add air or oxygen directly into the digestion chamber, doing so reduces the hydrogen sulfur levels by up to 95%. Safety measures have to be taken into account when adding air or oxygen to biogas, since methane is explosive in the range of 5-15% air. Biofiltration of hydrogen sulfur is mostly implemented in biotrickling filters due to their efficient gas–liquid mass transfer, easy control of operational variables and cost effectiveness. Biotrickling filters used for desulfurization are packed bed columns. Membranes can also be used for removing hydrogen by using membranes that are permeable to hydrogen sulfur but not to methane, thus separating the two.

Removal of siloxane from biogas is important, as it has a tendency to form microcrystalline silica when combusted. The silica gradually coats the combustion equipment and can lead to serious damage, if not properly removed from the gas. Removal is done by either adsorption or absorption. Adsorption-based cleaning technologies include using activated carbon, which can only be used for treating dry biogas. Molecular sieves can also be used as well as polymer pellets. Silica gel in particular has proven to be a promising treatment method, since it also dries the biogas. Absorption of siloxane is done by utilizing non-volatile organic solvents. An alternative method is chemical abatement using acidic- or caustic-catalyzed hydrolysis of the silicon-oxygen bond (Borja & Rincón, 2017).

2.7.3 Biohydrogen

Biohydrogen can be produced through biological conversion of biomass or thermochemically. Syngas produced through gasification can be converted to biohydrogen by steam reforming. Bio-oils resulting from fast pyrolysis can also be reformed to biohydrogen. The bio-oil is reformed by using steam, heat and a noble metal as catalyst. This produces synthesis gas, which can then be reformed to biohydrogen. Biohydrogen is produced through the water-gas shift reaction with steam and involves the carbon monoxide in the syngas reacting with the steam to produce carbon dioxide and hydrogen. Two types of reactors can be used for this: low- or high temperature shift reactor. After the water-gas shift reaction, gas mixtures with high contents of hydrogen are obtained. Before the hydrogen can be used as fuel or a chemical, purification is needed. This is done by a pressure swing adsorption system with a series of columns in which the gas mixture is successively pressurized and depressurized. This separates the hydrogen from the other gases (Kumar & Sarkar, 2011).

Biochemical production of hydrogen is done via dark or light fermentation and direct or indirect biophotolysis. Light fermentation does not have a high hydrogen yield due to limited substrates and the requirement for a large reactor area. Dark fermentation, however, seems to be a more effective method for producing hydrogen from biomass, since it is not restricted to the feedstock suitability requirements of light fermentation nor the complex and expensive reactor design associated with light fermentation (Stamatelatou, Antonopoulou & Michailides, 2014).

2.7.4 Bioethanol

Bioethanol can be produced from many different feedstocks with lignocellulosic biomass being the most promising. Karimi and Chisti (2017), have described bioethanol production as having four steps: preparation of feedstock, fermentation of sugars to ethanol, distillation and finally dehydration to obtain anhydrous ethanol. Pretreatment of the feedstock depends on the sort of feedstock. Lignocellulose is the most abundant and cheapest source for fermentable sugars.

Producing ethanol from lignocellulosic biomass is much more difficult than from starch- or sugar-rich materials. Pretreatment of lignocellulosic biomass usually involves milling the biomass into smaller, more uniform particles which are then often subjected to dilute acid pretreatment, which is often considered the most cost-effective way of pretreating lignocellulosic biomass that is to become ethanol. Treating the biomass with acid also yields other high-value chemicals such as furfural and aldehydes. Steam explosion is also a viable method for pretreating the biomass (Capodaglio & Bolognesi, 2019).

Halder and colleagues, (2019) have presented some technological challenges with producing ethanol from lignocellulosic biomass. Pretreatment of the feedstock is both energy- and cost-intensive because some of the chemicals used in pretreating the biomass are difficult to recycle and pose environmental and health hazards. The possibility of enzymatic inhibition is also a potential problem since they can hamper the fermentation or hydrolysis process. Some form of detoxification is needed to be added to the ethanol production process. Selecting the most suitable enzyme for hydrolysis and suitable microorganisms for fermentation is also a technical challenge. In order to ensure that the process is cost-effective, the concentration of sugar has to be at a high enough level in the hydrolysate, since lignocellulosic biomass can in some cases produce a low concentration of sugar in the hydrolysate.

Bioethanol can also be produced from syngas. Doing so has the advantage of being able to use the lignin portion of the lignocellulosic biomass. There are two ways of producing ethanol from syngas: metal-catalytic (Fischer-Tropsch) or biocatalytic. After the synthesis gas has been filtered, the gas is heated to 300 °C and the pressure is raised to 69 bar before it enters the reaction chamber. The gas is also mixed with methanol and water to improve the yield of higher alcohols. This mixture is then passed through a synthetic catalyst to obtain ethanol, methanol, other higher alcohols such as pentanol, methane and water. The reaction rate of this process is high, with over 60% of the carbon monoxide converting to ethanol. The gas is then cooled, allowing the alcohols to condense and separate from the unconverted synthesis gas. The condensed alcohols are then refined further by alcohol separation and purification steps. The most promising metal catalyst for converting syngas to ethanol appears to be Rhodium (Vohra, et al., 2014).

Ethanol can also be produced by fermenting the syngas. The advantages of using this process are lower temperature and pressure requirements. This can often be done at atmospheric conditions, and this process is less susceptible to varying compositions of the feed gas. As with the previous method, the gas is cleaned and it is in contrast to the previous method, cooled to ambient temperature and stored at high pressure. The clean and cool gas is then fed into the ethanol conversion chamber where the gas is fermented by microbes into ethanol and acetic acid. Once fermentation is complete, the liquid is distilled to ethanol from the other formed products. The ethanol is then dehydrated to make it fuel quality ethanol. There are some drawbacks with this method for ethanol production, a major drawback being the low productivity of this process. Other factors such as inhibition of the biological catalyst by the products, the inability of the process to yield only the desired product and low gas-liquid mass transfer need to be addressed before this method of ethanol production can become economically feasible (Vohra, et al., 2014).

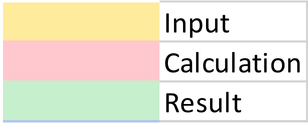
2.7.5 Biodiesel

Biodiesel can be made from synthesis gas by using the Fischer-Tropsch process. There are two classes of Fischer-Tropsch technology, low temperature and high temperature. Low temperature FT operates at temperatures between 200 and 240 °C and uses a cobalt-based catalyst and produces mostly linear paraffins with a small fraction of oxygenates and olefins. High temperature FT, in contrast, operates at 300-350 °C and uses an iron-based catalyst and is mostly used to produce liquid fuels. Both iron and cobalt catalysts can be used in low temperature FT. The feedstock also dictates, to some extent, which catalyst should be used. A fixed bed or slurry reactor is used as the synthesis reactor. There are several types of biomass which can be used for making FT-liquids. The biodiesel produced via FT is very similar to fossil diesel in terms of energy content, flash point and viscosity (Bezergianni & Dimitriadis, 2013; Lappas & Heracleous, 2016).

3 MATERIAL AND METHODS

Using the data found in the literature review for different energy crops, an Excel spreadsheet was prepared, which was used to calculate values needed in the comparison of combustion of the biomass and anaerobic digestion of the biomass and combustion of the resulting biogas. The cultivation area used for growing the energy crops in the calculations represents 10%, about 19 570 ha, of the cultivated area in Ostrobothnia. The cultivated area in Ostrobothnia was on average 195 700 hectares between 2013 and 2020, based on data from the Natural Resources Insitute Finland, (2021). According to the same source, the area used to grow grains, such as wheat and rye, was in the same time period, on average 99 180 ha. As shown in Table 1, the average straw yield is 2 t/ha/a and according to Bentsen, Nilsson & Larsen (2018), the amount of straw that should be harvested from the field is between 15 and 60% to ensure that there are enough nutirents left in the field.

The data in the tables in the Theory chapter was used as input data in the calculations. The file uses color-coded cells for different meanings.



🟨	Input
🟥	Calculation
🟩	Result

Figure 5 Explanation of the cell colors.

The equation used for calculating the lower heating value, (LHV when used, in the Excel-file), of the various biomasses was done by using Equation 1, which was used by Alakangas et al. (2016), in their work.

$$q_{p,net,ar} = q_{p,net,d} \times \left(\frac{100-M_{ar}}{100}\right) - 0.02443 \times M_{ar} \qquad (1)$$

$q_{p,net,ar}$ is the lower heating value of the biomass at a certain moisture content,

$q_{p,net,d}$ is the higher heating value of dry matter

M_{ar} is the moisture content in the fuel

0.02443 is a correction factor for the vaporization of water at constant pressure at 25 °C, MJ/kg per 1 weight-% of moisture.

Biogas yields are presented in the table below.

Biomass	**Yield(m³/1000 kg VS)**	**Source**
Hemp	355–409	(Kulichkova, et al., 2020)
Reed Canary Grass	340-430	(Kulichkova, et al., 2020)
Miscanthus	179-218	(Kulichkova, et al., 2020)
Willow	0.13-0.37	(Raposo, et al., 2012)
Poplar	0.23-0.42	(Raposo, et al., 2012)
Straw	242-324	(Kulichkova, et al., 2020)

Raposo et al. (2012) presented their findings for the biogas yields of poplar and willow in mL CH_4/g VS, so their values had to converted to m^3 CH_4/1000 kg VS.

To simplify the calculations, the conversion of biomass to biogas was assumed to be 1. The biogas yield presented in the results was calculated by using the theoretical yield of the energy crops, subtracting the ash content from it and then multiplying the results with the average biogas yield (based on the values in Table 7). The result obtained is the biogas yield in m^3/ha/a. The fuel yield ,(MWh/ha/a), is calculated by using the energy content of methane in kWh/m^3 and multiplying that with the biogas yield.

When calculating the results, average values were used when an interval of values for different parameters, such as heating value, biogas yield or moisture content of the biomass, were presented in the source materials.

When calculating the average yield of willow, areas 20 and 21 were chosen from research done by Tahvanainen and Rytkönen (1999), because the areas were the closest to Ostrobothnia.

With regard to the amount harvestable of the theoretical crops yield a loss of 10% was assumed stemming from various harvesting-related inefficiencies. This combined with the moisture content of the biomass when used was used to calculate the biomass yield at operational moisture.

The Excel-file can be found in Appendices.

4 RESULTS

Using the data obtained from the literature review and the resulting calculations, the following results were obtained for the energy potential of various energy crops. If the biomasses were combusted the amounts of energy presented in Tabell 7 could be extracted.

Tabell 8 Fuel yields of the plants and heat and power yields from their combustion

COMBUSTION

BIOMASS		Hemp	RCG	Miscanthus	Willow**	Poplar***	Straw, 15% left in the field	Straw, 60% left in the field
Fuel yield	MWh/ha/a	44.69	40.88	48.65	17.18	38.37	7.59	3.57
Fuel yield, Ostrobothnia	GWh/a	874.67	799.98	952.23	336.23	751.02	148.5	69.88
Biomass Combustion								
Efficiency (CHP)	%	85	85	85	85	85	85	85
Heat and power to the end user	MWh/ha/a	37.99	34.74	41.36	14.60	32.62	6.45	3.04
Heat and power to the end user	GWh/a	743.47	679.98	809.39	285.80	638.37	126.22	59.40

**Harvested once every three years

***Harvested once every 10-15 years, assumption: 15 years

If the biomasses were to be combusted the best alternative would be to combust Miscanthus which would generate 809 GWh/a of heat and power, followed by hemp with 743 GWh/a and reed canary grass with 680 GWh/a. The values for poplar and willow are 638 and 285 GWh/a respectively. Combustion of the straw, a byproduct from food production, would generate between 59 and 126 GWh/a, depending on the amount of straw left in the field for soil improvement purposes.

Values for anaerobic digestion and combustion of the resulting biogas are presented on the next page.

Table 9 Biogas yields of the plants and heat and power yields from combustion of the resulting biogas

ANAEROBIC DIGESTION

BIOMASS		Hemp	RCG	Miscanthus	Willow**	Poplar***	Straw, 15% left in the field	Straw, 60% left in the field
Biogas yield	MWh/ha/a	50.91	35.63	21.66	3.43E-03	2.01E-03	4.69	2.21
Biogas yield, Ostrobothnia	GWh/a	996.33	697.33	423.87	0.07	0.04	91.72	43.16
Biogas Combustion								
Efficiency (CHP)	%	85	85	85	85	85	85	85
Heat and power to the end user	MWh/ha/a	43.27	30.29	18.41	2.91E-03	1.71E-03	3.98	1.87
Heat and power to the end user	GWh/a	846.88	592.73	360.29	0.06	0.03	77.97	36.69

**Harvested once every three years

***Harvested once every 10-15 years, assumption: 15 years

If the biomasses would be used as feedstock for anaerobic digestion and the resulting biogas was combusted, hemp would be the best alternative, it could generate 846 GWh/a of heat and power, followed by reed canary grass with 592 GWh/a and Miscanthus with 360 GWh/a. The values for poplar and willow are 0.06 and 0.03 GWh/a respectively. Anaerobic digestion of the straw would generate between 36 and 77 GWh/a, depending on the amount of straw left in the field for soil improvement purposes.

5 DISCUSSION

The amount of heat and power that could be produced from the energy crops or fuels derived from them was investigated to see which crops should be grown based on the amount of energy obtained from them. Based on the calculations the best option for combustion is Miscanthus, which could produce 809 GWh/a. If anaerobic digestion and burning of the resulting biogas is preferred, then hemp is the best option, producing 846 GWh/a of heat and power. The conversion of biomass to biogas was assumed to be one. In reality, however, this is not the case, and as such the yield of biogas would be lower.

The impact of transportation on the overall energy efficiency of using biomass was not considered. Transporting loose biomass, such as straw, for long distances is not economical. Lindh et al. (2009), researched the transportation of reed canary grass and found that the transport distance from field to plant should be between 20 and 120 kilometers to be economically feasible. This could possibly also be the case for other biomasses presented in this thesis.

To give some scope to the results: Vaskiluodon Voima in Vaasa produces between 0.9 and 1.7 TWh/a of electricity and 400-480 GWh/a of district heat (Vaskiloudon Voima, 2021). Another powerplant in the region, Westenergy, combusts municipal waste to produce heat and power. Their CHP production in 2020 was 402 GWh heat and 89 GWh power (Westenergy, 2021).

Based on the calculation presented in the Results section it could be, at least theoretically, possible to switch to utilizing only energy crops in the production of heat and power.

6 CONCLUSIONS AND RECOMMENDATIONS

In Ostrobothnia, approximately 195 700 hectares of land is cultivated, and 99 180 hectares are used for grain production. Of the entire cultivated area 10% was assumed to be land of poorer quality and could be used for growing energy crops. Fallow land could also be an alternative area for growing energy crops since, on average, 16 000 hectares of land is in fallow based on (Natural Resources Institute Finland - Statistics service, 2021) and is quite close to the area used in the calculations.

Based on the calculations, some energy crops are better suitable to be combusted than anaerobically gasified. Miscanthus seems to be well suitable for combustion, as does hemp. Willow and poplar should also be combusted due to their poor performance when used as feedstock for anaerobic digestion. Hemp seems to the best choice for anaerobic digestion, based on the calculations.

The effects of growing energy crops on farmland used for food production should be investigated to make sure that the energy crops do not compete with food crops and impact the food supply in a negative way. Another area of investigation should be the availability of enough marginal land not suitable for food crops, that could be used for growing energy crops instead, and how large the area of the marginal land should be since marginal land is not necessarily as nutrient rich as farmland.

The literature used in this thesis only gave an alternative harvest yield for hemp when it would be used for feedstock for anaerobic gasification. Since the biomasses can be harvested green if they are to be digested, they have a higher moisture content and therefore the biomass yield is higher than when they are to be combusted. Because of this, the results obtained for anaerobic digestion of hemp are significantly higher than for other energy crops presented in this thesis.

The effects of pretreatment of the biomass was not taken into account in this work and is something that merits more study, since it may have a significant impact on the amount of energy that can be obtained from both combustion and of the biomass and the biogas resulting from gasification. Willow and poplar did not yield large quantities of biogas, since wood based biomass is not easily digested in anaerobic conditions, pretreatment of them might improve the results.

The cost of growing these plants was not considered in this study.

Research should be done into which energy crops would the most economical as a whole to grow. The effect of fertilization was not considered in this work and therefore there exists the possibility that using fertilizers when growing the energy crops, the yields could improve. Other areas which merit more research are the transportation of the biomasses from the fields to the power plant and how the biomass should be stored and what challenges need to be overcome with the transport and storage of biomass.

POTENTIELLA ENERGIGRÖDOR OCH DERAS UTNYTTJNINGSTEKNIK I ÖSTERBOTTEN

Det finns ett ökande behov att ersätta fossila bränslen med miljövänligare alternativ för att minska mängden växthusgaser som förorsakas av användningen av fossila bränslen. Detta betyder att användningen av förnyelsebara energikällor måste öka. Ett möjligt sätt att uppnå detta är att odla biomassa som kan användas som råmaterial för att tillverka olika bränslen eller användas i olika former för att producera elektricitet och fjärrvärme. Biomassan som odlas måste vara av en art som tål de varierande förhållanden i Finland, måste ha hög avkastning per hektar och måste relativt lätt kunna konverteras till bränsle av något slag. Österbotten har valts som exempelområde eftersom det finns många företag i regionen som är aktiva inom energisektorn och det torde därför finnas kunskap för att mest effektivt utnyttja biomassan för energiproduktion.

Halm av olika sädesslag som råg, korn, vete och havre kan vara möjliga energikällor. Halm kan förbrännas eller förgasas och har väldigt liknande kemisk sammansättning som trä. Halm har ene hög askhalt och låg asksmältningstemperatur och är därför något problematisk att förbränna.

Vide är ett snabbväxande trädslag som kan producera stora mängder biomassa och används oftast som fast bränsle men kan även vara en källa för bränslen i gas- och vätskeform. Avkastningen från en välskött videplantering kan vara upp till 10 ton torrsubstans per hektar. Vide är förutom en möjlig energikälla också en växt som förbättrar och renar marken från föroreningar som tungmetaller.

Poppel är ett trädslag som är snabbt växande och har stor biomassa produktionspotential. Etablering av en poppelodling är enkelt eftersom den kan planteras på många olika sätt, till exempel som sticklingar eller som plantor. Det flesta poppelarter kräver en jordmån med hög fuktighet men det finns arter som klarar av torrare jordtyper. Avkastningen från en poppelodling beror på arten, jordmånen och väderleken.

Hampa är en växt som har långa odlingsanor i Finland, det kan ha odlats här för upptill 5000 år sedan. Hampa har traditionellt odlats för sina fibrer och har använts för att tillverka rep, kläder och andra textiler. Hampfrön har använts som föda eller djurfoder. Hampa kan användas som fast bränsle i form av pellets eller briketter men den kan också förbrännas utan förbehandling istället för torv. Biogas- och etanoltillverkning ur hampa är något som undersöks. Jämfört med andra energigrödor är hampa ett utmärkt alternativ eftersom dess egenskaper är ofta bättre. Under tillväxtfasen binder hampa koldioxid i sig effektivare än träd och andra jordbruksväxter.

Rörflen är en gräsart med stor avkastning av biomassa. Det är en billig växt att etablera och kräver ingen specialutrustning att skörda. Rörflen mognar tidigt och det är möjligt att skörda det redan tidigt på våren. Förutom energianvändning kan det också användas som djurströ, råmaterial för papper eller som djurfoder.

Miscanthus är ett släkte av olika gräsarter från Ostasien med hög av kastning och god förmåga att klara sig i kalla klimat. Förutom bränsle kan växten användas för att tillverka papper, djurströ och byggnadsmaterial.

Alla växter som presenterats i detta arbete är lignocellulosiska och är uppbyggda av polymererna cellulosa, hemicellulosa och lignin. För att kunna använda lignocellulosisk biomassa är någon form av förbehandling ofta ett nödvändigt steg i processen. Förbehandlingsmetoderna kan delas in i fyra kategorier: fysisk, kemisk, biologisk och fysikalisk-kemisk. Vilken metod som väljs beror på till exempel förhållandet av cellulosa, hemicellulosa och lignin i biomassan.

Fysisk förbehandling förbättrar biomassans smältbarhet genom att minska partikelstorleken genom att mala, krossa, beskära och värma. Kemisk förbehandling använder sig olika kemikalier för att förstöra de kemiska banden i biomassan. Fysikalisk-kemiska metoder innebär användning av ånga för att förändra den kemiska sammansättningen av biomassa och göra den mera lämplig för förädlingsprocessen.

Den förbehandlade biomassan kan konverteras till energi eller bränsle genom följande konverteringsmetoder: termisk, termokemisk, biokemisk, anaerobisk och jäsning. Termisk konversion av biomassa är förbränning av den och användningen av den frigjorda värmen för att producera elektricitet genom Rankine-cykeln. Termokemisk konversion innebär förgasning av biomassan i höga temperaturer med hjälp av ett förgasningsämne, till exempel vattenånga eller koldioxid och slutprodukten är syngas. Anaerobisk konversion (rötning) använder sig av mikroorganismer som inte behöver syre för producera biogas. Jäsning kan delas in i två grupper: foto- och mörkjäsning. Dessa metoder används mest för att producera vätgas från biomassa.

Biomassa kan användas som råmaterial för bland annat följande: syngas, biogas, vätgas, bioetanol och biodiesel. Syngas produceras genom att förgasa biomassa och kan brännas som sådan eller användas som råmaterial för att producera vätgas, metanol och etanol. Detta görs ofta genom att utnyttja Fischer-Tropsch processen. Biogas produceras genom under anaeroba förhållanden och är en blandning av metan och koldioxid. Biogas kan förbränna för att producera elektricitet och värme eller användas som bränsle för fordon. Vätgas kan produceras biologiskt eller termokemisk från biomassa. Genom att använda ånga kan syngas eller bio olja omvandlas till vätgas. Biokemiska sätt att producera vätgas är användning av foto- eller mörkjäsning eller direkt- eller indirekt fotosyntes. Bioetanol kan tillverkas från många olika råmaterial men lignocellulosisk biomassa är den mest lovande råvaran. Biodiesel kan tillverkas från syngas via Fischer-Tropsch processen.

Genom att använda data från källorna i teoridelen framställdes ett Excel kalkylblad so användes för att beräkna värden som användes för att jämföra mängden energi som skulle kunna tas tillvara från förbränning av fast biomassa och från förbränning av biogasen som bildats om biomassan hade förgasats. Värden som användes i beräkningar är i många fall medeltal baserat på data från källor. För att få någon uppfattning om förhållandet mellan energimängd och landareal valdes tio procent av Österbottens odlade area att användas för odling av de olika energiväxterna som presenterats.

Resultaten från beräkningarna visar att anaerob rötning och förbränning av den producerade biogasen är ett bättre alternativ med tanke på energimängden.

För att göra resultaten mera jämförelsebara med varandra borde växternas fukthalt vara samma för alla men detta skulle innebära att det behövs torkningsutrustning som skulle medföra att vissa biomassor skulle vara mindre energieffektiva bränslekällor än andra.

Baserat på dessa beräkningar kan en relativt liten landareal ge upphov till stora mängder energi om växter som kan skördas årligen odlas. Något som inte beaktats i detta arbete är hur förbehandling av biomassan påverkar på resultaten längre ner i produktionskedjan.

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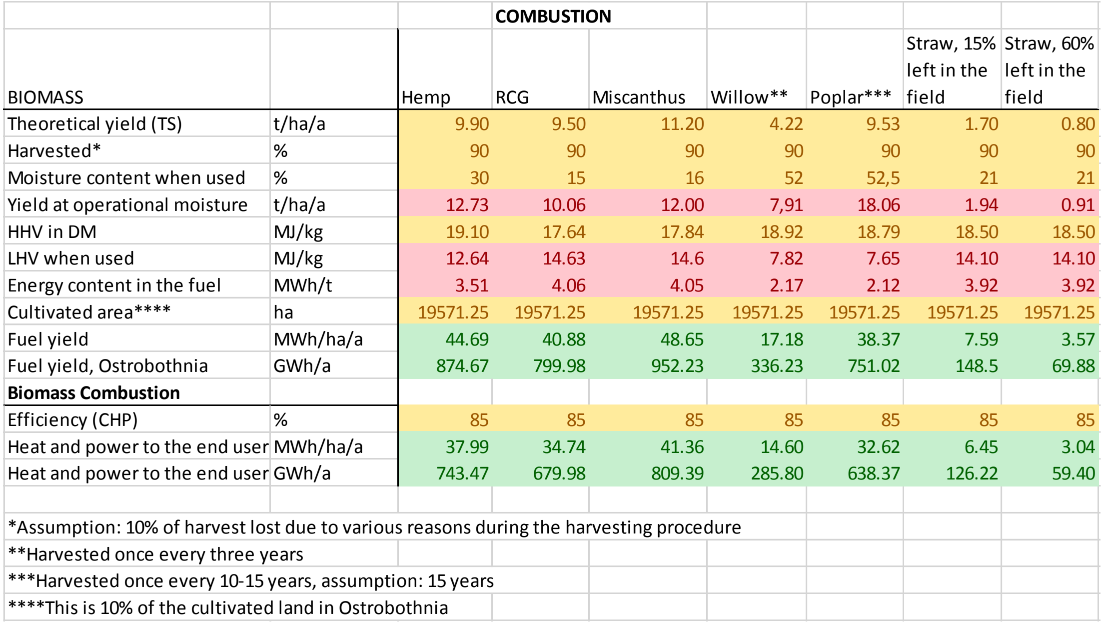
APPENDICES



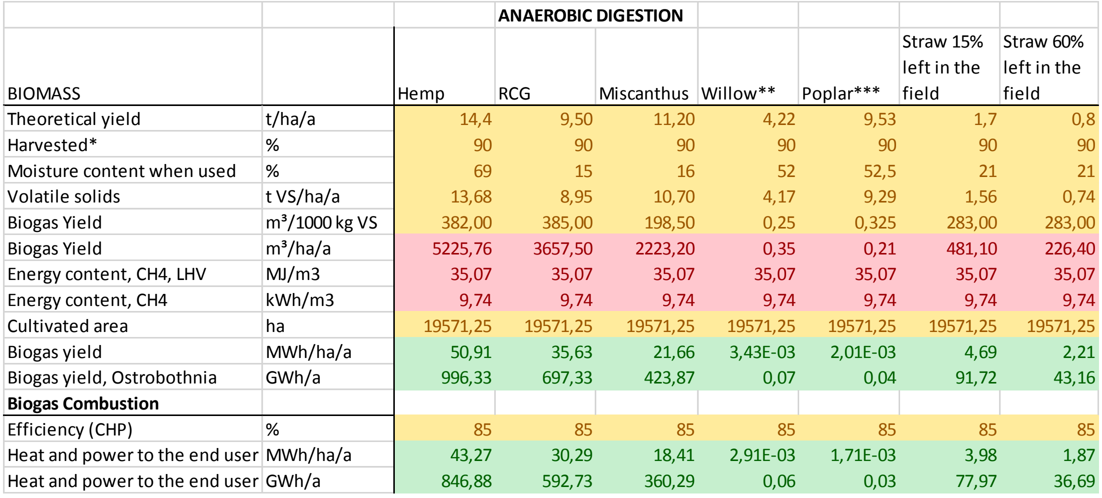
			COMBUSTION					
BIOMASS		Hemp	RCG	Miscanthus	Willow**	Poplar***	Straw, 15% left in the field	Straw, 60% left in the field
Theoretical yield (TS)	t/ha/a	9.90	9.50	11.20	4.22	9.53	1.70	0.80
Harvested*	%	90	90	90	90	90	90	90
Moisture content when used	%	30	15	16	52	52,5	21	21
Yield at operational moisture	t/ha/a	12.73	10.06	12.00	7,91	18.06	1.94	0.91
HHV in DM	MJ/kg	19.10	17.64	17.84	18.92	18.79	18.50	18.50
LHV when used	MJ/kg	12.64	14.63	14.6	7.82	7.65	14.10	14.10
Energy content in the fuel	MWh/t	3.51	4.06	4.05	2.17	2.12	3.92	3.92
Cultivated area****	ha	19571.25	19571.25	19571.25	19571.25	19571.25	19571.25	19571.25
Fuel yield	MWh/ha/a	44.69	40.88	48.65	17.18	38.37	7.59	3.57
Fuel yield, Ostrobothnia	GWh/a	874.67	799.98	952.23	336.23	751.02	148.5	69.88
Biomass Combustion								
Efficiency (CHP)	%	85	85	85	85	85	85	85
Heat and power to the end user	MWh/ha/a	37.99	34.74	41.36	14.60	32.62	6.45	3.04
Heat and power to the end user	GWh/a	743.47	679.98	809.39	285.80	638.37	126.22	59.40

*Assumption: 10% of harvest lost due to various reasons during the harvesting procedure

**Harvested once every three years

***Harvested once every 10-15 years, assumption: 15 years

****This is 10% of the cultivated land in Ostrobothnia



			ANAEROBIC DIGESTION					
BIOMASS		Hemp	RCG	Miscanthus	Willow**	Poplar***	Straw 15% left in the field	Straw 60% left in the field
Theoretical yield	t/ha/a	14,4	9,50	11,20	4,22	9,53	1,7	0,8
Harvested*	%	90	90	90	90	90	90	90
Moisture content when used	%	69	15	16	52	52,5	21	21
Volatile solids	t VS/ha/a	13,68	8,95	10,70	4,17	9,29	1,56	0,74
Biogas Yield	m^3/1000 kg VS	382,00	385,00	198,50	0,25	0,325	283,00	283,00
Biogas Yield	m^3/ha/a	5225,76	3657,50	2223,20	0,35	0,21	481,10	226,40
Energy content, CH4, LHV	MJ/m3	35,07	35,07	35,07	35,07	35,07	35,07	35,07
Energy content, CH4	kWh/m3	9,74	9,74	9,74	9,74	9,74	9,74	9,74
Cultivated area	ha	19571,25	19571,25	19571,25	19571,25	19571,25	19571,25	19571,25
Biogas yield	MWh/ha/a	50,91	35,63	21,66	3,43E-03	2,01E-03	4,69	2,21
Biogas yield, Ostrobothnia	GWh/a	996,33	697,33	423,87	0,07	0,04	91,72	43,16
Biogas Combustion								
Efficiency (CHP)	%	85	85	85	85	85	85	85
Heat and power to the end user	MWh/ha/a	43,27	30,29	18,41	2,91E-03	1,71E-03	3,98	1,87
Heat and power to the end user	GWh/a	846,88	592,73	360,29	0,06	0,03	77,97	36,69