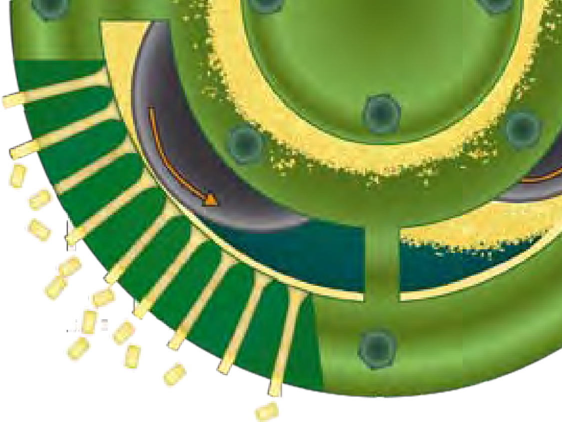
MicrE

Micro Energy
to Rural Enterprise



Biomass and Waste-to-Energy Technologies

Installation, Safety and Troubleshooting
of Anaerobic Digestion, Gasification, Combustion,
Pyrolysis and Alcohol Fermentation

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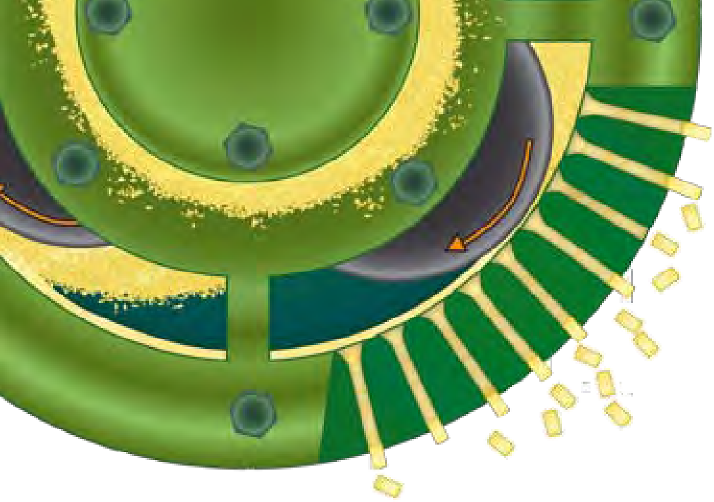

Report based on the activities of WP3
(Technology Development and Adaptation) of the Micro Energy to Rural Enterprise (MicrE) Northern Periphery Programme project

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Introduction

Biomass, containing all organic material that stem from plants, accounts for about half of the renewable energy used in the European Union. As a very versatile energy source, biomass can be used in transport, electricity and heating. The European Union aims to promote and support all these sectors in the purpose to diversify its energy supply, to increase the share of renewable energy, to reduce reliance on imported energy, and to decrease greenhouse gas emissions.

Biomass, and biomass-based waste materials can be converted to energy by thermo-chemical, biochemical, mechanical, chemical, or electro-chemical process routes. From these, thermo-chemical and biochemical conversion technologies are suited to the wide range of biomass while the others have more limitations on the feedstock. Thermo-chemical conversion methods, such as combustion, gasification and pyrolysis are suited to relative dry woody and herbaceous biomass whereas biochemical technologies, such as anaerobic digestion and alcohol fermentation can also handle biomass with high moisture content.

This report was compiled as part of the Micro Waste to Energy (MicrE) project financed by the Northern Periphery Programme. MicrE aims to promote innovative, small-scale renewable energy solutions for rural SMEs and local organizations. The project reviewed the most suitable conversion technologies for Northern areas such as those that produce energy commercially also in small scale and are inexpensive and simple to construct and maintain. The report is intended for local organisations and entrepreneurs who need information on the feasibility of biomass and waste-to-energy technologies. Anaerobic digestion, gasification and combustion are presented as they are well suited from small- to large scale applications in rural Northern Periphery conditions. In addition, technologies favouring larger scale applications such as pyrolysis and alcohol fermentation are also presented, as they have a potential of producing liquid fuels with high market value and a versatility of uses, once the economies of scale have been achieved.

Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process in which biogas is produced from organic matter by micro-organisms in the absence of oxygen. The biogas can be produced from bio-waste, waste waters, energy crops and organic by-products from industry and agriculture. Biogas consists mainly of methane and carbon dioxide. (EUBIA 2011)

Anaerobic digestion occurs in a bioreactor, which can be classified as wet and dry reactors. Municipal organic waste and vegetable waste are used in dry reactors, while wet reactors are more commonly used for manure and sludge waste. The operating temperatures are also divided to mesophilic (35 °C) and thermophilic (55 °C) temperatures. The advantage of thermophilic reactors is shorter retention time, but maintaining a higher temperature requires higher energy input. (EUBIA 2011)

The anaerobic digestion process occurs mainly in four steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. In hydrolysis insoluble organic matter is converted to soluble form. The main idea of acidogenesis is to produce acetate, volatile fatty acids, carbon dioxide and hydrogen. Volatile acids are degraded to acetate and hydrogen by acetogenesis. In the final step, acetate and hydrogen are converted to methane and carbon dioxide by methanogenesis. (EUBIA 2011)

The final product (biogas) can be used for combined heat and power production. The biogas can be also purified to methane and used as a fuel for vehicles. The residues from the anaerobic digestion can provide further benefits as a fertilizer. (MicrE 2011)

Installation of a biogas plant

The design process of a biogas plant starts by defining the properties of raw material s. Raw material can include products from a farm, such as manure, sludge and grass but it also includes external raw material sources. External raw material sources tend to have stricter requirements than raw materials straight from the farm. However, additional payments can be required from external inputs. (Tavitsainen 2006)

In cases when there are two or more raw material sources near to each other it may be profitable to build one biogas plant as a joint effort. In this case, the post-treatment of process waste has to be agreed between farmers. Business registration and the amounts of raw materials must be defined and reported. In addition, the use of the raw material can require the permission of a veterinarian. (Tavitsainen 2006)

Requirements for an anaerobic digestion process are strongly dependent on biomass feedstock properties. There are no special requirements for a biogas process if it handles only the manure or sludge straight from the farm. External feedstock should be handled properly to guarantee adequate hygiene standards. (Tavitsainen 2006)

Raw material may require sterilization as a pre-treatment process. Sterilization kills pathogenic bacteria and, conventionally, this is done by using high temperature in the sterilization chamber. In addition, the sludge that comes out of the bioreactor need to be post-treated by composting, for instance. (Erjava 2009)

One important step is the determination of the computational biogas potential of a biogas plant. Calculation is done by multiplying the annual solid raw material production with the methane productivity potential. (Tavitsainen 2006)

Determination of heat and power consumption of the plant is also an essential operation in the beginning. Electricity and heat produced by the plant can be used to run the plant and to heat up households that are nearby. Excess electricity can be transferred to the electric grid and sold to a local electric company. (Tavitsainen 2006)

When there is enough background knowledge, the supplier for the process equipment is considered. Some suppliers can perform the energy calculations and preliminary budget offer. In some cases installation costs of a biogas plant can be decreased, if the buyer of a plant helps with construction work. (Tavitsainen 2006)

Production of biogas is regulated by several legislation systems related to environment, energy production and agriculture, for instance. At first, the construction permission is needed to build an anaerobic digester. A zoning plan may be useful to check also in the beginning. The supplier and agreement for a biogas plant are also necessary. (Erjava 2009)

Environmental legislation (and waste legislation) is also considered, since the possible environmental damage caused by biogas plant. Environmental legislation might require for instance environmental impact assessment. In addition, collection, storing and transportation of raw material and biogas require separate permissions. For example the requirements for a transportation tank may be strict. Fertilizer legislation is considered in the case when fertilizer is produced by biogas plant and then sold forward. (Erjava 2009)

The installation of a biogas plant usually needs an agreement with a local or regional energy company, especially if the purpose is to sell electricity. Electricity companies can be put out to tender to get good price for electricity, when selling and buying it. (Tavitsainen 2006)

Rescue plan and risk evaluation are also necessary to draft. Also the installation of a biogas plant can be reported to a local rescue authority. Furthermore, the documents related to an ATEX Directive[1] are essential because methane is a highly flammable gas in normal temperature and pressure conditions. (Tavitsainen 2006)

Permissions and legislative systems behind the installation and maintenance of gas pipes also need to be considered, as well as the legislation related to the maintenance of the anaerobic digestion process. Legislative systems and regulations related to biogas plants can vary from country to country substantially. (Tavitsainen 2006)

A checklist for the installation of a biogas plant is presented in Table 1. Compulsory parts are marked with red color, steps to be considered are marked with orange color and discretionary activities are marked with green color.

[1] The ATEX Directive consists of two EU Directives describing what equipment and work environment is allowed in an environment with an explosive atmosphere.

Collecting the data	Define the properties and amounts of the raw material
	Computational biogas potential
	Determination of heat and power consumption of the plant
	Searching a supplier for the process equipment
Permissions and legislation	Construction permission
	Environmental and waste legislation (EIA)
	Fertilizer legislation
	Permission to buy and sell electricity with an energy company
	Permissions and legislation related to maintenance and running the process, installation on other process equipments (pipes etc.) and transportation, handling and storage of raw material and final products
Others	Rescue plan
	Documents related to ATEX directive
	Risk evaluation
	Sterilization process and post-treatment process for the sludge
	Permission of a veterinarian
	Agreements with other raw material suppliers (responsibilities etc).

Table 1. Checklist for a biogas plant.

Safety and hygiene issues

There are always some inhibitors and hazardous compounds related to every process. In the case of a biogas plant, they are highly dependent on the feedstock and the process equipment. The best way to avoid accidents is to follow security instructions and do a preliminary risk evaluation. A rescue plan is also necessary to have. (Tavitsainen 2006)

Biogas consists mainly of methane (CH4) and carbon dioxide (CO2). The desired final product, methane, is a highly flammable gas and it can explode when meeting a spark and reacting with oxygen. Risks can be avoided by designing tanks, reactor and pipes properly to prevent methane leaks. In addition, efficient ventilation is also contributing to preventing the risk of explosion. An alarm instrument detenting high methane concentrations is hence necessary. (Tavitsainen 2006)

Hydrogen sulfide (H2S) is also minor a component of biogas and it possesses flammable, hazardous and toxic properties. The ventilation must work on the floor level because hydrogen sulfide is heavier than air. In a reactor, H2S has also corrosive effects. To prevent the damage of process equipment, H2S is oxidized with 2-5 vol-% air mixture. This is a strict limit for the amount of air because otherwise it would react with methane and cause an explosion. (OSHA 2005, Tavitsainen 2006))

Blockages in the pipes can lead to overpressure, which may cause an uncontrollable discharge. Due to this, homogenous inputs are preferable to heterogeneous inputs. Blockages can occur also in the gas pipes, which are also considered as a safety issue. Special exhaust valve is designed to lead excess gas away controlled manner. (Tavitsainen 2006)

The feedstock, which may include pathogenic bacteria is sterilized. Moreover, the digestate from the reactor is post-treated to fulfill the regulations of the fertilizer legislation. Fertilizer consisting pathogenic bacteria and other inhabitants is not allowed to be used as a fertilizer. Pathogenic bacteria can cause diseases for livestock, for instance. (Tavitsainen 2006)

The categories of animal by-products are illustrated in Figure 1. Feedstock including the material of category 3 is sterilized before further anaerobic digestion to reach adequate hygiene standards. Sterilization is done usually on a temperature of 70 °C for 60 minutes. Sterilization is also done for feedstock including animal-based foodstock and food waste. (Evira 2011)

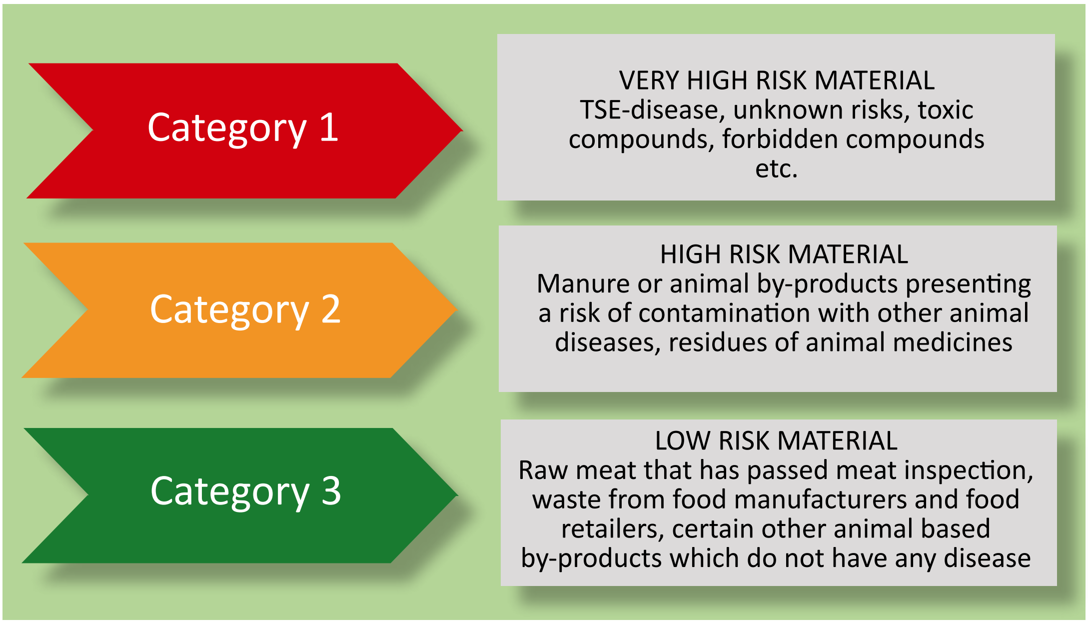

Figure 1. Categorization of animal by-products (Based on Tavitsainen 2006).

Thermophilic anaerobic digestion (when temperature is over 50 °C and retention time is at least 20 days) plus composting is an appropriate process combination for the feedstock of category 2. Feedstock related to category 1 is not allowed to be processed by anaerobic digestion. (Evira 2011, Tavitsainen 2006)

There are no special requirements for the anaerobic digestion process if it processing only own manure, milk and washing water from the farm. If the plant is shared with two or more raw material suppliers and the plant processes manure, milk and waste waters from those farms, there are no special requirements for the process. (Tavitsai-nen 2006)

Treatment of manure from slaughterhouses does not need any special process requirements, except a composting process as a post-treatment. Otherwise the slurry from the process is not allowed to be used as a fertilizer. (Tavitsainen 2006)

If a biogas plant processes only sludge from communities, following processes are appropriate:

- Thermophilic process (55 °C, retention time 4 h)
- Mesophilic process and some of the following alternatives
  - Thermal drying (> 80 °C for 10 min)
  - Composting and post-maturation (6 months)
  - Sterilization (70 °C, 30 min)

Troubleshooting

Appropriate temperature is essential to maintain due to slow methane fermentation process since product yield decreases immediately when temperature decreases. Adequate retention time and moisture content up to 50 % is a base for productive bio reactor. Moreover pH around 7,5 is optimal for microbial growth and metabolism of these microorganisms. For example if pH exceeds the level of 8, the biogas plant is recommended to be stopped. Formic acid can be added in the case of too high pH. (ECOFYS 2004)

Too high organic load can cause troubles for the process. Recommended amount of organic input varies between 0, 5 – 5 kg per m^3.

In addition, a healthy carbon to nitrogen ratio should be between 20:1 and 40:1. It is also to be considered that too large particle sizes and lack of auxiliary substances can restrict the microbiological process. (ECOFYS 2004)

Mixing is also needed to avoid pressure build-up and improve the substrate diffusion in the whole reactor. Without mixing, the gas bubbles may not reach the surface, which can cause troubles in the reactor. (ECOFYS 2004)

Feedstock containing antibiotics, disinfectants, heavy metals and organic acids can restrict microbial activity in the reactor or even kill them. If there is electronics default, a professional electrician is needed. The CHP unit can also have malfunctions. In this case, the gas supply from the CHP unit is cut. If there is a gas odor, ventilation is done and sparks and open fire ought to be avoided. (ECOFYS 2004)

Blockages are removed immediately, if the pipes malfunction. If there is malfunction in the pumps, be sure that valves are closed and pumps are switched off. There can be also malfunction in the biogas storage. In this case, the storage is to be ventilated, emptied and the gas supply is stopped. (Tavitsainen 2006)

Sterile process equipment are the base of the process, otherwise it might contaminate by unwanted micro-organisms. Keeping process equipment sterile and preparing with inoculation storage is the best way to avoid contamination. (Vogel 1983)

Gasification

Gasification is a thermochemical process, which uses biomass as a feedstock in order to produce syngas and other outputs. In other words, gasification packs energy into chemical bonds in the product gas leading to higher energy density. Possible feedstock for gasification includes wood, wood residues, bark, shrubs, sawdust, energy crops and other wood-based raw materials. Wastes, such as agricultural wastes and crop residues, are also suitable raw materials. (MicrE 2011, Basu 2010)

A conventional gasification process consists of biomass drying, pyrolysis, oxidation and reduction steps. In the pyrolysis chamber, large hydrocarbon molecules of biomass break up into smaller molecules in the absence of oxygen. Therefore, relatively volatile compounds of the biomass are separated from the char. Temperature in the pyrolysis chamber varies between 400–650°C. (Basu 2010, MicrE 2011)

Endothermic pyrolysis and gasification reactions occur in the oxidation chamber at temperatures between 900–1200°C. Syngas is formed in the reduction chamber through several reactions. Gasification processes can be divided to updraft and downdraft gasifiers. Furthermore, reactors can be roughly classified to moving bed reactor, fluidized bed reactor and entrained flow reactor. (Basu 2010, MicrE 2011)

The most significant impurities, such as tars and particulates are separated from the final product. Conventional separation processes for tar and particulate removal are usually cyclones, filters, electrostatic precipitators and scrubbers. Tar can also be treated by catalyst or thermal cracking. Companies have been developing also a plasma technique for the gasification process. (Basu 2010)

The final product, syngas (a mixture of hydrogen and carbon monoxide) can be utilized as a fuel in the internal combustion engine or to run a gas turbine. Ash from the process can be utilized as a fertilizer or as an additive in construction materials. (MicrE 2011)

Installation of a gasification plant

Construction and operation of a gasification plant is connected to several different requirements and legislative systems. Before making further applications for building a plant, it is necessary to determine the raw material input (biomass or waste etc.), so the equipment, circumstances and type of the process can be defined. In addition, the use of the end product is to be thought over, so the possible needs and regulations of CHP-unit or agreements with bio fuel companies can be considered. (Gasification guide 2009)

Firstly, a construction permit is needed for a plant. Regulation of land use planning is taken into account in order to find an appropriate

place for the gasification plant. It is also possible that city plan is also taken into consideration here. (Ministry of Environment 2011a)

Environmental permit for the gasification plant is essential. To this end, an environmental impact assessment is necessary to conduct in order to ascertain possible impacts to the environment such as emissions to the atmosphere, noise pollution, soil protection, waste generation and possible waste water discharges. Obligations related to the IPPC Directive vary from country to country and can depend on the size of the gasification plant. (Gasification guide 2009, Ministry of Environment 2011a)

Rescue plan, hazard identification and risk assessment for the plant is also composed and the ATEX directive is followed. Health and safety at work must be ensured by following the regulations related to fire and explosion hazards. Moreover the regulations involved to electrical and pressure equipment and machinery are also necessary to consider. Adequate handling, transportation and storing of several hazardous substances is essential to avoid accidents. Special monitoring may be required for certain installations. Fire safety and stability regulations of the plant building are essential. (Gasification guide 2009, Ministry of Environment 2011a)

The use of energy may need requirements connected to feeding electricity to the power grid. In this case, a possible buyer for the electricity is to be selected and the terms of electricity transactions are agreed upon. (Gasification guide 2009)

Legislative systems and regulations related to installation of pipes and storages are also required. Transportation of waste is also regulated. The produced syngas can be sold to companies, which must be agreed upon with the companies. In addition, agreements with raw material suppliers can be made. In this case the possible seasonality of raw material supply is to be considered. (Malla2 2006)

Differences in national and regional regulations can exist. To avoid the major problems with legislative systems and regulations, it is necessary to discuss with local environmental authorities at an early stage of the gasification plant planning process. (Ministry of Environment 2011a)

Gasification safety issues

The gasification process is inwardly related to production, utilization and handling of toxic and flammable compounds. Carbon monoxide (CO) is a very poisonous compound, which can be dangerous for life. Very small concentrations of CO can cause headache, dizziness and nausea. Therefore, an alarm system for too high CO concentrations is necessary. In addition, due to possible CO leaks, a ventilation system is necessary. (Gasification guide 2009)

Explosion hazard can occur, if there is spark available for ignition and the concentrations of CO2, H2 and O2 are suitable. Moreover specific concentration of dust and source of ignition can cause a dust explosion. Product gas can also auto-ignite in temperatures of 600-650 °C. Glowing particles, gases and explosions can also start the fire in the plant. During repairs, an explosion can occur, if there is still gas inside the reactor. During the storage and transportation of product gas it is also necessary to follow safety regulations. (Gasification guide 2009)

Overpressure can also lead to gas escaping, leading to gas intoxication. In addition to CO, also other compounds from the process can be hazardous. For example Polycyclic aromatic hydrocarbon (PAH) compounds are toxic and carcinogenic, and can leak from the process. Inadequate control system programming can cause severe consequences. Other malfunction, for example in the reactor and pumps, can cause gas leaks leading to mentioned outcomes. (Gasification guide 2009)

Fluctuating and too high pressure can cause material damage to process equipment and hence it can be a safety hazard, causing leakages, for example. Also too high temperature can cause problems to process material and cause malfunctions or even self-ignition of some gas mixtures. In addition, occupational health and safety hazards have to be considered as a part of risk assessment. Possible occupational safety and health hazards are also: noise emissions, exhaust gas, heat stress, hot surfaces and electricity. Electrical hazards can lead to static electricity build up and sparks, causing, in the worst case, an explosion. (Gasification guide 2009)

The best way to avoid these safety hazards is to follow the ATEX Directive. Gasification facilities should be constructed by following international standards. Also having appropriate equipment to monitor concentration of chemicals is essential. In addition, the education of staff is mandatory. (Gasification guide 2009)

Troubleshooting

There are several chemical and physical factors affecting the yield of the product gas. Firstly, high moisture content is essential to be removed, by drying the raw material input in a specific drying chamber. If the biomass entering the pyrolysis chamber has too high moisture content (over 30 %), it can inhibit the gasification process and lead to decreased thermal efficiency. In addition, an adequate particle size is important factor to get good yield of gasification. Specific hydrogen-to-carbon ratio of the raw material, among others, affects the gasification yield, especially in the pyrolysis chamber. (Basu 2010)

Tar can cause troubles to the gasification process, when the tar-containing gas is cooled. Tar will condense on cooler surfaces or remaining in small aerosol drops. Tar can condense also on cooler pipeline surfaces, causing blockage, but it can also block engines and filters. Formation of liquid tar can be avoided by keeping the temperature above the dew point of tar before a tar separation unit. Without separation of tar, it will greatly inhibit the subsequent use of syngas, for example in an internal combustion engines. (Basu 2010)

Heavy metals, such as lead, copper and zinc, especially as chlorides, inhibit the gasification process. Most of heavy metals slow down gasification reactions, leading to longer retention time. In addition, some alkali metals can be harmful for the gasification process, because they can foul heat transfer surfaces and react with other inorganic compounds, causing corrosion. (Chartier et al. 1996)

If the gasification chamber is fed by too high oxygen concentration, it can lead to combustion, and thus weaken the yield of product gas. To this effect, an adequate temperature and pressure is necessary to maintain. Appropriate retention time of the process affects greatly on the result. In addition, too high ash content (over 15 %) can inhibit the process. Raw materials possessing low ash content can also minimize disposal issues. (Basu 2010)

Product gas yield can be low due to inefficient catalyst. Catalysts need to be recovered at times and the surface of the catalyst can foul. In case of electrical and machinery malfunctions, a professional mechanic will need to fix the problem. Such malfunctions can cause unknown and diverse consequences in the process, so it is hard to consider them in advance. (Basu 2010)

Combustion

Combustion is one of the oldest ways to convert fuel to useful energy. Combustion of biomass is a process in which oxygen reacts with carbon in the fuel and produces carbon dioxide, water and heat. Gaseous combustion products include also nitrogen oxidants, carbon monoxide and aromatic compounds. Solid products include charcoal and ash, for example. (Loo & Koppejan 2008)

Adequate input for the combustion process includes wood waste, pellets and bio waste with relatively low moisture content. In a combustion reactor or furnace, raw material reacts with oxygen in high temperature (> 800 °C). Usually, an initial step of combustion is drying. The second and third steps include pyrolysis and gasification. The final step is combustion, in which overall efficiency is highly dependent on temperature, available oxygen and raw material properties. Combustion can use either natural or forced draught. (Loo & Koppejan 2008) (MicrE 2011)

In general, combustion processes can be divided to batch and continuous processes. In households, wood-stove is a conventional batch combustion process, when larger continuous combustion reactors, with higher technological properties and larger scale, are more common in industry. These combustion reactors can be divided to fixed bed, bubbling fluidized bed, circulating fluidized bed and pulverized fuel reactors. Furthermore, several types of wood-fired stoves are also available commercially. (Loo & Koppejan 2008)

Combustion can be utilized to produce heat for households and for industrial processes. In addition, hot gases from the process can also heat up water in heating boilers in order to produce electricity. In some cases combustion can also produce gaseous and liquid fuels. Ash from the process can be utilized as fertilizer. (Loo & Koppejan 2008)

Installation of a combustion plant

Permissions for the installation of a combustion plant vary depending on the scale of the plant. In small-scale applications, such as stoves, no significant requirements are needed. Small-scale combustion stoves usually need only construction permission. After construction, the stove needs to be verified by a rescue authority. (FINLEX 2011)

In case of larger biomass combustion plants, the input raw material defines the suitable process. As well, the type of output, heat or combined heat and electricity production, characterizes the technology needed. In larger scale plants, agreements will need to be made with possible raw material suppliers. Some raw materials may require pretreatment in order to reach good combustion efficiency, as well as satisfy the requirements of emission levels and bottom ash quality. (FINLEX 2011)

Larger scale combustion plants also require a construction plan and land use plan. City plans will have to be taken into account as well. In addition, storages, pipes and other process equipment will need construction permission. Stability and fire safety regulations are compulsory to follow. (Ministry of Environment 2011a)

Environmental permits are compulsory for larger combustion plants. Air emissions, such as CO2 as well as output ash amounts, are significant. Environmental Impact Assessment will have to be conducted to estimate overall emissions and impacts to environment. Moreover, the solid waste streams from the plant will have to be evaluated by environmental authorities. Combustion plants also fall under the IPPC Directive; therefore, best available technologies will have to be adopted in order to protect theenvironment. (Ministry of Environment 2011a, FINLEX 2011)

The combustion process produces mainly heat, however, when electricity is also generated, the excess electricity can be sold to electricity companies. Before distributing electricity or heat, agreements and permits will have to be done with receiving companies. Standards and regulations related to possible boilers, turbines and CHP-unit are compulsory to follow. (FINLEX 2011)

In larger combustion plants, rescue plan, hazard identification and risk evaluation are necessary to compose, since there are hazardous chemical compounds and high temperature present in the process. Safe working environment is also ensured by following these safety requirements. (Ministry of Environment 2011a)

Legislation and regulations guiding a combustion process is largely dependent on the scale of the process. In the case that heat production of the combustion plant is 20 MW or more, the emission trade directive is taken into account. Co-combustion may require stricter requirements for combustion circumstances. Legislation and regulations for the combustion process may also have national varieties. (Ministry of Environment 2011a)

Combustion safety issues

In small-scale applications, the main safety-related issues originate from the spillage or backdraft of exhaust gas, which should be led outside. Carbon monoxide (CO) is one of the most hazardous compounds from the combustion process. CO forms when combustion temperature is low and available oxygen levels are low. CO is an odorless, tasteless and initially non-irritating and, therefore, difficult to detect. Yet even at relatively low concentrations, CO can cause lightheadedness and confusion. A CO detector, adequate ventilation and appropriate combustion conditions are essential to avoid problems with CO. (EREC 2008, DeKieffer 1995)

If the exhaust gas is not properly ventilated, there can be problems with moisture. Moisture may condensate on the walls and windows, increasing humidity levels. High humidity levels can greatly contribute to mold formation, leading to health hazard. Too high humidity levels can also cause wood deterioration and structural problems of the house. Exhaust gas contains also nitrogen oxides, which can be a health hazard. (EREC 2008)

The high temperature of the combustion process can also lead to hot surfaces. Hot steam can also be dangerous. In the case of mishandling or malfunction of the combustion process, fire can spread to the ambient environment. In addition, gas leaks from the process can set up fires or cause an explosion. (DeKieffer 1995)

To ensure the safe operation of a combustion plant, especially in larger units, proper ventilation system, automatic fuel turn-off valve, gas detectors and flame sensing devices are valuable. These devices need to be inspected and tested at times. Furthermore, accidents prevention may also require education of staff and clients. It is also necessary to clean process equipment at times and check for possible structural damage. (EREC 2008)

If corrosion happens in the process, it can cause structural problems in the heat exchangers. Spillages from heat exchangers can be very hot and dangerous. Also malfunction of boiler, electricity and machinery can cause a safety hazard. (Loo & Koppejan 2008)

Raw material may also require chemical or mechanical pre-treatment, which can also be a source of safety hazards from machinery to hazardous chemicals. These are dependant on raw material properties pre-treatment processes. (Loo & Koppejan 2008)

Troubleshooting

Properties of raw material have a great impact on combustion process efficiency. At first, moisture content is significant factor. Increasing moisture content can reduce the maximum temperature of the combustion and increase also retention time. High moisture content leads to incomplete combustion and high amounts emissions. Drying of raw material may be needed to decrease moisture content of raw material. (Loo & Koppejan 2008)

Appropriate temperature (more than 800 °C) is important to maintain due to its significant influence on reaction rates. Temperature is also important to optimize in order to reduce emissions from the combustion process. Higher temperatures can be reached also by improving the insulation of the combustion chamber. (Loo & Koppejan 2008)

The amount of available oxygen can restrict the combustion process. Due to this, excessive air ratio is used, but it is necessary to optimize it. Too high oxygen content can decrease the temperature of combustion. In large-scale applications, it is important to ensure sufficient mixing of excess air and ensure also the amount of forced draught to the combustion process. In small-scale applications, the problem of inefficient combustion can be inefficient natural drought. (Loo & Koppejan 2008)

Fuel type and properties, such as density, porosity, size and surface area, can affect significantly the combustion process. Larger particle sizes requires longer retention times, while more porous and finer materials have better reactivity. It is not recommended to use manure and municipal wet organic wastes in the combustion process because they can inhibit it. Also impregnated and painted woods are not suitable for the combustion process. In addition excessive fuel load can also inhibit a small-scale combustion process. (Loo & Koppejan 2008)

In small-scale combustion systems, too large glass area can cause heat losses, because heat radiates easily through it. Adequate retention time is also necessary to maintain, especially in batch processes. In large-scale applications air preheating may also be needed to raise the temperature of the process. (Loo & Koppejan 2008)

Ash from biomass combustion process can contain high alkali and heavy metal concentrations, causing corrosive effects to a boiler. Moreover, ash and slag can foul surfaces, causing harm especially for heat exchange systems. Agglomeration of ash particles can also inhibit the combustion equipment and lead to poor combustion conditions, but high ash levels can affect also downstream processes. These conditions will lead to inefficient combustion productivity, therefore, process equipment must be cleaned at times, and adequate combustion conditions are important to maintain. (Loo & Koppejan 2008)

In large-scale systems electrical and machinery malfunctions can have numerous unpredictable consequences to the combustion process. For example malfunction of forced air system in large-scale applications can disturb the system significantly. Boilers, CHP-units and turbines can also foul and corrode. Therefore, a proper maintenance schedule needs to be upheld. (Loo & Koppejan 2008)

Pyrolysis

In pyrolysis, large hydrocarbon molecules (cellulose, hemicelluloses and part of the lignin) break down into smaller and lighter molecules. Unlike combustion and gasification, pyrolysis occurs in total absence of oxygen. Oxygen can be added to the pyrolysis chamber, when some combustion is allowed to produce heat for the process. (Basu 2010)

The initial steps of conventional pyrolysis are usually drying and milling. From milling, raw material enters the pyrolysis chamber, where temperature is high. Condensable volatile gases (heavy hydrocarbons) are recovered and condensed after separation step. Solid products (charcoal) and liquid tar are separated for further treatment and utilization. (Basu 2010)

Pyrolysis can be divided to slow and fast pyrolysis. In slow pyrolysis, biomass is heated slowly to pyrolysis temperature (400-800 °C) with long residence time. Slow pyrolysis produces more tar and charcoal and less gases. The purpose of fast pyrolysis is to maximize the yield of liquid or gases. In fast pyrolysis, biomass is heated rapidly to the adequate temperature (up to 650°C), and held there only for few seconds or less than second. Also flash and ultra-rapid pyrolysis has been researched. Known reactor types are fixed bed, moving bed, bubbling fluidized bed and circulating fluidized bed reactors. (Basu 2010, EUBIA 2011)

Condensable pyrolysis gases can be condensed into bio-oil, which can be utilized for vehicles or in CHP-units. Other lighter gases (CO2, CO, CH4) can be combusted and thus heat can be produced. Tar from the process can be also treated to improve bio-oil yield. Solid residues, especially charcoal, can be sold or utilized in heat production or barbeques. (Basu 2010)

Installation of a pyrolysis plant

Installation of a pyrolysis plant starts with determining the amounts and properties of feedstock, so the circumstances, catalysts, reactor size etc. can be considered. Also it is good to define desired end product, which can be gas, charcoal or bio-oil, so operating temperatures, residence time, product yield and heating rate can be thought out. In addition, raw material suppliers are essential to find and make agreements with them. (Basu 2010)

After determination of raw materials, construction permit is needed to the plant. Land use can also be regulated, and it is possible to consider the city plan to find an appropriate location for the pyrolysis plant. Properties of pipes and storages are regulated and their installation of them may need permission. Installation of liquid and gas devices is done by following appropriate requirements. (Ministry of Environment 2011a)

Environmental permit for the pyrolysis plant is compulsory, due to its potential environmental hazards. Environmental Impact Assessment is necessary to compose, and regulations and legislative systems related to waste streams are taken into account. In addition, it is possible to consider also the IPPC Directive, but the need of this directive varies from country to country and can depend on the size of the pyrolysis plant. Also the collection and transportation of waste is regulated by the EU. These regulations vary also from country to country. (Ministry of Environment 2011a)

Safety issues are one of the fundamentals of the pyrolysis plant because of several fire and explosion hazards. Hazard identification, risk assessment and possible rescue plan is thus necessary to compose. In small-scale applications, at least a notification to the local rescue authority is compulsory. Regulations regarding electrical and pressure equipment and machinery are necessary to follow. Adequate handling, transportation and storing of several hazardous substances is essential to avoid accidents. (Ministry of Environment 2011a, Basu 2010)

Selling bio-oil, heat, electricity and charcoal from the pyrolysis plant requires agreement with companies. Possible buyers and markets are taken into consideration in an early stage of the planning process. (Ministry of Environment 2011a)

Legislative systems and requirements can have national and regional differences. To avoid major problems with legislative systems and regulations, discussions with local authorities at an early stage of the gasification plant planning process is a necessity.

Pyrolysis safety issues

The pyrolysis process is producing and handling hazardous compounds, such ase CO, H2 and hydrocarbons. Carbon monoxide is very toxic compound; it can cause dizziness and even in low. For the possible leaks of CO, a ventilation system and a CO detection device are necessary. Furthermore, glowing particles can ignite or cause an explosion, if there is a source for ignition present. (Gasification guide 2009)

Hydrogen can also be a source of safety hazard in the pyrolysis plant. For humans, hydrogen is an undetectable compound, so it can be detected only by special device. At high concentrations, hydrogen can ignite very easily, causing fires and explosions. Also hydrocarbons can cause fire and explosion hazard, if there is source for ignition. Transportation and storage of CO, hydrocarbons and H2 is hence necessary to do following adequate requirements and standards. The ATEX Directive is to be considered at very early stage of design. (DOE 2006) (Basu 2010)

Fluctuating and too high pressure can cause damage to process equipment and lead to leaks and malfunctions. High temperature can lead to hot surfaces and thermal shock. Occupational safety issues have to be considered also during risk assessment. Occupation hazards include, among others, hot surfaces, noise emissions and electrical, machinery and exhaust gas hazards. Electrical hazards can lead to static electricity build up and sparks, causing an explosion in the worst case. (Basu 2010, Gasification guide 2009)

Malfunction in the process, for example electrical malfunction, or inadequate activity of boiler can cause hazards. In addition, boiler feed-water and steam loss can cause boiler malfunctions. Electrical malfunction can cause problems with control systems, with severe consequences. Finally, the bio-oil and charcoal have be stored, handled and transported properly to prevent any safety and health hazards. (Basu 2010)

Troubleshooting

Pyrolysis temperature, heating rate and residence time together affect significantly to product yield. The context between these parameters and those effecting on product yield is presented as follows:

- Slow heating rate (< 0,01- 2,0 °C/s), low temperature and long residence time maximize the production of char

- High heating rate, intermediate temperature (450-600 °C) and short gas residence time maximize the liquid yield

- Slow heating rate, high final temperature (700-900 °C) and long gas residence time maximize the gas yield.

Gas production can be controlled mostly by temperature. CO2 yield is high at low temperatures, and decreases when temperature increases. Hydrogen production increases, when temperature increases. (Basu 2010)

The particle size is essential to consider, especially because it can affect greatly on the formation of desired end product. In general, smaller particle size leads to increased gas and liquid yield, while larger particle size produces more charcoal. Particle size can affect also to required residence time of the process. In many cases, automation systems work properly, when raw material is as homogenous as possible. (Basu 2010)

Tar formation can be harmful for the pyrolysis process, because it condenses on cooler surfaces, causing blockages. It also inhibits other process equipment, such as filters. Tar must be separated from the product gas, especially if the gas is the desired end product. (Basu 2010)

Raw materials containing large amounts of potassium, as well as other alkali metals and chlorine are not beneficial to a pyrolysis reactor due to their corrosive effect. These compounds can corrode the reactor walls, boilers and other process equipment, causing malfunctions, leaks and structural problems. In addition, too high moisture content (up to 30 %) can inhibit the pyrolysis process, and lead to higher consumption of thermal energy. Specific hydrogen-to-carbon ratio of the raw material affects also the product yield. (Basu 2010)

The pyrolysis reactor works in the total absence of oxygen. If air leaks occur, the process does will not work properly. Certain amounts of air or oxygen can be used in a reactor to allow combustion, in order to produce thermal energy for the process. Also inefficient action of catalyst can decrease desired product yield. (Basu 2010)

Electrical and machinery malfunctions can cause diverse and unpredictable consequences and will require a professional mechanic to fix the problem.

Alcohol fermentation

Alcohol fermentation is a process in which sugar containing biomass is converted to alcohol, e.g. ethanol by the metabolism of microorganisms. The fermentation is usually anaerobic, but also aerobic conditions can be feasible. Fermentation processes can be batch, fed-batch or continuous processes. (Nag 2007)

Raw materials with high sugar content, such as corn and sugar beet, are the most suitable for the fermentation process. In addition, lignocellulosic raw materials, like wood and straw can be also utilized in order to produce ethanol. However, lignocellulosic raw materials require acid or enzyme pre-treatment, because cellulose and hemicelluloses need to be converted into sugars that the microbes can use. Notwithstanding, lignocellulosic raw materials are considered to be more sustainable since they do not use food resources. (Nag 2007)

The conventional fermentation process consists of hydrolysis, fermentation, separation and purification steps. If the process uses lignocellulosic raw materials, milling and acid or enzymatic hydrolysis is required. After pre-treatment, sugars go through the fermentation process. The produced alcohol is removed from the process at concentrations around 6%, because ethanol concentration at 15% and above start to be toxic for the microbes. In the end, ethanol is enriched to 99% bioethanol. (Nag 2007, MicrE 2011)

The most conventional process to separation of water and ethanol is distillation. Distillation is an expensive and energy intensive solution. Current research efforts concentrate at low energy separation processes, such as membrane processes, in particular pervaporation. (Nag 2007)

Available commercial size for a bioethanol plant varies very much, but annual ethanol yield up to 100 m3 can be reached (Vogel 1983). The alcohol produced can be used either in CHP units in order to produce electricity and heat or as a fuel for vehicles. Solid residues from the fermentation process can be used as fertilizer or as animal feedstock. (Scragg 2006)

Installation of a fermentation plant

Installation a fermentation plant starts with defining the raw materials. It is necessary to know what goes into the fermentation process, since it defines the needed alcohol producing microorganisms. The properties of raw materials determine also the need and type of a pre-treatment process, for instance milling and hydrolysis. (Nag 2007)

Once the data for the input is defined, the supplier for the ethanol plant is considered. Agreements with other raw material suppliers can also be done. (Tavitsevainen 2006)

An essential part of the installation of a fermentation plant is having a construction permit for it. Land use planning regulation and city plans will also need to considered. Landscape permission may also be necessary in some countries. (Ministry of Environment 2011b)

Environmental permits, including Environmental Impact Assessment is essential to complete before further planning of a plant. Legislation related to water and water supply may also be considered, if the process water is taken from a lake or river. In addition, regulations related to wastes and emissions to the atmosphere and possible noise emissions need to be taken into account. (PÖYRY 2006)

Permits to execute both the process and the production of high concentrate ethanol are required. Ethanol is a dangerous chemical with flammable properties, therefore, requirements, standards and permissions related to processing, transportation and storing of a hazardous chemical and waste need to be followed. (PÖYRY 2006)

A rescue plan, hazard identification and risk evaluation are also preferable to compose. Regulations related to fire safety and stability of the building is necessary to follow, in order to ensure a safe working environment. (PÖYRY 2006)

The end product, bioethanol, can be sold to fuel companies after completing agreement with them. In addition, the possible utilization of solid and liquid by-products for animal feedstock will be required. Installation of a bioethanol plant requires also legislative systems and regulations, which are linked with installation of pipes, storage and transportation. (PÖYRY 2006) (EPA 2007)

Fermentation safety issues

Ethanol is a harmful and highly flammable compound, which is in liquid phase in normal temperature and pressure conditions. This organic compound is also toxic for humans and animals, especially in high concentrations. Because of these properties, ethanol must be handled, stored and transported properly. Following safety requirements, considering ventilation and keeping sources from ignition away prevents accidents. Bringing a safety professional to check and evaluate the

safety of the process is necessary. (Safety data 2011)

If there is grinding or milling process as a pretreatment process of raw material, respiratory protection is essential due to high dust concentrations. The possibility of high CO2 concentrations near the fermentation tanks requires also the use of respiratory protection. In addition, coolant compounds such as ammonia, glycol, propane to cool down the fermentation process are considered to be hazardous. (Liao & Saffron 2008)

Malfunction causing excess pressure and temperature in the distillation column can be safety hazard. In case of uncontrollable process circumstances, the column can broke and release highly flammable ethanol into air. The cooling system must work properly, otherwise the temperature of the process will rise rapidly. As well, leaks from distillation column can be hazardous. (Tham 2011)

Acidic or chemical hydrolysis as a pre-treatment process for starchy and lingocellulosic material can cause safety hazard depending on the type and concentration of the compounds. Sulfuric acid is a conventional chemical compound to hydrolyze starchy feedstock, and it poses a safety hazard being highly toxic

and corrosive. Furthermore, some enzymes can also be hazardous. (Nag 2007)

Adequate pressure gauges and valves are necessary in the pressurized CO2 and fermentation vessel to avoid accidents. Also leaks from pipes and tanks can cause safety problems. (Liao & Saffron 2008)

We can say that fermentation is quite a safe process, although the safety issues depend highly on the process type, which is used. However, if the process uses conventional yeast, saccharomyces cerevisiae, as an ethanol producer, toxic and hazardous affects related to that certain microbe are rather minimal. There are still cases when fermentation process can include genetically modified microorganisms. This kind of organisms can be considered a hazard to humans and the environment. (Nag 2007)

Troubleshooting

It is necessary to know what micro-organisms are working in the process, because they also define the material input for the process. Some micro-organisms cannot use some specific sugar in their metabolism, which can restrict the fermentation process. The length of retention time also affects greatly the ethanol yield. (Nag 2007)

Possible inhibitors for the process are usually ash, furfur, levulinic acids and both aromatic and inorganic compounds. Antibiotics-containing input can restrict or even kill the micro-organisms. (MicrE 2011)

In a fermentation process, the process conditions have to be optimal for microbial growth and action. At first, the temperature should be appropriate for the used microbe. Lack of possible coolant compounds can raise the temperature of the process significantly. In addition, the water content of a growth medium has to be right. (Scragg 2005, 52)

Lack of nutrients can cause inefficient ethanol yield. Micro-organisms need several nutrients and trace elements, such as carbon, hydrogen, phosphorus, sulphur, vitamins, kalium and calcium. Adequate pH-level is also vital for fermentative micro-organisms. Accurate pH-level can be controlled by adding ammonia to the input, for example. (Scragg 2005, 51)

The fermentation process must be free from oxygen. Otherwise the presence of oxygen restricts the production of ethanol considerably. Stirring is usually needed to improve mass and heat transfer in a bio-reactor, especially in continuous reactors. (Scragg 2005 et. al)

Feed conditions can vary from design specifications, which affect the performance of the distillation column, especially the location of a feed tray and the amount of stages needed for the separation. For example changes in upstream input and different process operating conditions can inhibit the profitability of distillation. (Tham 2011)

Incorrect reflux ratio can also impact on the result of distillation. If the reflux ratio is too small, an infinite number of trays are needed to reach the separation result. Moreover the efficiency of trays can decrease by fouling. Vapor flow conditions such as foaming, entrainment and flooding can also disturb the work of distillation. These phenomena can root from too small column diameter or incorrect pressure in the column. (Tham 2011)

Sterile conditions are also essential to maintain. The whole process can be contaminated if an unknown micro-organism enters the process. Therefore, the sterility of all process equipment needs to be ensured regularly. Electrical malfunctions and blockages in the pipes can also happen. (Micre 2011)

Summary

At the present, commercial conversion technologies producing energy in small-scale are the most suitable for the Northern Periphery. Also an inexpensive and simple construction is an advantage. Occasionally, plants with capacities of few MW can be defined as small-scale but these plants are industrial sized and inhabitants of rural areas might oppose the plants.

The characteristics of biomass-to-energy technologies are summarized in Table 2.

Gasification and anaerobic digestion are, in general, the most suitable technologies for northern periphery conditions. Anaerobic digestion is an excellent technology to produce energy from wastes also in very small scale while gasification is maybe a slightly more demanding technology in small-scale with special feedstock requirements. Anaerobic digestion is a fully commercial technology and is suited well to energy production from biomass-based wastes. The produced biogas can be utilised as transportation fuel or via heat and power production.

Gasification has long been a commercial technology but the number of gasification plants in operation is currently rather low. However, there are now numerous providers of small scale gasification plants. The product gas can be used to combined heat and power production or as transportation fuel in special vehicles, or it can be processed further to liquid transportation fuels.

Combustion is an ancient and very common technology for heat production purposes but not effective to generate electricity in small scale. Fuels cannot be produced from biomass through direct combustion either.

Pyrolysis is expected to be commercial in large-scale, but there are challenges. The product, pyrolysis oil, is demanding to upgrade to the quality of transport fuel. The oil can be used for combined heat and power production but the overall efficiency of the pyrolysis process is rather low.

Fermentation from first-generation raw materials is a commercial technology but competes with food production. Second-generation fermentation from wood and herbaceous raw material starts to be commercial technology in large-scale. The produced alcohol can be used for heat and power production and preferably as transportation fuel.

	Anaerobic digestion	Gasification	Combustion	Pyrolysis	Fermentation
Scale	Reactor size 50-10.000 m^3	1 kWe – 150 MWe depending on the technology used	Small to large scale	Pilot plant of 200kg/h, with 66% energy yield	Ethanol yield 102-106 m^3 annually
Input materials (preferable)	Biowaste &waste waters, by-products, energy crops	Forest products, energy crops, biowaste	Pellets, Biomass, wood wastes,	Forest products, energy crops, mill wood waste, agriculture and urban organic wastes	Food crops and by products, forest residues, energy crops, biowaste
Limiting factors	Total solids 4–40%	Moisture <45% Ash <15%	Moisture <50%	Moisture <45% Ash <25%	Homogenous input, Nutrients, pH, Moisture
Operating temperature	Optimum 35°C or 55°C	650–1200°C	>800°C	400–800°C	15–60°C
Oxygen requirements	Absence of oxygen	Partial oxidation	Excess of oxygen	Absence of oxygen	Depends on microbes
Product	Biogas	Syngas	Heat	Pyrolysis oils	Alcohol
By-products	Reject, water	Char	Ash	Gases, char	Reject, gases, water
Post-treatment	Moisture removal	Particulates and tars removal	No	Oxygen removal	Water removal
Applications and use	Transportation, fuel, CHP; digestate as fertilizer or soil conditioner	CHP, synthetic fuel production	Electricity and heat production, liquid or gaseous fuels	CHP and fuel for engines	Transportation, fuel, CHP; digestate as fertilizer or animal feed

Table 2. Characteristics of biomass-to-energy technologies (Based on Austerman et al. 2007, Austerman & Whiting 2007, Kauriinoja 2010, Kelleher et al. 2002, McKendry 2002, Soltes 1987, Uslu et al. 2008, Ward et al. 2008 & Wisbiorefine 2004)

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