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Assessment of Miscanthus cultivation for solid biofuels (briquettes) production

Diploma Thesis

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Declaration

I hereby declare, that I have written this diploma Thesis "Assessment of Miscanthus cultivation for solid biofuels (briquettes) production" myself with help of the literature listed in references.

Date ………………………… Signature…………………………

Lucie Podzimková

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Abstract

Biomass from plants, namely energy crops, can serve as a promising energy alternative to fossil fuels. It is an environmentally friendly renewable source of energy used not only for production of solid biofuels. One of the most promising energy crops seems to be Miscanthus.

The Thesis was divided into two parts: the main aim of theoretical part was to sum up scientific knowledge about biomass, biofuels as well as about Miscanthus, its utilization, properties and requirements. The main aim of the practical part was to bring assessment and comparison of two varieties of Miscanthus (*Miscanthus sinensis* and *Miscanthus x giganteus*) for energy purposes. To achieve the research goal, briquettes made of Miscanthus were produced and the main quality parameters such as gross calorific values, ash content, contents of C,H,N and volatile matter content were determined. Father, CO, CO_2 and NO_x emissions during combustion were analysed and biomass energy potentials of selected crops were calculated.

Two varieties of Miscanthus demonstrated very similar resulting values of most of basic explored properties. It was found that briquettes made of Miscanthus fulfilled requirements for classification into non-woody briquettes quality “class A” according to EN ISO 17225-7 (2014). Combustion emissions were also satisfactory in both cases. However, due to higher energy yield *M. x giganteus* is evaluated as more suitable for energy purposes.

Key Words: biomass, *Miscanthus sinensis*, *Miscanthus x giganteus*, combustion, briquettes, emissions, energy yield

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1. Introduction

In the twentieth century, large amounts of natural resources including food and energy were used to maintain a lifestyle of a mass production, mass consumption and mass disposal. One factor necessary for developing of a sustainable society is decreasing, or at least not increasing, of the total amount of energy used. Another required criterion is to reduce the dependence on petroleum as a source of energy. Thus, renewable energy developing has received considerable attention in the world. Among these renewable energies, densified biomass, especially briquettes has drawn the global attention due to its advantage over raw biomass such as its physical and combustion characteristic (Iqbal et al., 2016).

Miscanthus, which was in the past exclusively used as a solid fuel and for industrial applications, is characterized by simple crop management and high yields on a stable level for more than two decades. Moreover, Miscanthus provides several beneficial ecosystems services supporting biodiversity and carbon sequestration, improves water quality and requires no disease and pest control measures and low or no fertilisation. In general, Miscanthus has been identified as a typical low-input energy crop (Ruf et al., 2016). Moreover, Miscanthus has been considered as one of the best energy crops because comparing with other energy crops it has a high energy content and low moisture content after harvest, that are important characteristics for maximizing the energy output (Morandi et al., 2016). Miscanthus is mainly used to provide solid fuel to power plants with many smaller-scale areas supplying biomass for domestic heating plants. Currently, energy from Miscanthus is mainly produced through direct combustion of its biomass. However, the efficiency of this power generation depends on the composition of the solid being combusted. During the combustion, high moisture content of the harvested biomass leads to higher energy input for drying prior to combustion and low calorific value (Iqbal et al., 2016).

This Thesis is focused on assessment of two common varieties of Miscanthus for solid biofuel (briquettes) production with a focus on their properties and emission characteristics.

2. Literature review

2.1. Renewable energy sources

In the modern present world, power sector is one of the main factors which influence the economy of a country. Increasing living standards and population are demanding excessive power from the utility. These issues lead to the development of new energy sources which may help to slow down the pollution and global warming as the most warning criteria. To cope with these issues renewable energy sources (RES) became a promising alternative (Graovac et al., 2007).

According to FAOSTAT (2014), 25.5% of total produced primary energy in 2014 comes from RES, while more than 50% was obtained from biomass and waste. Production of primary energy from available sources shows Figure 1.

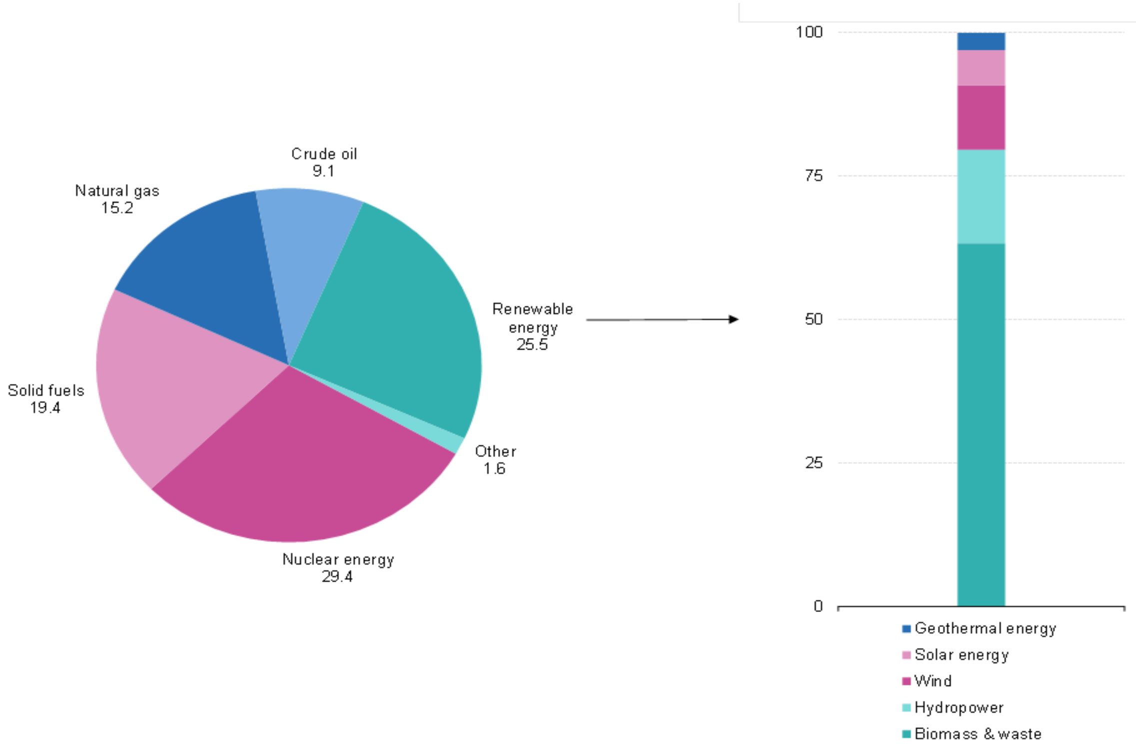

Figure 1: Production of primary energy, EU-28, 2014 (% of total, based on tonnes of oil equivalent)

Source: FAOSTAT (2014)

Thus, the population interest nowadays is focusing on renewable and sustainable energy sources which are required. Biomass seems to be widespread and effective resource of energy (Moskalík et al., 2008).

Enormous increase of primary energy production from renewable sources has been seen in the recent period (see Figure 2).

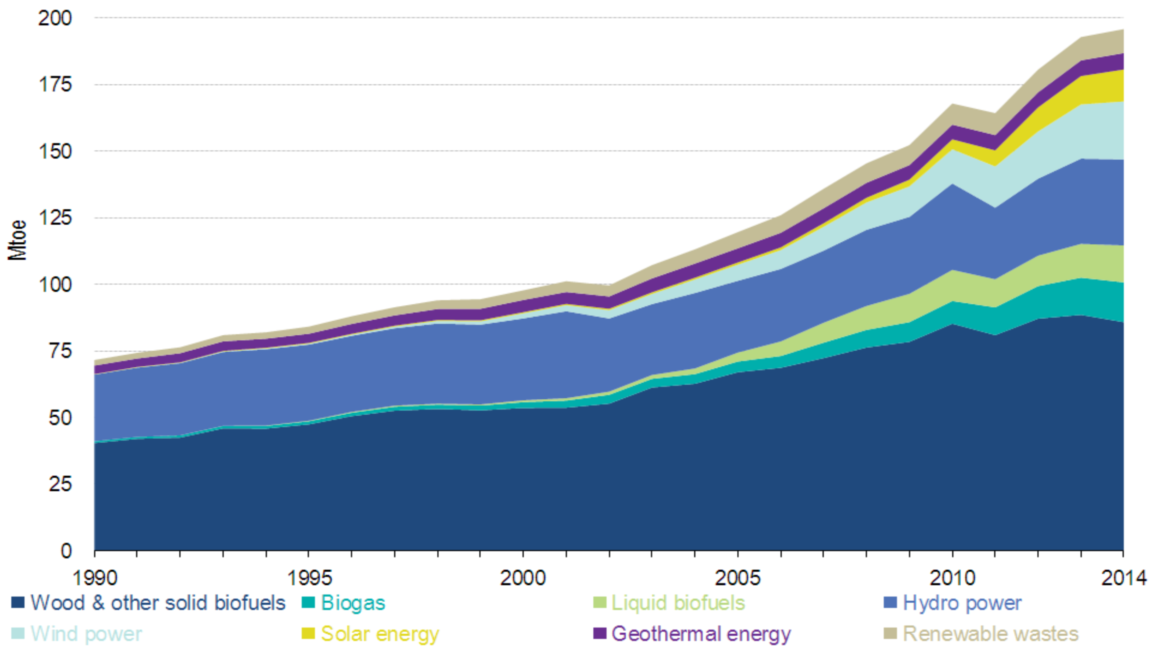

Figure 2: Primary production of energy from renewable sources

Source: FAOSTAT (2014)

Currently, different levels of policy and legislation were promulgated to encourage renewable energy, especially in developed countries. As of 2013, at least 144 countries which have set different renewable energy targets and policies have been supported at the national level for renewable energy development. The number of supported countries was only 55 in 2005. In 1012, an investment totaling $244 bilion was made on renewable energy, global investment increased by 8% compared to 2010. Approximately 19% of the word's energy consumption was provided by renewable energy sources in 2012 (Özakle et al., 2016).

The increasing of utilization of renewable energy sources leads to achieve one of Sustainable evelopment goals, namely goal number 7: Ensure access to affordable, reliable, sustainable and modern energy for all. This position puts renewable energy into higher awarness and gives it more importance and attention (UN, 2015).

The following chapters will outline each type of RES with emphasis on biomass (according to the focus of the present Thesis).

Solar energy

Solar energy has manadvantages in contrast with fossil-based energy sources and some renewables, since it is recognised as a clean, free, unlimited, easily accessible, and environmental and economical friendly energy source (Li et al., 2016). Solar energy use can be grouped into three categories: electricity production (mainly by solar PV panel), solar thermal energy and passive solar energy.

Photovoltaic systems (PV panels) allow the direct conversion of radiations into electricity through a photoelectric effect; in fact the term “photo” means light, while “voltaic” electricity. The intensity of the light determines the electrical power generated by each cell contained in PV panels. The efficiency of the photovoltaic modules is influenced by several parameters as solar irradiance, packing factor, and cell temperature (Arteconi et al., 2016; Tiwari et al., 2016).

The solar thermal systems were introduced in the 1970 s and respect to PV cooling systems can utilize more incident sunlight. The system produces electricity and also acts as a thermal absorber. A solar collector is linked with a photovoltaic panel to extract the excess heat from the module and to reduce the cell temperature, improving the cell efficiency. A fluid, in general, air, water, glycol, oil is used as a heat transfer medium in the solar collector. The thermal energy produced by solar collector can be used in space heating, water heating, and steam generation or stored in thermal storage (Tiwari et al., 2016).

According to Long et al. (2016) passive solar systems are refers to the use of sun’s energy for the heating and cooling of living spaces. In this systems, the buildings itself or some element of it takes advantage of natural energy characteristic in materials and air created by exposure to the sun. Passive systems are simple, have a few moving parts, and require minimal maintenance and no mechanical systems.

Wind energy

Much like solar energy, wind power comprises only a small amount of the total energy that reaches the Earth. Wind flows when the sun's rays unevenly heat the air in the atmosphere (Kumar et al., 2016). Wind energy can be used either directly as mechanical power or indirectly by converting the kinetic energy of wind into electrical energy. The most important part of any wind energy system is the wind turbine, which converts wind energy into mechanical power that can be utilizes in various applications. The design and size of turbine play a crucial role in electricity generation. Maximum wind capture and cost reductions are two primary motives of wind turbine research. Modern wind turbines can be divided into two types: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). HAWTs dominate the majority of the wind industry due to their greater efficiency and energy output in comparison to VAWTs. VAWTs are inherently problematic in that they are installed close to the ground and therefore have less exposure to wind, which in turn leads to less power output. In order to achieve the same outputs as that of HAWTs, VAWTs require more material and a greater size, which in turn result in a significantly greater cost. Nevertheless, VAWTs still have their share of advantages such as lower cuts in speed, low level of noise, and have been proven to be effective in rooftop and small scale applications (AWEA, 2014; Gasch, 2012).

Hydropower

"*Hydropower or hydroelectricity refers to the conversion of energy from flowing water into electricity. It is considered a renewable energy resource because the water cycle is constantly renewed by the sun*" (Muise, 2016).

Historically, one of the first uses of hydropower was for mechanical milling, such as grinding grains. Modern hydro plants produce electricity using turbine and generators. Hydropower is abundant, low cost source of power, despite high upfront building costs. It is also a flexible and reliable source of electricity compared to other renewable sources (except biomass), as it may be stored for use at a later time. Dammed reservoirs can also improve flood control, serve as a reliable water supply, and may be used for recreation purposes. Nevertheless, there are many concerns with hydropower. Damming a river has a significant impact on the regional ecosystem, by flooding upstream landscapes, impairing habitats for wildlife, blocking fish passages, and displacing local communities. Finally, dam failures can be catastrophic (Tahseen et al., 2016).

Geothermal energy

Geothermal energy is the heat energy present inside the earth surface in the form of hot springs, fumaroles, volcanoes, and geysers. This heat inside the earth is naturally created due to the continuous decay of fossil fuels (20%) and radioactive minerals (80%). The occurrence of geothermal energy is analysed in four different types, namely hydrothermal (the most explored), geo-pressured, hot rock, and dry rock (Younas et al., 2016).

Accessible geothermal resources have been used for more than a century for direct use (heating and cooling) and for indirect use (electricity generation by power plants). Geothermal technologies are currently producing base load electric generation in 24 countries and are used directly for heating and cooling in 78 countries. Thanks to recent technological development it is estimated that future geothermal deployment could meet more than 3% of global electricity demand and about 5% of the global demand for heat by 2015 (Bertani, 2015). Geothermal technologies are considered to be environmentally advantageous because they do not need combustion process emitting carbon dioxide (CO_2), with the only direct emissions coming from the underground fluids in the reservoir. Local hazards arising from natural phenomena, such as micro-earthquakes, may be influenced by the operation of geothermal fields, but they seldom reached levels high enough to lead to human injury or relevant property damage, and the expertise developed in such cases should be sufficient to prevent similar events in the future. Although geothermal energy has the potential to provide long-term, secure base-load energy and greenhouse gas emissions reductions with minimum and manageable environmental risks, it currently enjoys only modest growth per year with respect to solar or wind technologies (Pellizuone et al., 2016).

Biomass sources seem to be a prominent alternative energy source among others available regarding to the accessibility (Bilgili et al., 2016). Due to the focus of this Thesis next chapter is devoted to this topic.

2.1.1. Biomass

Biomass is defined by the solid fuels standard EN ISO 16559 (2014):

"An organic material that is plant or animal based, including but not limited to dedicated energy crops, agricultural crops and trees, food, feed and fiber crop residues, aquatic plants, algae, forestry and wood residues, agricultural wastes, processing by-products and other non-fossil organic matters".

According to Rawel et al. (2016) research on biomass conversion has been gaining a lot of interest because biomass is sustainable and renewable in nature and products from biomass can be obtained by different methods.

Biomass is generally available in localised manner in varying quantities and qualities trought the year and hance, region specific technologies have to be developed considering the end user requiment (Rawel et al., 2016).

Environmental assessment of biomass used as feedstock for energy production are more and more requested for understanding the real assets of bioenergy systems. In the last decades, biomass became one of the main feedstock for renewable energy production to be able to reach third target proposed by the EU commission: 20% of total energy consumption must be covered by renewables till 2020 (Morandi et al., 2016). The importance of biomass is increasing year by year due the fact that it is renewable feedstock, which is available in both rural and urban areas of all countries and it may be stored. According to Brown (2010) biomass energy supply chains were historically developed on available resources such as forest, agricultural and urban residues. Energy crops, i.e. plants, which are cultivated for production of energy, allow a better management of quantity and quality of biomass. There is, however, a trade-off with respect of land use available for food and feed production (Brown, 2015).

Biomass has been reported as a fourth largest available energy resource of the world. Biomass can also be referred as natural and inexpensive form of storage device for energy and energy could be utilized at any time (Acma et al., 2010). According to Abuelnuor et al. (2016) today, biomass contributed about 14% of the world total energy consumption, which is ranked as the fourth source of energy in the globe. It is main source of energy for many developing countries. This is as high as 20% to 33%, but for the industrialized countries, biomass contributed about 9% to 14% of the total energy supplies.

Biomass can be transformed into gas or liquid fuels via a variety of methods, such as gasification, pyrolysis, anaerobic digestion, fermentation and transesterification. It can also be utilized as a solid fuel and burned directly for the generation of the heat and power. However, biomass is characterized by its high moisture content, low calorific value and large volume or low density, which result in a low conversion efficiency as well as difficulties in its collection, grinding, storage and transportation. For those reasons, biomass is usually blended with coal for co-firing rather than used alone in power plants. In the past, a number of biomass pre-treatment methods have been developed to address the aforementioned disadvantages (Chen et al., 2015).

The energy density of biomass is usually in the range of 14,651 – 16,744 kJ (Chen et al., 2016). According to Toklu (2016) the net energy available from biomass when it is combusted ranges from about 8 $MJ.kg^{-1}$ for green wood to 20 $MJ.kg^{-1}$ for dry plant matter, to 55 $MJ.kg^{-1}$ for methane.

Biomass composition

The components of biomass include cellulose, hemicelluloses, lignin, lipids, proteins, simple sugars, starches, water, hydrocarbon, ash and other compounds. The species, type of plant tissue, stage of growth, growing conditions – these parameters affect the concentration of each class of compound varies (Khan et al., 2008).

The bulk composition of biomass in terms of carbon, hydrogen, and oxygen (C, H, O) does not differ much among different biomass sources. Typical (dry) weight percentages for C, H, and O are 30 to 60%, 5 to 6%, and 30 to 45% respectively. Share of C, H, O can be different for characteristic fuels. Nitrogen, sulphur and chlorine can also be found in quantities usually less than 1% dry matter, but occasionally over this. Nitrogen is a micronutrient for plants, it is critical for their growth. Certain inorganic elements can be found in high concentration as well. Biomass in general has less carbon, more oxygen, more silica, chlorine and potassium, less aluminium, iron, titanium and sulphur relative to coal (Faaij, 2004).

Khan et al. (2008) and Faaij (2004) note that certain types of biomass can also contain contaminating species on trace amounts depending upon the source of the fuel. For clarification, heavy metals (cadmium, lead etc.) are commonly found in woody fuels (mainly demolition food) from paints and atmospheric deposition source. These heavy metals make an important role of the emitted pollutants.

Fig. 3 shows the compositions and structural component of lignocellulose biomass.

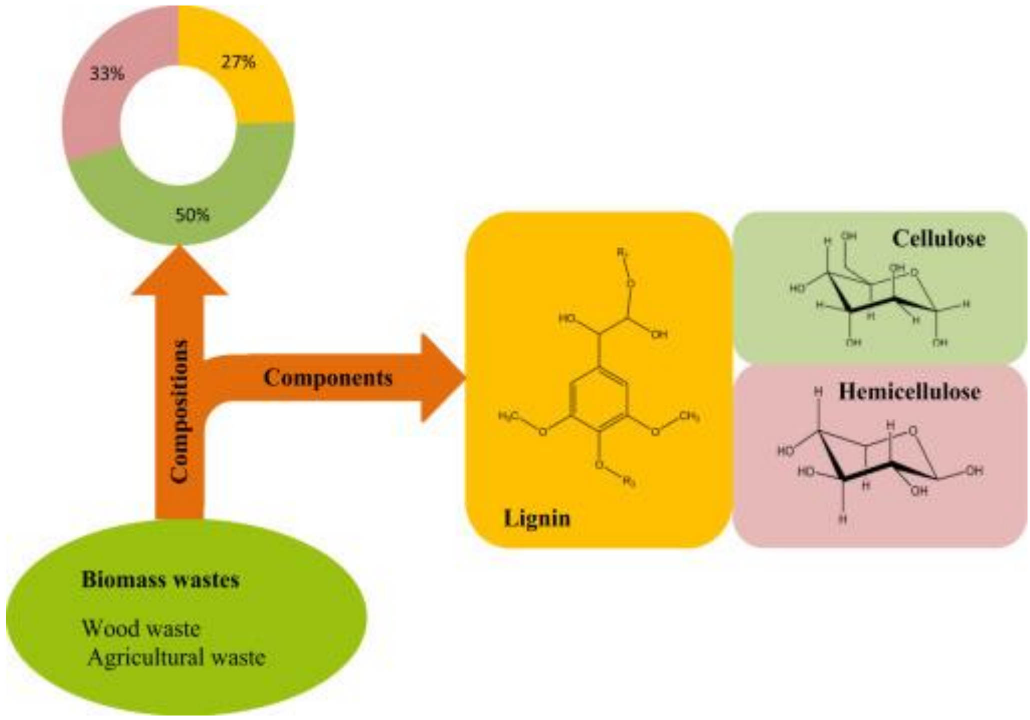

Figure 3: Composition and component of lignocellulosic biomass

Source: Kabir et al. (2016)

2.2. Biofuels

According to Escobar et al. (2009) researchers are continuously working in the biofuel production from the sustainable biomass since it is being an efficient alternative to replace non-renewable fuels.

The advantages of biofuels over petroleum fuels are:

- They can be easily extracted from the biomass
- They are sustainable due to biodegradable property
- Its combustion based on carbon-dioxide cycle
- More environment friendly (Escobar et al., 2009)

According to Gaurav et al. (2016) the biofuels are classified into three generations:

- First (biodiesel, vegetable oils - produced from the crop plants)
- Second (bioethanol, and biohydrogen - produced from agricultural by-products and energy plants which requires fertile lands for growth)
- Third (biogas, bioethanol and biobuthanol - produced from marine resources, seaweeds and cyanobacteria)

Biofuels of second and third generations are referred as advanced because they are still in research and development. There are biofuels based on lignocellulosic biomass, cellulosic-ethanol, and biomass-to-liquid and bio-synthetic gas. Second generation is made from non-food crops, corn, wood and energy crops (IEA, 2015; Converti et al., 2009).

On the other hand biofuels of first generation are referred as conventional biofuels. It includes well-established processes that are already produced on a commercial scale. The feedstock contains sugar-crops and starch-crops based ethanol, oil-crops and straight vegetable oil based biodiesel; thereafter in some cases animal fats and cooking oils or biogas derived through anaerobic digestion (IEA, 2015).

Biofuels produced from biomass are referred:

2.2.1. Gaseous and liquid biofuels

Gaseous biofuels

Biogas and syngas are two main examples of gaseous biofuel and their birth description is presented below.

Generally, the composition of **biogas** can be divided into two constituents: combustible components and non-combustible components. Guo et al., (2010) summarized that the composition of biological gas is likely to be methane (approximately 55-70% by volume) and carbon dioxide (30-40%). Depending on the raw materials and preparation technologies of biogas, other components include carbon monoxide, hydrogen, nitrogen and hydrogen sulphide (Papurello et al., 2015).

According to Guo et al. (2010) studies have shown that biogas can be prepared from various raw materials by thermochemical or biochemical conversion. The raw material properties have little influence on the thermodynamic process but have great impact on the progress of biochemical conversion. In particular, the composition and moisture of a raw material greatly influences biochemical conversion. The conversion enzyme is useful for one or several types of raw materials and cannot be applied to most types of raw materials. Compared to the biochemical method, the thermodynamic method generally requires higher temperature to achieve better conversion efficiency. This will consume extra energy. In the preparation of biogas, the selection of technical route is mainly determined by the types of raw materials and the distribution of resources. Papurello et al. (2015) noted that generally, the properties of raw materials in a particular region are relatively stable in each season every year. A biological preparation method for raw materials in a certain season is attractive for a particular region as it can ensure a low energy input and reasonable biogas output. However, it is worth noting that biological fermentation may consume water resource, which may lead to water pollution.

Conventional **syngas** production using gasification thermochemical process is a well-established practice. Synthesis gas or shortly syngas is a mixture of carbon monoxide, carbon dioxide and hydrogen. It can be obtained from different sources, for example from natural gas, biomass, coal or virtually any hydrocarbon feedstock, by reaction with steam or oxygen. Syngas is predominant intermediate resource for production of hydrogen, ammonia, methanol, and synthetic hydrocarbon fuels.

The production of syngas is highly endothermic and requires high temperatures (Moral et al., 2016).

Liquid biofuels

The most popular liquid biofuels are biodiesel and bioethanol.

Biodiesel is potential renewable and biodegradable fuel source comprising of fatty acid methyl esters (FAME). It is produced from transesterification reaction of animal fats or vegetable oils. It has been selected as a suitable alternative to conventional diesel fuel as it furnished several advantages such as reduced environmental emissions, renewability and enhanced lubricity. It is non-toxic, biodegradable an environmental friendly. Moreover, biodiesel is completely miscible with conventional diesel and several blends of diesel-biodiesel can be used in the currently employed compression ignition engines

without any modification. The usage of diesel and biodiesel blends can improve effects on emissions (Al-Dawody et al., 2013; Vedaraman et al., 2011).
Sebayang et al. (2016) note that **bioethanol** is produced by the alcoholic fermentation of different kinds of raw materials, which are classified into three categories according to their chemical composition: sucrose-containing feedstock, starch materials and lignocellulosic materials. The most commonly used raw materials are wheat, corn, potatoes, sugar cane or sugar beet. However, the use of edible feedstock for fuel production raises concern on global food security, which hampers the worldwide acceptance of using bioethanol as a fuel. For this reason, much effort is being made to produce bioethanol from non-edible feedstock such as lignocellulosic and starchy agricultural feedstock (Alvira et al., 2010; Sebayang et al., 2016).

This Thesis is focused on solid biofuels, concretely on briquettes from Miscanthus. Solid biofuel is one of the means that is storable and transportable with low cost (Zhou et al., 2016). Therefore next chapters provide deeper attention into this topic.

2.2.2. Solid biofuels

Biomass for energy production includes a wide spectrum of materials which can be classified according to many criteria such as sources of biomass or type of conversion process (Dembiras, 2009). Solid biofuels are largely produced from lignocellulosic biomass. It is promising energy source, because it is available in large quantities that do not conflict with food production and may contribute to environmental sustainability. According to Tumuluru et al. (2010) and Dembiras (2009) primary sources of lignocellulosic biomass include:

- Agricultural residues
- Energy crops
- Forest products
- Municipal and solid waste

According to the norm EN ISO 17225-1 (2015) the sources from which the solid fuels could be produced are divided based on their origin into following four groups:

- Woody biomass
- Herbaceous biomass
- Fruit biomass (non-edible parts of fruit)
- Blends and mixture (where blends are intentionally mixed with known ratio and mixtures unintentionally mixed)

Solid biomass is used as a renewable energy source to replace non-renewable fossil fuels. Firing biomass instead of fossil fuels reduces carbon dioxide emissions. The use of solid biomass is a way of increasing energy independency in many areas, because various biomasses can be locally produced whereas fossil fuels are often imported (Popova et al., 2016).

Tumuluru et al. (1010) note that solid biofuels are produced by following processes:

- By grinding, chipping, cutting (products are woodchips, logs, shavings)
- By pressing – densification (products are briquettes, pellets and straw bales)
- By slow pyrolysis (product is charcoal)
- By torrefaction (products are torrefied fuels)

Densification of Biomass

Densified biofuel is defined by the standard EN ISO 16559 (2014) as "*solid biofuel made by mechanically compressing biomass or thermally treated biomass to mould the solid biofuel into a specific size and shape such as cubes, pressed logs, biofuel pellets or biofuel briquettes*".

Biomass is available in large quantities but to be utilised in energy systems the bulk density of the material should be increased. Due to the low bulk density and high moisture content of the raw and non-processed biomass is not suitable for producing energy directly. Therefore, densification is one of the essential pre-processing steps in the biomass conversion process for the successful use of biomass materials in various applications, as it provides more efficient handling, storage, transportation, and use of the material (Blasi, 2009).

A large number of process parameters influence biomass compression, and thus affect machinery efficiency and particular energy consumption. The mechanical behaviour of biomass depends on stress, strain, strain rate, material composition, moisture content, process temperature, material size and shape (Popova et al., 2016).

Pellets

Pellets are highly compressed granules of cylindrical shape, produced most often 6 mm diameter and length from 5 to 40 mm. It is usually made of wood residues- from sawdust or wood shavings, further from agricultural residues (Stupavský, 2010). The bulk density and mechanical strength of pellets depend on type of biomass resource used. Chen et al. (2016) found that the bulk density of wheat straw pellets is about 408 kg/m^3, whereas 567 kg/m^3 for maize straw pellets.
According to Chen et al. (2015) pelletisation is one of the technologies that have been proposed to mechanically increase the bulk density of biomass. The advantages of pelletisation go beyond increases in bulk density, as the handling and storage of pelleted biofuel can be performed similar to free-flowing granular products, such as corn, soybeans and wheat. Biomass pellets have multiple end use applications which range from smaller scale combustion for residential heating to more industrial scale where pellets could be co-fired with coal at the power plants. Worldwide, the total production of pellets increased 10 times from 2000 to 2010 with the US being one of the leaders in pellet production (Samuelsson et al., 2012).

Basics technical parameters of pellets produced from biomass according to Stupavský (2010):

- Calorific value: 16-18 MJ/kg
- Pellet density: about 850 kg/m^3
- Moisture content: max. 10%

The pelleting process is mainly adapted to the specific biomass feedstock, but usually includes the following stages (show Figure 4).

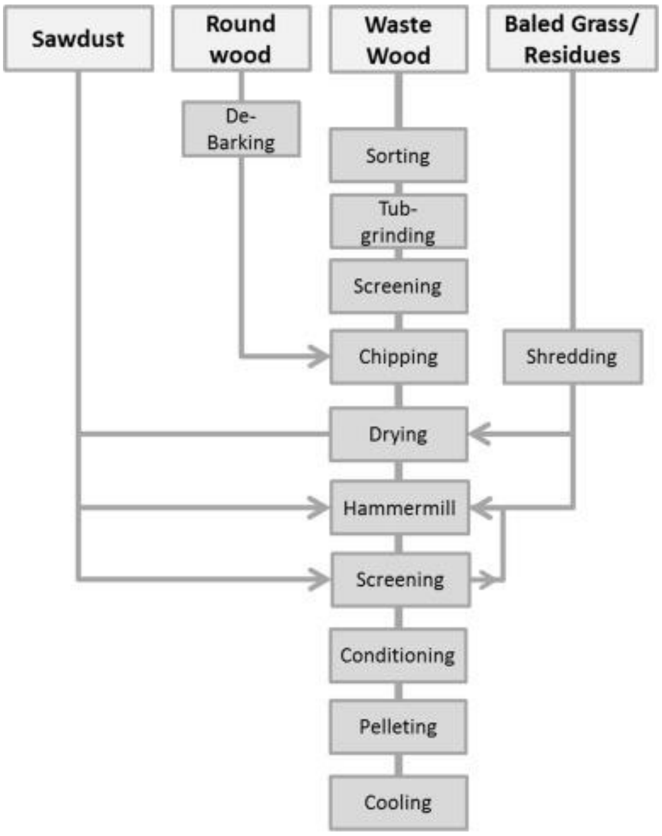

Figure 4: Typical pelleting process flow for wood and baled biomass

Source: Whittaker et al. (2016)

According to Stolarski et al. (2013), in general, briquette fuel has also better energy parameters, higher density, higher calorific value and lower moisture content as compared to the raw materials, and moreover locally produced briquette is an attractive energy carrier for individual consumers in different parts of the world, especially in developing countries (Stolarski et al., 2013). Next chapter describes briquettes.

2.2.2.1. Briquettes

The densification process of biomass, such as briquetting, consists of the application of pressure on a mass of disperse particles, aiming to produce a solid, compact, geometric high-density material (Stolarski et al., 2013).The briquettes are manufactured by pressing into diverse shapes which are shown below (Fig. 5).

The briquetting can increase the bulk density of biomass from 100-200 to about 1,200 kg/m^3. In comparison with loose raw biomass, the briquetting of biomass can greatly improve the burning efficiency and reduce pollutant emission and make biomass to be transported with long distance and co-fired with coal in conventional coal-fired plants (Chen et al., 2016). Due to the low moisture of the briquettes, the furnaces rapidly reach high temperatures, producing less smoke and soot. Moreover, the material resulting from compression higher flame temperatures and has increased thermal regularity, thus maintaining homogenous heat. The quality of briquettes from biomass relies on biomass properties such as heating value, moisture content and elemental composition.

Stolarski et al. (2013) have published that ash content is an inactive material and does not contribute to the total heat released by combustion. It reduces the heating value of the material. The chemical composition of ash is an important parameter which must be considered during the thermochemical conversion which can lead to significant operational issues such as formation of slag at higher temperatures. This factor reduces the process efficiency and increasing the process costs (Avelar et al., 2016).

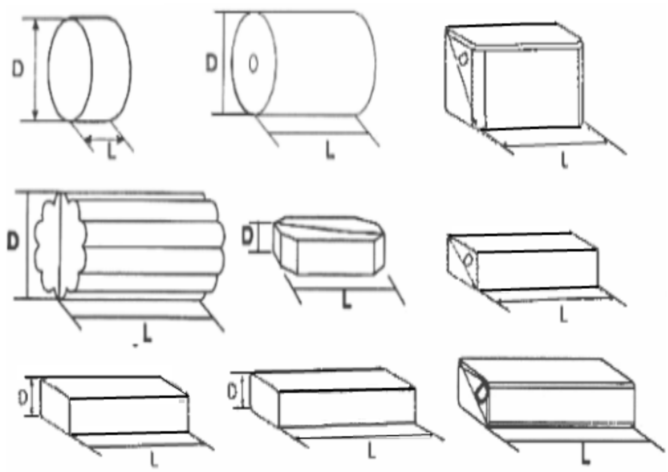

Figure 5: Species of briquettes shapes

Source: Standard EN ISO 17225-7 (2014)

Mechanical durability (DU) and particle density are the main parameters characterizing the mechanical quality of densified solid biofuels like pellets and briquettes. Both of the fuels are sensitive to mechanical wear, which leads to production of fine particles or dust during transport, storage or transhipment. Dust emission are not only an inconvenience for the customer, moreover they are also health hazard. In addition, fine particles and dust can disturb feed systems of boilers and may lead to inhomogeneous combustion processes. Finally, dust may contribute to fire and explosion risks during handling, storage and transhipment.

According to EN ISO 16559 (2014) mechanical DU is a quality parameter that is defined as the ability of densified biofuels to remain intact when handled. It is measured by the resistance of densified fuels towards shock or/and friction. Therefore, DU is an important quality parameter with regard to handling and transportation processes of briquettes and pellets (Temmerman et al., 2006).

2.2.3. Thermal processing of biomass

A large number of suitable technologies for energy production from biomass are available. The most appropriate technology depends on its availability, price, reliability, efficiency, environment and other criteria (Motlík et al., 2002). Biomass can be converted to various forms of energy by two types of processes: thermo-chemical and biochemical. Biochemical processes decompose the biomass into biofuels by the action of living organism or their products. Biochemical processes produce the large amount of hydrogen in comparison with the other processes. However, the efficiency of the biochemical process makes them less attractive for industries as compared to the thermo-chemical processes (Sharma et al., 2016). In thermo- chemical conversion processes, biomass breaks down into its constituents like bio-fuels, gases and chemicals by applying heat and pressure. Combustion, gasification and pyrolysis are types of thermo-chemical processes (Motlík et al., 2002; Sharma et al., 2016).

More detail insight into thermo-chemical processes, with emphasis on combustion which is crucial for this Thesis, provides the following chapters.

2.2.3.1. Combustion

In accordance with Mathioudakis et al. (2016) the process of the combustion is an overall exothermic set of reactions. The energy stored in the chemical bonds of a fuel is converted to heat energy. It can be used in different branch such as heavy industry and power plant to generate required steam for turbines that finally produce electricity and heat. In the case if biomass, the combustion means burning of organic materials. The most widely used fuel for burning is wood. Nevertheless there is an increasing interest in other biomass types such as tops, branches, bark, straw, sawdust waste wood and energy crops.

The biomass combustion is a series of chemical reactions in which carbon is oxidized into carbon dioxide, and hydrogen is oxidized into the water. Incomplete combustion leads to generation of many unwanted products due to lack of oxygen (Abuelnuor et al., 2014).

Fig. 6 shows the biomass combustion diagram and carbon cycle closed loop.

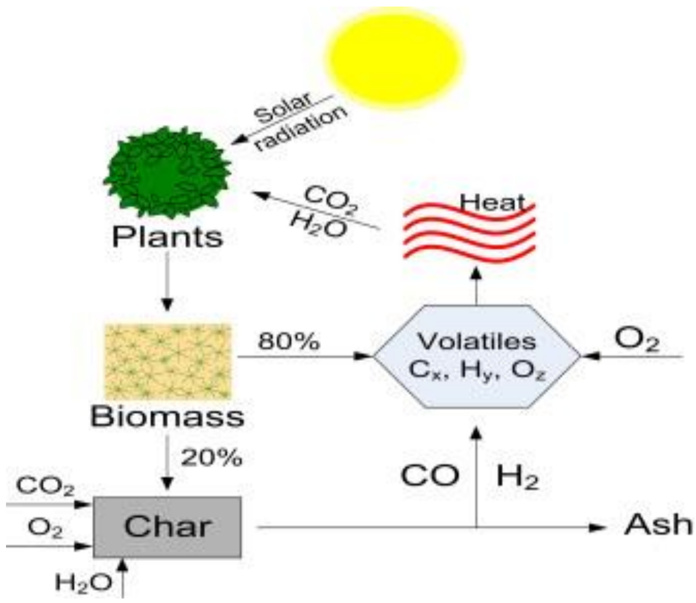

Figure 6: Biomass combustion diagram and carbon cycle closed loop

Source: Abuelnor et al. (2014)

Biomass combustion can be seen to occur in four steps. First it dries. Second, as surface temperature increases, biomass starts generation of organics, which exit through micropores in fuel. Then flames appear until the remaining char combustion takes over and fuel particle glows. Lastly, the remaining ash undergoes further reactions depending on the surroundings.

Further thermo-chemical processes are pyrolysis and gasification.

Pyrolysis is the thermal destruction of biomass in an anaerobic environment, without addition of steam or air. The products are gases and condensable vapours (Evans et al., 2010). Depending on the desired product (biochar or liquid oil), lignocellulosic matters are decomposed by slow or fast pyrolysis. Slow pyrolysis produces primarily biochar, the residual tar and syngas are rarely attended for any uses. Fast pyrolysis is a promising technology which converts lignocellulose biomass to mainly bio-oil and other chemical. In this process, biomass is heated up to 400-600 ˚C at a very high heating rate (500 ˚C.s^{-1}) in the absence of oxygen. The organics vapours are rapidly cooled down and condensed to a liquid product, known as bio-oil, which is main product of the fast pyrolysis. Bio-oil can either be combusted in boilers, engines and turbines to generate heat or power, or be upgraded to produce transportation fuels and commodity chemicals (Luo et al., 2017; Kabir et al., 2016).

In **gasification**, biomass is partly oxidises by controlling oxygen by the addition of steam. The products are combustible gases, which have a high calorific value (Evans et al., 2010). Gasification is performed at high temperatures, in the range of 800-1,000 ˚C. In gasification, steam gasification has attracted the highest interest as it offers higher amount of H2/CO and hydrogen yield. Reason for the transition from fossil fuels to hydrogen gas is its environmental advantages as a clean fuel and high calorific value which makes it more energy efficient. So, hydrogen has become a focus of renewed interest in the industries all over the world (Sharma et al., 2016).

2.3. Energy crops

Vegetative biomass consists of living plant species all around us. As the plant grows, they store sun’s energy in their leaves, bark, fruit, leaves and roots. Energy crops are so diverse that they grow in every part of the world (El Bassam, 2010). The term “energy crops” is used for both annual and perennial crops on agricultural land intended solely for energy purposes (Jezierska-Thöle et al., 2016). According to El Bassam (2010) the main goals of growing dedicated energy crops can be recapitulated as follows:

- The production of starch and sugar plant to produce ethanol (barley, potato, maize, sugar beet, sugar cane, etc.).
- The growing of oil crops as feedstock for production of biodiesel (cotton, oil palm, hemp, jojoba, sesame, rape, etc.).

- The cultivation of solid biomass to obtain electricity and heat by direct combustion or by conversion for use as fuels (willow, poplar etc.) (more details about biofuels production provide the chapter 2.2).
- The growing of energy crops to produce biogas (rape).

In accordance with Sladký et al. (2002) and Cosentino (2007) ideal energy crop should be characterized by the following features:

- High yield (maximum production of dry matter per hectare)
- Low energy inputs during production/cultivation
- Low costs
- Composition with the least contaminants
- Low nutrient requirements
- Positive energy balance

Desired characteristics will also depend on local climate and soil conditions. And thus, water requirements can be a major constraint in many areas of the world and makes the drought resistance of the crop an important factor. This is why energy crops should only be grown in climates to which they are adapted. Other important factors are pest resistance and fertilizer requirements (McKendry, 2002).

Among these energy crops, giant Miscanthus is less dependent on favourable soil and climatic conditions, requiring fewer inputs of agrochemical and not competing with food production (Kolodziej et al., 2016).

Next chapters provide information about above mentioned crop, which is a target crop for the presented research.

2.4. Miscanthus

Background on Miscanthus production:

2.4.1. General characteristic

Miscanthus is a large herbaceous, perennial and rhizomatous grass from Gramineae family (Poaceae) which was imported to Europe from East-Asia. Before being considered as an energy crop, Miscanthus was cultivated in Europe as an ornamental plant in 1930s (Heaton, 2004; Dierking et al., 2016).
Inflorescence and rhizomes of *Miscanthus sinensis* (shorten *M. sinensis*) are to see in Figure 7.

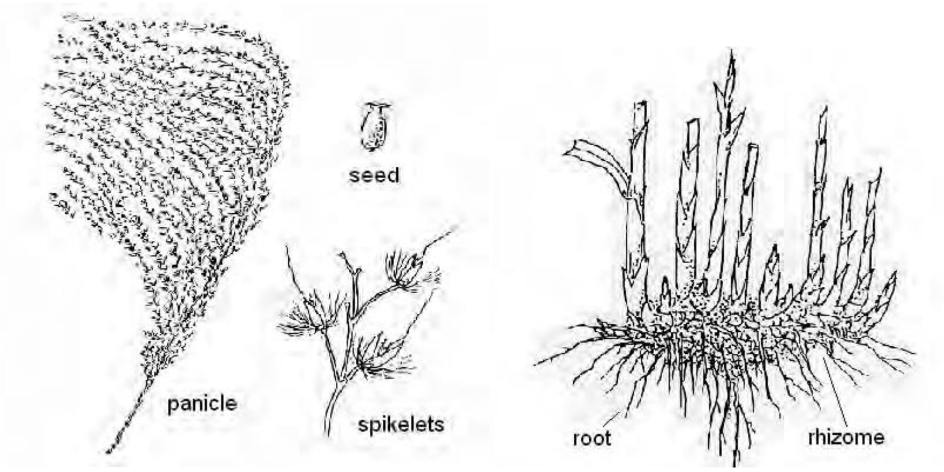

Figure 7: Inflorescence and rhizomes of *M. sinensis*

Source: Xi (2008)

The common name of Miscanthus applies both to species and to interspecific hybrids framed within the genus Miscanthus. Although there are about 17 botanical species, most European trials have involved clones of *M. x giganteus* Greef & Dauter, a vigorous triploid hybrid from *M. sinensis* (tetraploid) x *M. sacchariflorus* (diploid), both species also used individually. These three are of a great significance for energy purposes (El Bassam, 2010).

The yield potential of Miscanthus for cellulose fiber production was investigated in the late 1960s in Denmark. Then, trials for bioenergy production started in Denmark in 1983, spreading to Germany in 1987 before more widespread evaluation throughout Europe (El Bassam, 2010).

While there is very large variety of Miscanthus species, literature assessing the economics of Miscanthus nearly exclusively deals with *Miscanthus x giganteus*. According to Krasuska (2012) moreover using Miscanthus for energetic uses, this large perennial crop has also potential to serve as feedstock to textiles or construction materials. With its C4 photosynthesis process, typical for grasses of arid regions such a sugar cane, corn or millet, Miscanthus converts sunlight energy more efficiently into biomass energy than C3 crops and has the ability to cope with hot and dry areas that are exposed to high solar radiation, comparable to cropland which is alternatively dedicated to corn production (Vavrova et al,. 2012).

According to Witzel (2016) nevertheless even in cooler locations Miscanthus has proven high productivity, which qualifies it as a potential plant for a central to northern Europe setting, where there is high demand for biomass for energy uses.

The next section individually introduces key species of Miscanthus for present Thesis.

Miscanthus sinensis

M. sinensis is a perennial grass growing on hillsides and field margins in temperate regions, with short rhizomes. Culms are densely tufted, erect or half-erect 0.5-3.3 m tall and 3-7 mm in diameter near base. Leaf blades are 20-70 cm long and 0.6-1.2 cm wide with very rough margins, the midrib is white. The ligules are conspicuous, short ciliate on upper margin. The panicle has 10-25 racemes which are 10-30 cm long, slightly nodding, the central axis shorter than the racemes, i.e. shorter than half of the whole panicle. The flowering and seed-ripening time is from July to December (El Bassam, 2010).

Miscanthus x giganteus

M. x giganteus is a triploid perennial plant, with thick and stout rhizomes. The culms are 2.5-3.5 m long, the nodes without hairs. Root promodia and aerial branches at lower nodes sometimes observed. The leaves are cauline, the leaf blades linear, >50 x 3.0 cm, the ligule truncate with hairs (2-3 mm). The inflorescences are about 30 cm long, the rachis of the panicle 15 cm long. The spikelets are 4-6 mm long, longest pedicel 4 mm long. The three anthers are 2 mm long. The callus hairs are about twice as long as the spikelet. The flowering time is between September and November. *M. x giganteus* is a natural hybrid between *M. sacchariflorus* and *M. sinensis* (Lewandowski, 2003; El Bassam, 2010).

2.4.2. Propagation and cultivation

According to Aravindhakshan et al. (2010) Miscanthus is considered as a sterile and non-invasive plant. Therefore vegetative propagation of Miscanthus is required. Plantation on rhizomes or pre-cultivated plantlets (micro-propagation) with a density of 1-2 m^2 takes place in spring with attention to frost since rhizomes are sensitive to temperatures lower than -3 ˚C. Rhizome of *M. x giganteus* is illustrated in Figure 8. After soil preparation and plantation, which can be carried out mostly with common farm equipment such a plows and a modified potato planter, an establishment of 2-4 years follows, where only limited biomass yields are achieved (Venturi et al., 1999).

Figure 8: Rhizome of *Miscanthus x giganteus*

Source: Poncarová (2009)

During this establishment period maintenance work such as weed control and replanting of frost losses is necessary until Miscanthus reaches its competitiveness. Fertilization needs are low in compared to conventional crops, but clearly depend on soil properties and nutrient removal from the field (Aravindhaksah et al., 2010; Venturi et al., 1999).

Morandi et al. (2016) recommended following field operations during the cultivation of Miscanthus (show Fig. 9).

Year 1	Year 2	Years 3–15	Year 16 (4 months)
Ploughing	Weeding	Biomass harvesting	Crushing
Harrowing			
Cultivating			Harrowing
Planting			
Flattening	Biomass harvesting		Chiselling
Weeding			
Weeding			Weeding
Crushing			

Figure 9: Field operations for growing and harvesting Miscanthus biomass

Source: Morandi et al. (2016)

2.4.3. Harvest and yield

According to Hilst et al. (2010) the yield depends in particular on the harvest date. Storing huge amounts of nutrients such as K and N in its rhizomes during winter, a harvest date in spring allows Miscanthus to get along with low fertilization since only the withered above-ground parts of the plants are harvested. Additionally, only stems are harvested, while the litter remains on the ground, forming a layer of mulch. Another advantage of a late harvest date is high share of dry matter (moisture content approximately 15%) with low mineral content of the harvested material thus landing to reduced costs for transport, storage and higher calorific quality. Harvest can be carried out with conventional farm equipment like self-propelled corn harvesters and ballers (Diamantidis et al., 2010). Due to high cost of this machinery, Miscanthus harvest is usually outsourced to contractor. The yield potential of a fully established 3-4 m tall Miscanthus plantation usually reaches from 10 to 20 t $DM.ha^{-1}$ which depends on local agronomic conditions. The energy content of Miscanthus is comparable to wood with around 17 $MJ.t^{-1}$ potentially enabling Miscanthus to act as a substitute for woody biomass. As a perennial crop, Miscanthus needs to be planted only once (apart from selective replanting after the first winter) and afterwards provides annual yields over a lifespan of 10-20 years. At the end of lifespan, when yields are decreasing, the

Miscanthus plantation is closed using herbicides to kill the plants and underground parts of the plant are removed (Vitzel, 2016; Venturi et al., 1999).

2.4.4. Crop requirements

Climate

Miscanthus, as it originates from tropical and subtropical climates, it has similar climatic preferences; these are high temperatures, heavy and well distributed rains and high isolation. Miscanthus is the most adapted C4 crop to temperature climates. As it is C4 plant, if it grows in temperate climates, it has a low growth rate and low tolerance to cold. However, the fact that Miscanthus can grow in temperate climates, shows that there are several genotypes that become adapted to these climates. That is reason why this crop can be grown in Europe (Xi, 2008).

According to El Bassam (2010) more specific climate requirements, depends on the genotype. For example, *M. sinensis* is more cold resistant than *M. x giganteus. M. sinensis* rhizomes stand temperatures of -4.5 ˚C and rhizomes of M. x giganteus dies with temperatures below -3 ˚C. As regards *M. x giganteus*, it begins to grow from the dormant winter rhizome when soil temperatures reach 12 ˚C and leaf expansion occurs between 5 and 10 ˚C.

Soil

Miscanthus can be grown on a wide range of soils. The most important soil characteristic is the water holding capacity. Miscanthus should be cultivated on soil with high water holding capacity, but at the same time, without any risk of becoming flooded because Miscanthus cannot tolerate it (DEFRA, 2007).

Generally, the properties of a good soil for growing Miscanthus should be: soils with sandy or silt loam texture, well aerated, with high water holding capacity and rich in organic matter. It is also known that soils where corn can be grown could be also suitable for Miscanthus. It is tolerant of a wide range of pH, but the optimum is between 5.5 and 7.5 (El Bassam, 2010).

2.4.5. Studies focused on Miscanthus

Objectives of research which was held in US in 2010 were: (a) to determine differences in biomass yield among various *Miscanthus x giganteus* genotypes as influenced by N management during establishment, (b) to quantify the impact of genotype and N management composition and (c) to determine how *M. x giganteus* and N management influence nitrogen use efficiency (NUE). Four *M. x giganteus* genotypes were planted near Schochoh (Kentucky) and Lafaytte (Indiana) in 2010. A two-year total N application of 150 $kg.ha^{-1}$ was applied using various combinations of 50, 75 and 100 $kg.ha^{-1}$. Control N rates include 0 and 150 $kg.ha^{-1}$ each year. Yield, composition and NUE of the MS clone and IL clones were similar. Two-year cumulative yields of Nagara were higher than the other genotypes in KY, and the IL clone in IN. There was no response of yield to N on the silt loam soil in KY, whereas high biomass yields were achieved with 50 $kg.ha^{-1}$ of N on the sandy loam soil in IN. Yields of plots provided high N in Season 1 were similar to unfertilized control plots in Season 2 suggesting little N carry over from Season 1 to 2. Biomass fiber concentrations were not influenced by N-fertilization, but high leaf retention of the Nagara lines reduced biomass cellulose and lignin concentrations. Site-specific genotypic differences in NUE were observed. **Annual N application of 50 $kg.ha^{-1}$ was recommended to enhance Miscanthus yield during establishment on the coarse-textured soils** (Dierking et al., 2016).

In another experiment, Miscanthus was cultivated in the Bourgogne (France) region and it was used as feedstock to produce pellets. In this study, **emergy assessment of different logistic (harvesting) strategies for Miscanthus production** in the Bourgogne region was presented. Emergy assessment is a particular methodology suited to quantify the resource use of a process and to estimate the percentage of renewability of product or service. The case study included all phases from growing Miscanthus, harvest the biomass as chips or short- or long- stranded bales and its distribution to a bioenergy plant. The aim of this study was to evaluate the sustainability performance of the whole process, from the field to the plant’s gate. The emergy flow that represents the environmental cost of the whole process, the percentage of renewability (%R) and the Unit Emergy Values (UEV) that represent the resource use efficiency of the final products for each phase were calculated. Since Miscanthus is reproduced by rhizomes, in addition to the system for growing and distributing Miscanthus biomass, the system for producing Miscanthus rhizomes was also analysed and UEV for Miscanthus rhizomes of 1.19E+05 seJ/J was obtained. Moreover, due to the absence of other emergy assessments of Miscanthus biomass for comparison, a sensitivity analysis has been made by considering different transport distances and different aboveground biomass yields. Comparing the harvesting methodologies, **the bales made with short strands has the best performance**. The aboveground biomass production was found to have an Energy Return On Energy Investment (EROEI), which is the double of that from an experimental Miscanthus field in Italy. However, this implied a trade-off for the net energy production of about 50% (Morandi et al., 2016).

3. Objectives and hypothesis

3.1. Overall objective

The main aim of the Thesis was to compare two varieties of Miscanthus (*Miscanthus sinensis* and *Miscanthus x giganteus*) for energy purpose utilization based on assessment of briquettes quality, emissions released during combustion and biomass energy yields.

3.2. Specific objectives

To achieve the overall objective the following supplementing specific objectives were defined. Those specific objectives are set to meet the main objective and they had been defined as follow:

i. to determine physical and chemical properties of two varieties of Miscanthus according to EN and ISO standards;
ii. to densify Miscanthus biomass crushed into different fractions to the form of solid biofuel (briquettes);
iii. to analyse emission properties and suitability of Miscanthus based biofuel for combustion;
iv. to calculate maximum energy potential (biomass energy yield) for both crops.

3.3. Hypothesis

i. Both varieties of Miscanthus can be transformed into briquettes, which can meet the international standard for graded non-woody briquettes.
ii. *Miscanthus x giganteus* is more suitable for energy use due to better properties, in general.
iii. Different fractions used for briquettes' production have no effect on emission released during combustion.

4. Methodology

The methodology of this diploma Thesis is divided into two main parts. The first part of methodology is focused on compilation of literature review of this Thesis, the second and the key part describes practical part of this Thesis.

4.1. Methodology of literature review

The tool for elaboration of literature review of this Thesis was the web search for scientific articles and technical books. The scientific articles, which constitute large part of present Thesis, were obtained from scientific databases, namely Scopus and Science Direct and also from web search engine Google Scholar. The articles were searched based on combination of key words: *Miscanthus sinensis*, *Miscanthus x giganteus*, biomass, biofuels, solid biofuel, briquettes, combustion, pressing process, etc. The scientific articles citied in this Thesis were published in scientific journals, namely: Fuel, Biomass and Bioenergy, Renewable and Sustainable Reviews, Renewable energy, Journal of Cleaner Production, Journal of the Energy Institute, etc.

4.2. Methodology of practical research

The methodology of practical research is described below. It is including the following parts:

4.2.1. Material

In order to conduct the present research the above ground biomass of two kinds of Miscanthus (*Miscanthus sinensis* and *Miscanthus x giganteus*) was used. The biomass was gained from experimental field, which is located in CULS areal in Prague, Czech Republic (established in 2007). The harvest took place in May 2016. Above ground biomass was obtained with very low moisture content (*Miscanthus sinensis* 20.8% and *Miscanthus x giganteus* 15.4%). After harvest material was dried naturally in storage hall.

4.2.2. Methods

Firstly, obtaining of biomass was done. Secondly, there were determined physical and chemical properties of two kinds of Miscanthus biomass according to the standards for solid biofuels given by European Committee for Standardization. Thirdly, briquettes from different initial fractions of Miscanthus biomass were produced and finally determination of emission released during briquettes' combustion was conducted.

Individual parts of present research were performed in the Research Institute of Agricultural Engineering in Prague (RIAE), in the Laboratory of Biofuels FTA, CULS Prague, and also in the Faculty of Engineering, CULS.

4.2.2.1. Harvest

Harvesting of two kinds of Miscanthus (*Miscanthus sinensis* and *Miscanthus x giganteus*) took three days in May, 2016 and it was performed manually with the help of a gasoline-powered hedge trimmer Husqvarna 123 HD 65 X. The plants were tied into bundles (shown in Fig 10). Thereafter the bundles were cut from the bottom of the plants.

Figure 10: Harvest

Source: Author (2016)

4.2.2.2. Preparation of analytic sample

The preparation of analytic sample from dry above ground biomass of Miscanthus took place in the Laboratory of Biofuels, CULS. According to the standard EN 14780 (2011) the raw biomass was milled to the particles' size lower than 1 mm. This homogenous sample was prepared by using grinding knife mill Retsch Grindomix GM 100 (see Figure 11).

Figure 11: Preparation of analytical sample

Source: Author (2016)

4.2.2.3. Determination of moisture content

The moisture content of biomass for purposes of present Thesis was determined according to EN 14774-3 (2010): Solid biofuels- Determination of moisture content- Oven dry method. The measurement of moisture content was held in the Laboratory of Biofuels, CULS. For determination was used drying oven Memmert (model 100-800). For weighing during this procedure was used digital laboratory balance Kern (model EW 3000-2M) with readout 0.1 mg.

The principle of determination: Empty dishes were putted into the oven (shown in Figure 12) and then the oven was heated up to 105 ˚C. When temperature in the oven was constant, the dishes were removed out and putted into the desiccator for 15 minutes. The empty dishes were weighed in a moment when temperature of dishes was about room temperature. After that samples of Miscanthus were putted into dishes and it was weighed again. Next, the weighed samples were placed into the oven and dried out until constant weight of the samples. After described drying process the dishes were remove out from the oven and placed into the desiccator with silica gel for next 15 minutes and reweighed.

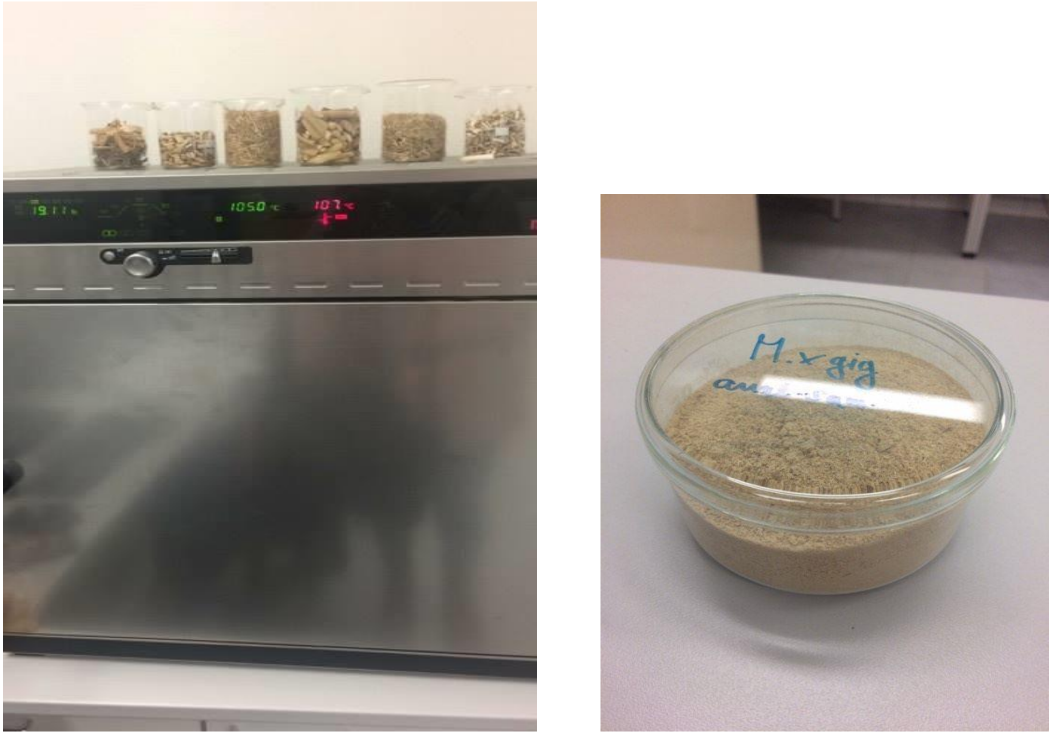

Figure 12: Drying oven Memmert (model 100-800) and measured sample

Source: Author (2016)

Moisture content was determined according to formula:

$$MC = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \ \ [\%]$$

Where:	MC	- moisture content [%]
	m_1	- the mass of empty dish [g]
	m_2	- the mass of the dish plus sample before drying [g]
	m_3	- the mass of dish plus sample after drying [g]

Samples were measured three times, and the resulting moisture content was found as the mean of duplicate determinations with respect to repeatability precision, i.e. difference between two individual results of each material was not more than 0.2 % absolute.

4.2.2.4. Determination of total content of carbon, hydrogen and nitrogen

Carbon (C), hydrogen (H) and nitrogen (N) content was determined according to the standard EN 15104 (2011): Solid biofuels- Determination of total carbon, hydrogen and nitrogen- Instrumental method. The measurement was carried out in the Bioenergy centrum of RIAE. Automatic Elemental Determinator LECO CHN628 was used.
The principle of procedure: 0.1 g of analytic sample was placed into aluminium foil and then into the equipment. The calibration and adjustment of the calibration functions was carried out in accordance with the manufacturer’s instructions. In the first stage in the equipment the atmospheric gas was removed. In the second stage during operating temperatures 1,050 ˚C with pure oxygen the samples were completely combusted.
The total content of C, H, N was recorded as percentage by mass, the arithmetic mean of two determinations was considered as a result.
Automatic Elemental Determinator LECO CHN628 is shown in Figure 13 below.

Figure 13: Automatic instrument LECO CHN628 Series Elemental Determinator

Source: Author (2017)

4.2.2.5. Determination of ash content

In present research the ash content was determined in Laboratory of Biofuels, CULS according to the standard EN 14775 (2009): Solid biofuels- Determination of ash content in Muffle furnace LAC. Biomass samples were crushed down to the particle size lower than 1 mm and dried in the oven before determination of ash content. Ash content was stated by calculation of weight of the inorganic residues after combustion of samples in defined temperature. Ash content analysis was performed on analytic samples.

The principle of procedure: In the course of first stage the empty dishes were heated up at 550 ˚C in the furnace for one hour. After that the dishes were cooled on heat resistant plate for 10 minutes and then putted into the empty desiccator and cooled to room temperature. In second stage, the minimum sample mass (about 1 g) was added into the dishes and weighed. As follows the dishes were placed into the cold muffle furnace and then the temperature inside the furnace was continuously raised up to 250 ˚C during 30 minutes and kept for 60 minutes to leave the volatiles before ignition of the samples. Next 30 minutes the temperature was increasing till 550 ˚C. This temperature was kept 120 more minutes to complete the burning. Muffle furnace and dishes with the samples are seen in Fig. 14.

Figure 14: Muffle furnace and dishes with the samples

Source: Author (2017)

Three samples were determined, and as the resulting value was considered an arithmetic mean of two nearest results (the difference between two results was not overlap 0.2%). Ash content was measured according to formula:

$$A_d = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \times \frac{100}{100 - M_{ad}} \ \ [\%]$$

Where: A_d - ash content [%]

m_1 - weight of empty dishes [g]

m_2 - weight of dishes with samples [g]

m_3 - weight of dishes with ash [g]

M_{ad} - moisture content of used samples [%]

4.2.2.6. Determination of gross calorific value

Gross calorific value was determined according to standard EN 14918: Solid biofuels-Determination of calorific value. In was performed in cooperation with IRAE, Prague, by calorimeter IKA (6000). Preparation of small pellets made from about 1 g of analytic samples was necessary for the measurement and it was done by manual press. The prepared pelleted samples were putted into the pressure vessel and were completely burned in the presence of compressed oxygen in the calorimeter. The gross calorific value was calculated automatically by the used device. Calorimeter IKA (left) and reparation of the pelleted sample by manual press for determination of gross calorific value (right) are illustrated in the Figure 15.

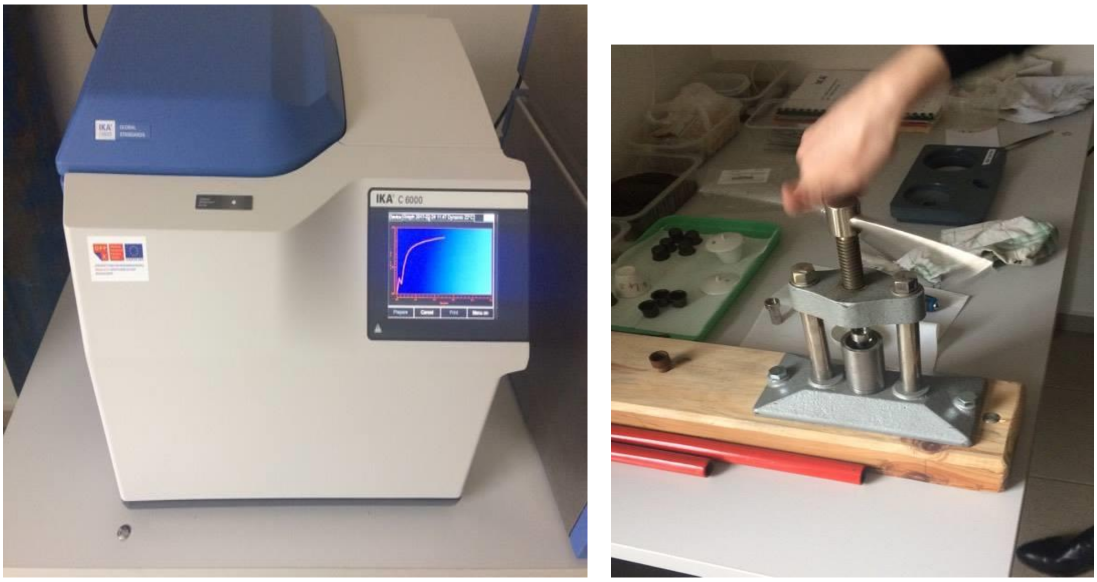

Figure 15: Calorimeter IKA (6000) and manual press

Source: Author (2017)

4.2.2.7. Determination of net calorific value

Net calorific value was also determined according to the standard EN 14918: Solid biofuels- Determination of calorific value. The net calorific value was simply calculated from identified gross calorific value by the following formula:

$$Q_i = Q_{gr} - 24.42 \times (M_{ad} + 8.94H)\ [J.g^{-1}]$$

Where:	Q_i	- net calorific value [J.g $^{-1}$]
	Q_{gr}	- gross calorific value [J.g $^{-1}$]
	24.42	- heat of water evaporation
	M_{ad}	- moisture content [%]
	8.94	- coefficient for conversion of hydrogen to water
	H	- hydrogen content in the material [%]

4.2.2.8. Determination of volatile matter content

Determination of volatile matter content was carried out in cooperation with RIAE. The muffle furnace ELSKLO (model MP5) was used (see Fig. 16). The volatile matter was determined according to standard EN 15148 (2009): Solid biofuels- Determination of the content of volatile matter. Measurements were performed with dry analytic samples (preparation of analytic samples is describe in the above chapter 4.2.2.2.).

Figure 16: Furnace ELSKLO (model MP5)

Source: Author (2017)

The principle of procedure: The empty ceramics dishes were placed into furnace for about 30 minutes until the temperature inside reaches 900 ˚C (± 10 ˚C). Thereafter the ceramics dishes were cooled in the desiccator to the room temperature. Then dishes filled up with analytical sample (1 g) and covered with lid were weighted and putted to the furnace for 7 minutes. After this the dishes were cooled, putted in the desiccator and weighed again.

Volatile matter under oxygenless conditions was calculated by following formula:

$$V_d = \left[\frac{100(m_2 - m_3)}{(m_2 - m_1)} - M_{ad}\right] \times \frac{100}{100 - M_{ad}} [\%]$$

Where: V_d -volatile matter content [%]

m_1 -weight of empty beaker with lid [g]

m_2 -weight of beaker with lid with sample before heating [g]

m_3 -weight of beaker with lid with sample after heating [g]

M_{ad} -moisture content of used material [%]

4.2.2.9. Grinding of the material for briquettes production

The above ground biomass of two kinds of Miscanthus was ground using the crusher type ŠV-15with engine input 15 kW and crusher production of 10 $t.h^{-1}$ (see Fig. 17). For solid biofuels – briquettes production in order of the present research the experimental biomass material were grinded into three fractions (4 mm, 8 mm and 12 mm). Biomass grinding took place at RIAE.

Figure 17: Crusher type ŠV-15

Author: Stoza (2017)

4.2.2.10. Briquetting

Briquettes were produced at RIAE using briquetting press Brikstar 30-12 with power input 4.4 kW, working pressure 18 MPa and production capacity of 40-60 $kg.h^{-1}$. Used briquetting press is illustrated in Figure 18. The used briquetting machine consists of the main parts like hopper for a material, hydraulic system, piston with attached conical chamber and its products briquettes of cylindrical shape. The diameter of briquetting piston chamber/die (approximately corresponding to the diameter of produced briquettes) was 65 mm.

It is necessary to declare that the samples were not mixed with any other type of biomass or binder and the briquettes were made from biomass dried just naturally.

Figure 18: Briquetting press Brikstar 30-12

Source: Author (2016)

4.2.2.11. Measurements of combustion emissions

The combustion emissions determination for totally 6 samples of briquettes was performed, i.e. briquettes of two types of Miscanthus (*Miscanthus sinensis, Miscanthus x giganteus*) made from three fraction of initial biomass (4 mm, 8 mm and 12 mm) were tested. Each type of briquettes was burned in tiled stove SK – 2 RETAP with output 8 kW (see Fig 19). The research was done in RIAE, Prague.

Combustion emissions (CO, CO2, NOx) were recorded during continuous burning by gas analyser Testo 350 XL, illustrated in Figure 20. Each type of briquettes was individually burned for 3× 20 minutes. Measured data were analysed and processes by Microsoft Office Excel software.

Figure 19: Tiled stove SK – 2 RETAP 8kW

Source: Author (2017)

Figure 20: Testo 350 XL

Source: Author (2017)

4.2.2.12. Determination of biomass energy yield

Maximum energy potential (BEY) is the total amount of energy stored in the biomass and it was calculated according the following formula:

$$BEY = GCV * DM \; [GJ.ha^{-1}]$$

Where:	GCV	-gross calorific value [GJ.ha^{-1}]
	DM	-dry matter yield [t.ha^{-1}]

5. Results and discussion

Following chapter provides the findings from the practical research, which lead to achievement of the objectives Thesis and confirmation/rejection of hypothesis. The present Thesis' results are compared with relevant results of other authors and standard requirements as well. Firstly, important properties such as moisture content, ash content, gross and net calorific value and contents of chemical elements, which are decisive for briquettes production and use are presented, analysed and compared. Mostly arithmetic means were noted as results according to repeatability limits of the standards for solid biofuels. Finally evaluation of emissions released during combustion and biomass energy yield are given. All protocols (results of laboratory measurements) necessary for calculation of the resulting values are seen in Annexes.

5.1. Analysis of the properties

5.1.1. Moisture Content

The moisture content (MC) of tested above-ground biomass before briquetting is presented in Table 1 below.

Table 1: Moisture content of examined biomass

Material	Moisture content [%]
M. x giganteus	6.5
M. sinensis	7.7

Source: Author, 2017

As the Table 1 shows, *Miscanthus x giganteus* is characterized by a little lower moisture content than *Miscanthus sinensis*. Bilandzija et al. (2016) claim that in general, MC can vary considerably and represents an undesirable ingredient in any fuel. MC influences calorific value, combustion efficiency and combustion temperature. An acceptable MC is critical for determining the optimal harvest time for Miscanthus. If the average moisture content is below 20%, it is considered that it is not necessary to apply the drying methods for the purpose of storage. Statistically the lowest moisture content was found in the springtime harvest time. It was to be expected that the springtime harvest would perform as the best since the crops spent the longest possible time in the field, i.e. in the conditions of natural drying. However, Borkowska et al. (2013) found average MC for *Miscanthus x giganteus* of 59.9% in autumn harvest and 25.5% in the spring harvest, which is in accordance with the values for MC emerged in this investigation (spring harvest). Soponpongpipat et al. (2013), Li et al. (2000) and Mani et al. (2006) stated that MC range 6-15% is recommended in order to produce briquettes with low elongation and high durability. According to Kaliyan (2008) the critical MC for safe storage of biomass is less than 15%. This is confirmed also by Chen et al. (2009).

It can be concluded based on many sources and technical standard EN ISO 17225-1 that generally MC of biomass material before densification should not exceed 15%. As the above results showed, the studied material belongs to this recommended and normatively set boundary.

Both of explored materials demonstrated very similar results and it's evident that briquettes produced from these biomass materials will fully meet requirements for graded non-woody briquettes "class A" (MC ≤ 12%) given by EN ISO 17225-7 (2014).

5.1.2. Carbon, hydrogen and nitrogen Content

The results of C, H, N analysis are presented in the Table 2.

Table 2: Total carbon, hydrogen and nitrogen content

Material	C d.b. [%]	H d.b. [%]	N d.b. [%]
M. x giganteus	48.12	5.87	0.55
M. sinensis	48.11	5.90	0.68

Source: Author, 2017

According to the technical standards EN ISO 17225-1 (2015): Solid biofuels- Fuel specifications and classes- Part 1: General requirements, the typical C, H, N value ranges are following:

- Carbon: 39.6 – 43.7%
- Hydrogen: 5.3 – 6.1%
- Nitrogen: 0.2 – 2.9%

Determination of total carbon, hydrogen and nitrogen is crucial with respect to emissions released during combustion (Sricharoenchaikul et al., 2011). Both of examined materials are characterized by high content of carbon and do not correspond to the typical standard values. On the other hand, during combustion of solid carbon greatest amount of heat is released (Čermáková et al., 2016). Both explored samples demonstrated similar hydrogen content meeting standard requirements. Even nitrogen content met recommended range while *M. sinensis* is characterized by slightly higher nitrogen content. Within evaluation of result values of this Thesis, the measured values were compared with data of other authors which were published previously. This data are listed in Table 3 below.

Table 3: Comparison of chemical components of other commonly used biomass feedstock

Material	C d.b.[%]	H d.b.[%]	N d.b.[%]
Corn stover	39.56	6.21	0.08
Switchgrass	44.21	6.14	0.56
Aspen	47.31	7.11	0.04
Oak	47.69	5.98	0.07
M. sinensis*	48.11	5.90	0.68
M. x giganteus*	48.12	5.87	0.55
Pine	48.32	6.73	0.06

Source: *Author (2017), Christensen et al. (2017)

After comparison of the present research data with the data from previous researches it is visible that both varieties of Miscanthus show the lowest values of hydrogen, which is highly recommended according to standard EN ISO 17255-1 (2015). In case of nitrogen content both varieties of Miscanthus exposed higher level of this chemical component with respect to other biomass feedstock. For *M. sinensis* was determined a little higher

nitrogen content than the one for M. x giganteus. Carbon content of *M. sinensis* and *M. x giganteus* bears great resemblance to carbon content of woody biomass.
In conclusion can be indicated that *Miscanthus x giganteus* and *Miscanthus sinensis* are characterized by satisfactory hydrogen, nitrogen and carbon level. According to EN ISO 17225-7 only nitrogen content is limited for graded non-woody briquettes and both investigated samples fulfilled requirements for briquettes "class A" ($N \leq 1.5\%$).

5.1.3. Ash Content

Ash content for purposes of this Thesis was determined according to the EN 14775 (2009). The results are shown below in the Table 4.

Table 4: Ash content

Material	Ash content d.b. [%]
M. x giganteus	2.37
M. sinensis	4.95

Source: Author, 2017

According to Mena et al. (2016) one of the most important issues of biomass combustion is the problematic related to the biomass ash content. The operational problems have been often reported in combustion chambers, furnaces and boilers as a consequence of the biomass ash content. This is problematic for the user's comfort, as well as for performance in reference to combustion efficiency and emissions.
In accordance with ISO 17225-1 the average ash content of herbaceous biomass reaches values up to 10% which is in line with results of this study (see Table 4).
Baxter et al. (2012) have published that ash content in steams of *Miscanthus x giganteus* is about 6%. In comparison with the results of this Thesis, where the whole aboveground biomass was used for measurements, it is almost three times higher. García et al. (2013) have found that ash content of *Miscanthus sinensis* is 9%, which is again higher value than the result presented in this Thesis. Application of mineral fertilizers in big quantity can have influence on increasing of ash content in biomass applied for solid biofuel production. Experimental field, where the crops were grown for

the purpose of this research was not fertilized at all. This fact may cause a lower ash content than authors reported from the previous researches.

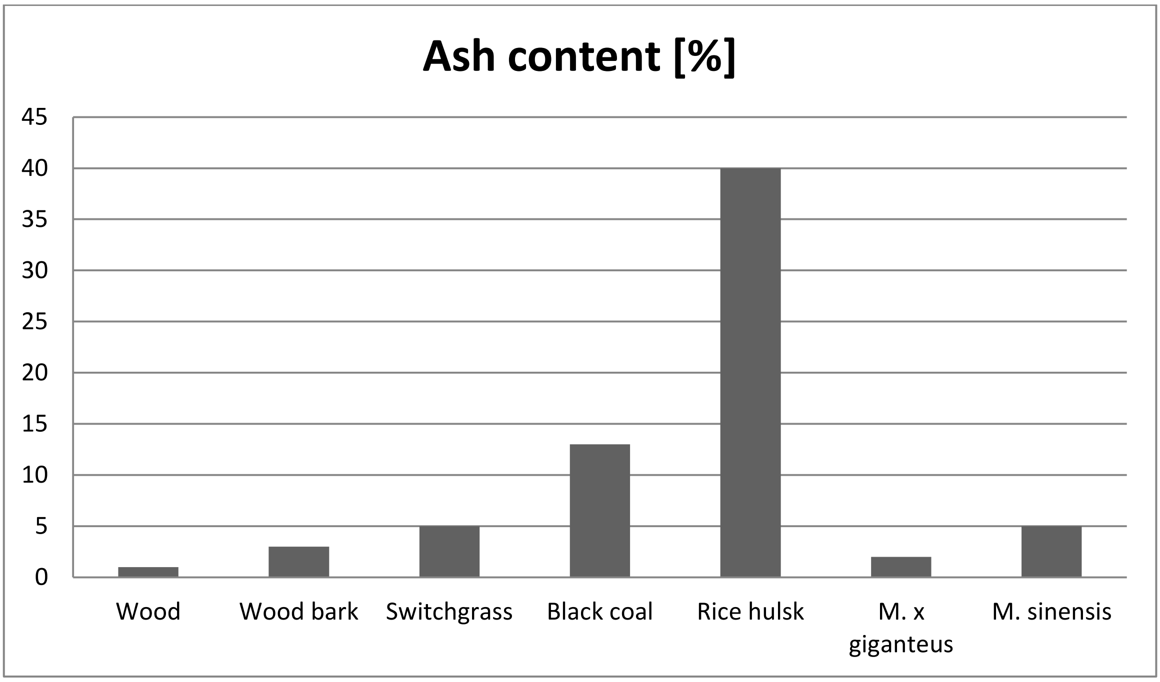

Figure 21: Comparison of average ash content of different materials

Source: Author (2017), Ochecová (2015)

Above-mentioned Figure 21 shows ash contents of different feedstock for biofuel production and compares the values with result of present study and black coal. The wood presents the best values, i.e. very low ash content, nevertheless, it can be concluded that the observed materials fulfil satisfactory level of this quality indicator.

The ash content and composition of a plant tends to vary depending on the part of the plant. Leaves for examples typically contain higher amounts of ash than stems (BISYPLAN, 2012). It was very visible that *Miscanthus sinensis* is a variety with a plurality of leaves comparing with *Miscanthus x giganteus.* Probably morphological construction of crop caused more than twice higher ash content for *M. sinensis.* Ochecová (2015) claim wood contains relatively low amount of ash (0.3-1%), while significantly higher values are found in straw (5%) or grasses (7%). On the basis of this statement it can be summed that ash content of *M. x giganteus* is slightly approaching the values of the wood (however, still higher) while *M. sinensis* ranges in values of straw or grass. Finally, both varieties complies required ash content of EN ISO 17225-7 (2014) and it is classified in “A class” (AC ≤ 6%).

5.1.4. Gross calorific value

The calorific value is the most important parameter in case of biofuels. The measurement of gross calorific value was performed by calorimeter method and the results are shown in Table 5.

Table 5: Gross calorific value

Material	GCV d.b.[MJ.kg^{-1}]
M. x giganteus	18.96
M. sinensis	19.03

Source: Author, 2017

Calorific value is the amount of energy per unit mass released upon complete combustion (Liorente et al., 2016). The factor that determines the usefulness of biomass is the calorific value. Higher calorific value indicates higher efficiency as an energy source (Tang et al. 2016). Everard et al. (2016) stated that gross calorific value of *Miscanthus x giganteus* ranges between 13.1 and 18.6 MJ.kg^{-1} which is comparable with the measured values (but lower). Kolodziej et al. (2015) found that the gross calorific value of *Miscanthus x giganteus* reaches from 17.7 to 18.2 MJ.kg^{-1}.

Table 6: GCV of selected biomass materials

Material	GCV [MJ.kg^{-1}]	Author
Rice straw	16.4	Špunarová (2016)
Sunflower	16.7	Součková (2005)
Bur	17.1	Garvalos et al. (2010)
Fruiting branches	17.4	Garvalos et al. (2010)
Sorghum	17.6	Součková (2005)
Barley straw	17.7	Satpathy et al. (2014)
Wheat straw	17.8	Satpathy et al. (2014)

Hemp	18.0	Součková (2005)
Straw	18.8	Dukiewicz et al (2014)
Miscanthus. x giganteus	18.9	Author (2017)
Miscanthus. sinensis	19.0	Author (2017)
Cotton plant	19.0	Stavjarská (2013)
Poplar	19.5	Cejlak (2010)
***Jatropha curcas L.* seed cake**	20.5	Vlachosová (2016)
Woody biomass	20.1-22.0	Dukiewicz et al. (2014)

Gross calorific values of several kinds of plants from previous researches by several authors are available for viewing in Table 6 above. From the Table 6 is clear that both varieties of Miscanthus show almost authentic and high results, even approaching values of woody biomass.

5.1.5. Net calorific value

Results from determination of net calorific value are shown in Table 7.

Table 7: Net calorific value

Material	NCV d.b.[MJ.kg^{-1}]
M. x giganteus	17.52
M. sinensis	17.74

Source: Author, 2017

Values of net calorific values founded during research are very similar for two examined varieties.

Listed results are a little bit higher in comparison with the statement of Kolodziej et al. (2015) that the net calorific value of *Miscanthus x giganteus* ranges between 16.2 and 16.8 MJ.kg^{-1}. According to Dukiewicz et al. (2014) the net calorific value of *M. sinensis* is 17.6 MJ.kg^{-1}, which bears a similarity with value detected in present research.

5.1.6. Volatile matter content

Determination of volatile matter was investigated on the basis of EN 15148 (2009). The results are to be seen in the Table 8 below.

Table 8: Volatile matter content

Material	Volatile matter content d.b. [%]
M. x giganteus	78.93
M. sinensis	79.38

Source: Author, 2017

Table 8 shows volatile matter reaches very similar values in case of both varieties of Miscanthus. García et al. (2013) stated volatile matter for *Miscanthus sinensis* equal 79% which is in accordance with present study. The values of both varieties of Miscanthus are comparable with values of wheat grain (80%) or close to pistachio shells (82.5%).

A large number of previous researches contained determination of volatile matter contents of many materials for solid biofuel production. Several of them were arranged for purposes of comparison with measured values (see Table 9).

Table 9: Values of volatile matter of different materials

Biomass material	Volatile matter content [%]
Pistachio shell	82.5
Wheat grain	80.0
M. sinensis*	79.4
M. x giganteus*	78.9
Hazelnut shell	77.0
Nectarine stone	76.0
Chestnut tree leaves	72.4
Rice husk	68.0
Barley straw	46.0

Source: *Author (2017), Li et al. (2016)

According to Sunphorka et al. (2016) high volatile matter is one of the properties of biomass. Disadvantage of high volatile matter is that it causes rapid combustion and easier combustion of residues. Beyond lower volatile matter toxic gases are released with present of high smoke (Werther et al. 2000). Due to high content of volatile matter it is necessary to operate with temperature below melting point of ash (Werther et al. 2000).

5.2. Processing of Miscanthus to solid biofuel - briquettes

It has been proven that compact briquettes may be produced from raw aboveground biomass of both varieties of Miscanthus without any additives. Briquetting conditions were as follows: material dried in natural way and moisture content of crushed biomass before briquetting was for *M. x giganteus* 6.5% and for *M. sinensis* 7.7%; briquetting machine working pressure of 18 MPa was applied.

Sun et al. (2016) claim moisture content higher than 18% lead to production of inconsistent briquettes which are falling to pieces. Other authors (Stolarski et al., 2013; Voicea et al., 2015) also produced compacted briquettes from Miscanthus.

Figure 22: Final product of briquetting of *Miscanthus x giganteus* without any additives

Source: Author (2017)

5.2.1. Combustion emissions analysis

The results of emissions concentration measured for three factions of each Miscanthus variety (*Miscanthus x giganteus* and *Miscanthus sinensis*) are presented in following Tables (see Table 10 and Table 11).

Table 10: Concentration of emission in briquettes (different factions) made of *Miscanthus x giganteus*

Faction [mm]	**CO [mg.m^{-3}]**	**CO_2 [%]**	**NO_x [mg.m^{-3}]**
4	1,076.7	9.9	239.3
8	424.6	9.9	236.1
12	1,963.0	9.8	174.0

Source: Author, 2017

Table 11: Concentration of emission in briquettes (different fractions) made of *Miscanthus sinensis*

Faction [mm]	**CO [mg.m^{-3}]**	**CO_2 [%]**	**NO_x [mg.m^{-3}]**
4	346.9	9.9	256.5
8	698.6	9.9	231.5
12	596.0	9.9	216.0

Source: Author, 2017

As the Table 10 and Table 11 shows, fraction of materials has absolutely no influence on CO_2 concentration and there is not difference between explored varieties. The lowest level of NO_x in case of both varieties have showed fraction 12 mm (the biggest the fraction - the lowest the emission) and in general values of both varieties are similar. Level of CO varies across varieties. It can be summarized that in general briquettes made of *M. x giganteus* released more CO emissions that the second variety.

The combustion process is one of the main sources of emissions of environmentally harmful chemicals such as sulphur and nitrogen oxides, halogens, volatile organic compounds and trace elements (Vassilev et al., 2010). **CO** is product of incomplete combustion however incomplete combustion of the fuels can result in the release and emission of pollutant gases and particulates to the atmosphere (Vassilev et al., 2010; Williams et al., 2012). From the results of C, H, N (chapter 5.1.2.) is obvious that a Miscanthus is material with high carbon content, which probably causes a high concentration of carbon oxides during combustion. In accordance with Čermáková et al. (2016) emission limit for getting label "environmentally friendly product" for CO is 2,000 $mg.m^{-3}$. It is obvious emission values obtained during analysis are satisfactory.

CO_2 represents an important greenhouse gas which is characterized by long atmospheric lifetime. CO_2 is constantly cycled between ocean, atmosphere and land sphere (Vassilev et al., 2010).

Dembiras (2004) stated that air flow rate is a critical factor in boiler flame temperature and affects CO and CO_2 emissions; Kaválek (2015) claimed that also power input of combustion installations considerably influenced emission factor, i.e. while higher input, emission concentration is lower. The chemical composition of biomass fuels is less complex than that of fossil fuels but they can also contain many elements that can be problematic during combustion, especially nitrogen. This can directly influence gaseous nitrogenous emissions.

NO_x emissions consist of compounds of nitric oxide (NO) and nitrogen dioxide (NO_2) and it is the largest component of N emissions. Fossil fuel NO_x contributes significantly to atmospheric pollution and it is linked to many environmental problems whereas the contribution from biomass in much lower and potentially may reduce overall levels (Saidur et al., 2011; Dembiras 2004; Vassilev et al. 2010; Williams et al. 2012). According to Čermáková et al. (2016) "environmentally friendly product" lists NO_x as for biomass combustion value of 250 $mg.m^{-3}$, which is securely satisfied except for *M. sinensis* – fraction 4 mm, which is slightly above.

Sun et al. (2008) observed a close linkage between the oxygen and NO emissions during combustion, so it was concluded that these emissions may be reduced by appropriate measures, e.g. air staging.

According to Vlachosová (2016) woody pellets are characterized by following emission concentrations: CO (624.8 $mg.m^{-3}$) and CO_2 (3.0%). Compared with results from this Thesis, briquettes made of *M. sinensis* are fuel of very similar CO concentration and higher CO_2 concentration. Briquettes made of *M. x giganteus* are characterized by higher amount of CO emissions compared with woody pellets, higher CO_2 concentration and lower NO_x level of emissions released during combustion.

Graph 2, Graph 3 and Graph 4 below graphically illustrate the course of CO and NO_x concentrations during combustion time (case of *M. x giganteus*). Graphs describing these courses for *M. sinensis* can be seen in Annexes.

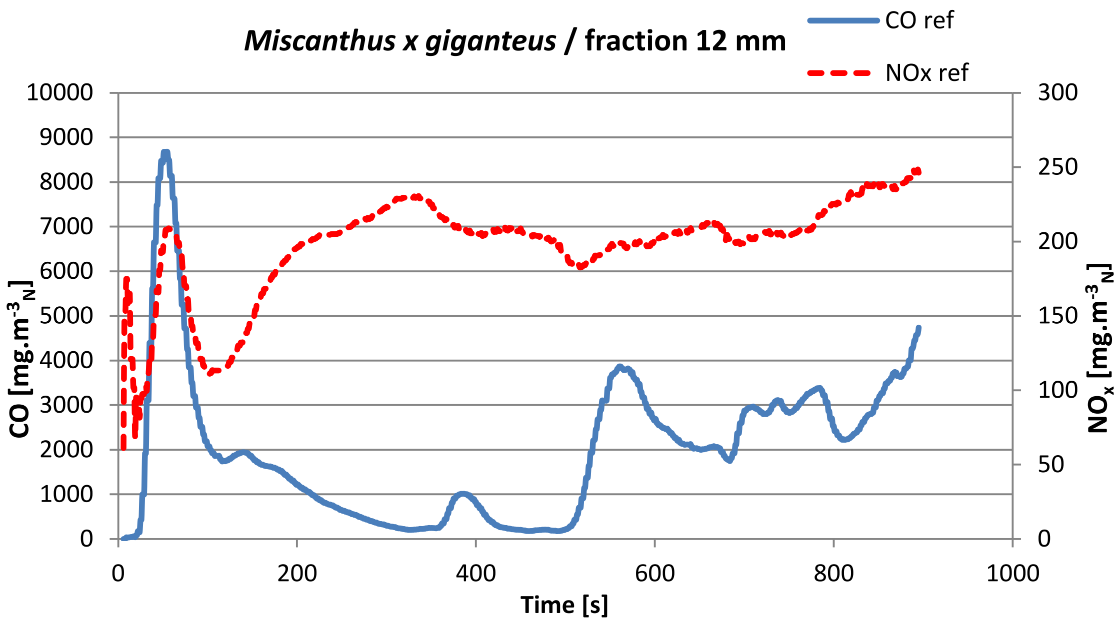

Figure 23: Example of measurement of CO and NOx (*M. x giganteus* fraction 12mm)

Source: Author (2017)

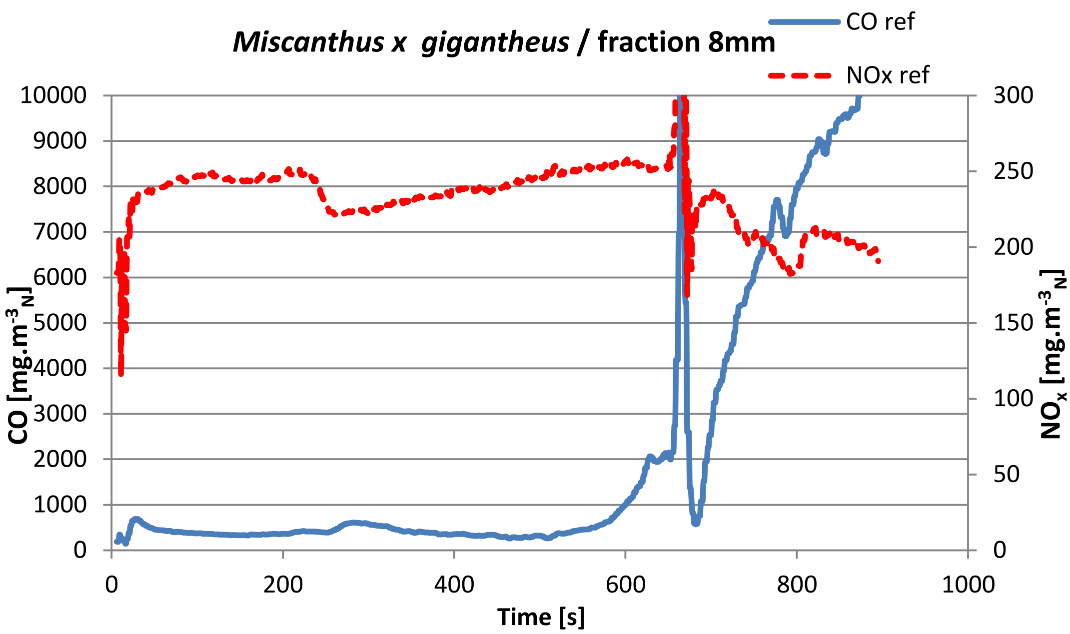

Figure 24: Example of measurement of CO and NOx (M. x giganteus fraction 8mm)

Source: Author (2017)

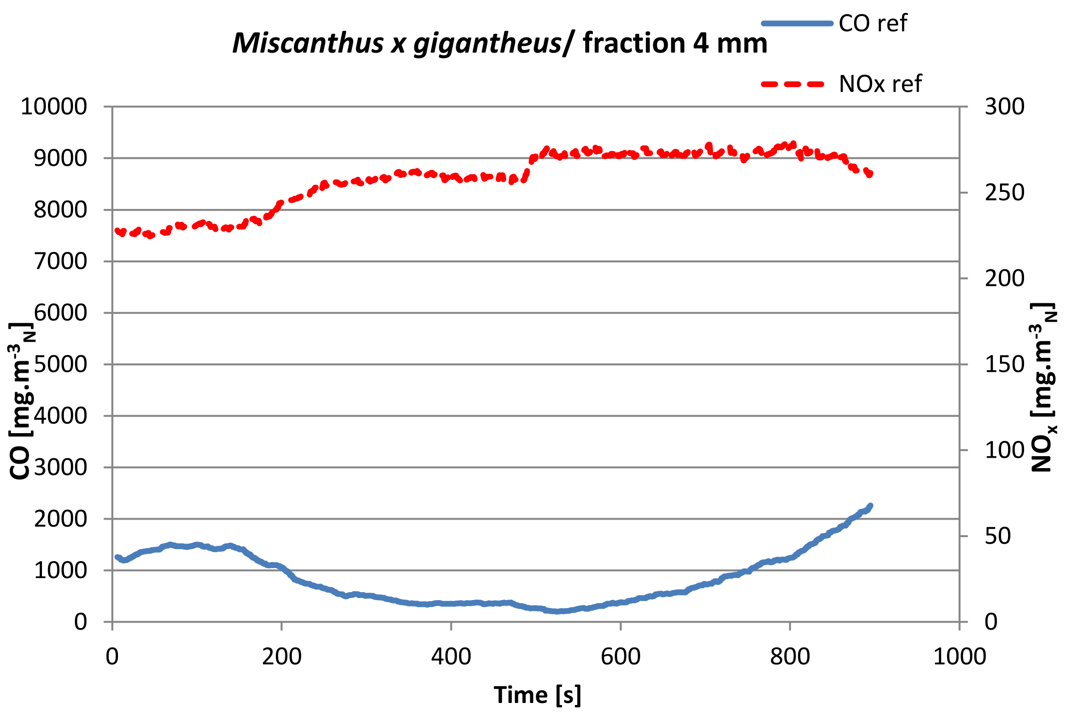

Figure 25: Example of measurement of CO and NOx (M. x giganteus fraction 4mm)

Source: Author (2017)

5.2.1.1. Biomass gross energy yield

During the spring harvest, yields of dry matter of *M. x giganteus* reached 30.8 $t.ha^{-1}$ and yields of dry matter of *M. sinensis* was 21.3 $t.ha^{-1}$.
The results of determination of biomass gross energy yield are presented in Table 12.

Table 12: Gross energy yield of *M. sinensis* and *M. x giganteus*

Material	**BEY [$GJ.ha^{-1}$]**
M. x giganteus	584
M. sinensis	405

Source: Author, 2017

BEY was calculated for spring harvest (2016). It was found that *M. x giganteus* greatly exceeds *M. sinensis* with regard to this important parameter.
Havrland et al. (2013) presents slightly lower values, specifically for *M. sinensis* argues 362.8 $GJ.ha^{-1}$ and for *M. x giganteus* 531.9 $GJ.ha^{-1}$. This difference occurred due to the fact that author calculated with lower dry matter yields.
Havrland et al. (2013) also examined maximum energy yields for another energy crops with the following findings: Giant reed (451.6 $GJ.ha^{-1}$), Giant knotweed (387.7 $GJ.ha^{-1}$), Sweet sorghum (345.7 $GJ.ha^{-1}$) and hemp (213.6 $GJ.ha^{-1}$).
It is evident from the paragraph above that *M. x giganteus* is considered as biomass with enormous maximum energy yield. Even *M. sinensis* is material with very high resulting values with respect to other mentioned energy crops.

6. Conclusion and recommendation

Solid biofuels made of energy crops are appropriate sources of energy to replace some amount of fossil fuels thanks to their many benefits in comparison to non-renewable fuels as other renewables as well. The suitability of energy crop for specific region depends on many factors. Miscanthus is considered as a very promising energy crop.

This diploma Thesis was devoted to the mentioned topic, expressly on assessment of Miscanthus cultivation (two different varieties) for solid biofuels production. The findings resulting from presented research were formulated and compared with reliably findings from other authors.

The research investigations validated the **first hypothesis**. From the results was obvious, that *M. sinensis* and *M. x giganteus* were materials suitable for briquettes production without any additives. The results of explored properties were similar for both varieties. It was found that investigated material is characterized by high calorific value even approaching calorific value of woody biomass. Briquettes made of Miscanthus were distinguished by high carbon content, on the other hand, values of ash content analysis were low in comparison with herbaceous biomass (especially in case of *M x. giganteus*). Generally, due to stated chemical and physical properties of briquettes made of *M. sinensis* and *M. x giganteus*, the briquettes fulfilled requirements of EN ISO 17225-7 (2014) and were classified into "class A" of graded non-woody briquettes.

Research confirmed the **second hypothesis**. It was proved that *M. x giganteus* is more suitable for energy purposes than *M. sinensis.* However, results of properties of two varieties of Miscanthus were in most cases very similar, the decisive factor was maximum energy yield, which was significantly higher for *M. x giganteus*.

Presented investigation partly confirmed the **third hypothesis**. The findings from combustion emission analysis were very positive due to fulfilling of requirements for labelling "environmentally friendly product". During the measurements, no clear influence of fractions was detected in case of CO and CO_2 emissions and minimal differences were found in $NO_{x.}$ In general, both Miscanthus had very similar values of

NO_x and CO_2, but *Miscanthus x giganteus* is characterized by higher CO concentrations.

Despite all the findings, in comparison to many other energy crops both Miscanthus species are suitable biomass source for solid biofuels production, nerveless, *M. x giganteus* is more valuable due to great energy yield.

It is recommended to concentrate further researches on economic study of the whole briquetting process.

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8. Annexes

Annex 1: Moisture content - *Miscanthus x giganteus*

Number of sample	The mass of empty dish [g]	The mass of the dish plus sample		Moisture content [%]
		Before drying [g]	After drying [g]	
1.	24.8933	25.9589	25.8887	6.5878
2.	24.9794	26.0405	25.9728	6.3801
3.	26.3727	27.4744	27.4034	6.6771

Annex 2: Moisture content - *Miscanthus sinensis*

Number of sample	The mass of empty dish [g]	The mass of the dish plus sample		Moisture content [%]
		Before drying [g]	After drying [g]	
1.	26.3676	27.4398	27.3576	7.6664
2.	28.0071	29.2569	29.1587	7.8234
3.	25.7784	26.8269	26.7456	7.7539

Annex 3: Ash content - *Miscanthus x giganteus*

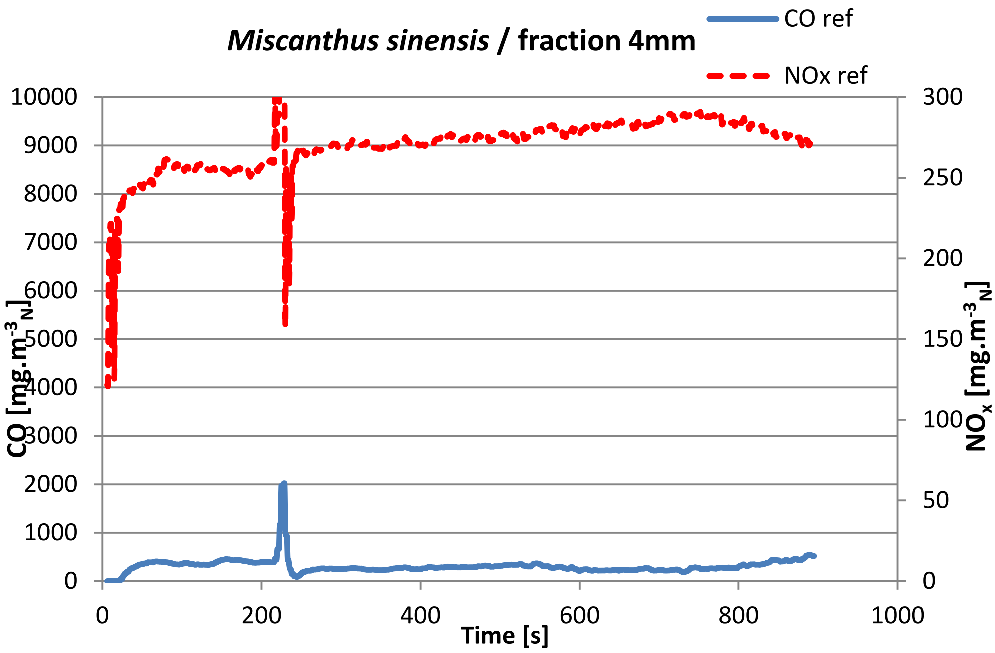
Number of sample	The mass of empty dish [g]	The mass of the dish plus sample		Ash content [%]
		Before heating [g]	After heating [g]	
1.	18.0676	19.1184	18.0924	2.3601
2.	15.6328	16.6693	15.6573	2.3637
3.	16.7128	17.7702	16.7375	2.3359

Annex 4: Volatile matter - *Miscanthus x giganteus*

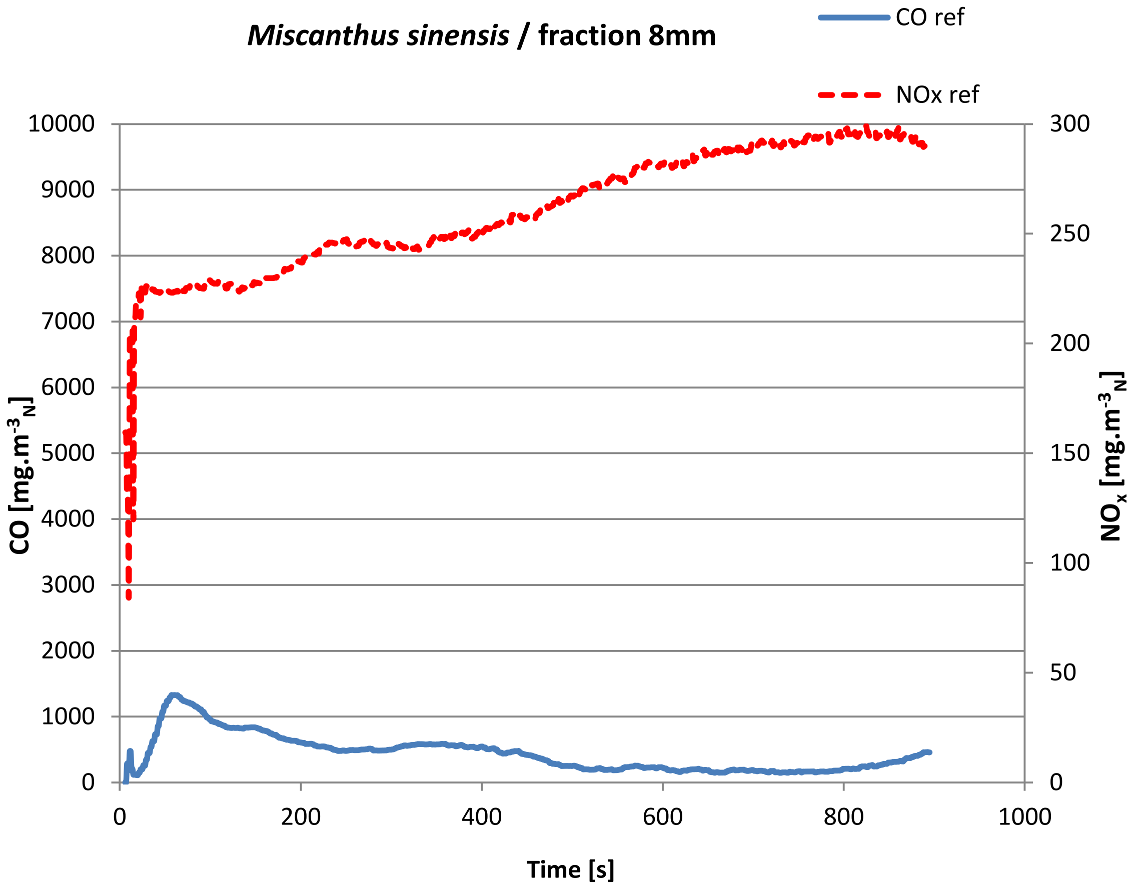
Number of sample	The weight of empty vessel [g]	The weight of the vessel plus sample		Volatile matter [%]
		Before heating [g]	After heating [g]	
1.	21.3025	22.3047	21.4991	79.0133
2.	20.4210	21.4268	20.6231	78.5034

Annex 5: Volatile matter - *Miscanthus sinensis*

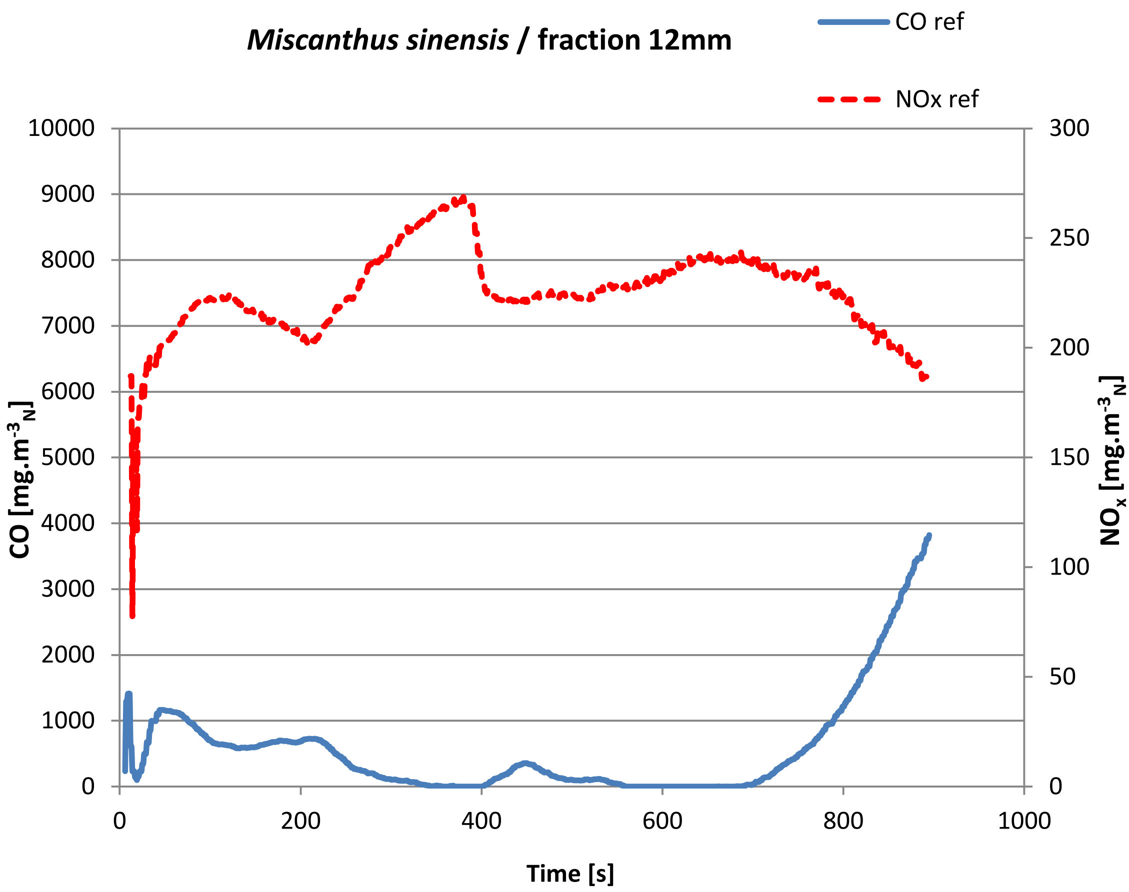
Number of sample	The weight of empty vessel [g]	The weight of the vessel plus sample		Volatile matter [%]
		Before heating [g]	After heating [g]	
1.	18.6466	19.6500	18.8393	79.4089
2.	20.5639	21.5655	20.7567	79.3612



Annex 6: Example of measurement of CO and NOx (*M. sinensis* fraction 4mm)



Annex 7: Example of measurement of CO and NOx (*M. sinensis* fraction 8mm)



Annex 8: Example of measurement of CO and NOx (*M. sinensis* fraction 12mm)

Annex 9: Determination of energy yield

Material	**GCV [MJ.kg^{-1}]**	**DM* [t.ha^{-1}]**	**BEY [GJ.ha^{-1}]**
M. sinensis	19.03	21.30	405.33
M. x giganteus	18.96	30.8	583.97

*Values of DM were calculated by weighing of harvested biomass. Weighted values were recalculated into dry matter yields per hectare.