

OULUN YLIOPISTO
UNIVERSITY of OULU

FACULTY OF TECHNOLOGY

**Biomass-based energy carriers in iron and steel
industry: Techno-economic assessment of
thermochemical conversion technologies**

Aleksi Lakkala

PROCESS ENGINEERING

Bachelor's thesis

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Tutors: Eetu-Pekka Heikkinen, Hannu Suopajarvi

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TIIVISTELMÄ

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<p>Rauta- ja terästuotannon aiheuttamat kasvihuonepäästöt ovat merkittävä osa maailman kokonaiskasvihuonepäästöistä. Kandidaatintyön tavoitteena on vertailla eri biopolttoaineita, joilla olisi mahdollista korvata prosessissa käytettäviä fossiilisia polttoaineita. Vertailu tapahtuu pääosin tuotantokustannuksien ja –teknologioiden näkökulmista.</p> <p>Työssä käytetyt tiedot ovat koottu vuonna 2005 ja sen jälkeen julkaistuista bioenergiaa ja –polttoaineita koskevista artikkeleista. Biopolttoaineita vertaillessa on otettu huomioon niiden valmistuksessa käytettävät raaka-aineet, tuotantokapasiteetti, tuotantoteknologia, sijainti, perusvuosi ja tuotantokustannukset. Jokainen työssä käsitelty biopolttoaine on myös analysoitu tarkemmin omassa alaotsikossaan. Tiedot ovat lopuksi taulukoitu helpompaa vertailua varten. Vaihtoehtojen valmistuskustannuksia on myös pyritty yhtenäistämään taulukossa.</p> <p>Tuloksista voidaan todeta tarkasteltavien biopolttoaineiden olevan pääsääntöisesti taloudellisesti kannattamattomia verrattuna rauta- ja terästeollisuudessa käytössä oleviin fossiilisiin polttoaineisiin. Biopelkistimien saaman kasvavan huomion voidaan kuitenkin olettaa tuovan uusia valmistusmenetelmiä sekä mahdollisuuksia niiden hyödyntämiselle tulevaisuuden teollisuudessa korvaten fossiilisten polttoaineiden käyttöä, samalla kasvihuonepäästöjä pienentäen.</p>			
Muita tietoja			

ABSTRACT FOR THESIS

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Major Subject	Type of Thesis Bachelor's thesis	Submission Date August 2016	Number of Pages 27
Abstract <p>Greenhouse gas emissions caused by iron and steel industry are an important part of the world's total greenhouse gas emissions. This bachelor's thesis aims to compare different biofuels, which could replace the fossil fuels use in the process. The comparison takes place mainly in production costs and production technologies angles.</p> <p>The data used in this work is collected together from articles about bioenergy and biofuels, that are published in year 2005 or after. When comparing the biofuels, their feedstock, production capacity, production technology, location, base year and production costs are taken into account. Each biofuel is also analysed in more detail in their own sub-headings. Finally, the data is tabulated for easier comparison. Production costs of different biofuels are also tried to standardize in the table.</p> <p>It can be stated from the results, that as a general rule, the surveyed biofuels are uneconomical compared to the fossil fuels used in the iron and steel industry. However, as bio reductants are receiving constantly more attention, new production methods as well as new possibilities for their future exploitation in industry can be assumed, while replacing fossil fuels and reducing greenhouse gas emissions.</p>			
Additional Information			

SISÄLLYSLUETTELO

TIIVISTELMÄ

ABSTRACT

SISÄLLYSLUETTELO

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MARKS AND ABBREVIATIONS

BF	Blast furnace
GHG	Greenhouse gases
PCI	Pulverized Coal Injection
LHV	Lower heating value

1 INTRODUCTION

Biofuel production has been increasing since millennium, mainly led by government policies targeting different objectives, such as global warming, reducing fossil fuel prices or promoting rural economic growth. At the moment the most commercialized biofuels, such as ethanol and biodiesel, are first-generation biofuels based on food crops. Biofuels presented 4% of all transportation fuels in the EU in 2009 and the portion is rapidly growing. (Zilberman & Serra 2013)

Discovering and researching new, more environmentally friendly, ways to produce steel is also a subject undergoing intense study in the industry. Increased CO₂ emissions are considered a real concern in nearly every branch of industry, as industries covered 21% of global greenhouse gas emissions in 2010, primarily from fossil fuels burned on-site for energy. (EPA 2016) One of the main challenges is to make the process more environmentally friendly, but also keep the economics of the production under control at the same time.

In steel industry, one of the most effective way to have an impact on greenhouse gas emissions is to replace the fossil fuels, used in BFs, with biomass-based energy carriers, such as charcoal or torrefied biomass. In fact, wood-based charcoal is already commonly used in ironmaking in Brazil, as short rotation forests are used as feedstock. Currently, the feedstock availability has only been studied in Finland and Brazil. More research on the subject is needed to discover more similar possibilities around the world. (Suopajärvi et al. 2013)

The goal of this research is to examine and compare if it is economic to use more bioenergy instead of fossil-based fuels in iron and steelmaking. Conclusions are made by comparing properties and economics between traditionally used fossil fuels and biomass-based reductants.

2 BIOMASS-BASED REDUCTANTS

As primary metal production contributes about 5% of all greenhouse gas emissions in the world (of which iron and steel production covers about 70%), substitutive, more environmentally friendly ways to produce iron and steel must be discovered to lower CO₂ emissions. Biomass based-reductants in integrated steel plants and blast furnaces might be a solution to accomplish these lower emissions. Currently, Brazil is the only country to utilize biomass-based reductants in steel industry, as charcoal is being used in mini BFs. (Suopajarvi et al. 2013)

Other ways to use bioreductants in industry, could include injection of different bioreductants to BF, such as ethanol, biodiesel, natural gas and polythene (but their injection rate must be lower than charcoals, 60kg/thm, because their combustion is calculated to produce insufficient heat). (Wang et al. 2012) As Mathieson et al. (2011) state, the BF's CO₂ emissions decrease when injectants with high energy value, as well as low ash and oxygen contents are injected into the BF. Different biomass-based products rely on different production processes, such as slow (charcoal), and fast pyrolysis (bio-oil) technologies and gasification (bio-SNG).

In this thesis seven bioreducers and their features are presented: torrefied biomass, charcoal, bio-SNG, bio-oil, hydrogen, methanol and ethanol, all of which may have potential use in an integrated steel plant and blast furnace. The bioreducers may be used in BF in the form of solid, liquid or gas. According to Wang et al. (2012), biomass products have several advantages when used instead of PCI. The amount of limestone needed for sulphur removal from hot metal is low, as biomass products are naturally low in sulphur content. Another advantage of biomass use in BF is its low ash content, which allows to keep the alkali load at the same level as when PCI is used and also leads to a low slag rate in BF. The report points out however, that the amount of phosphorus in hot metal would be a bit higher. In the future, the most plausible solution is to replace only a part of the used fossil-based reductants by bio-reducers. Mixtures, such as pulverized coal and charcoal could be used and the relation of these reductants would be defined by their economics and required chemical properties of the reductant. (Wang et al. 2012)

3 TECHNO-ECONOMIC ASSESSMENT OF THERMOCHEMICAL CONVERSION TECHNOLOGIES

3.1 Torrefied biomass

Torrefaction is a mild pre-treatment technology to upgrade biofuel quality for combustion and gasification applications. Torrefaction takes place at temperatures between 200-300°C under inert condition. Biomass partly decomposes in the process, which leads to loss of mass and chemical energy to the gas phase. The typical yield values for torrefaction are 0.8 for mass yield and 0.9 for energy yield from the original biomass dry basis. The values are strongly dependent on process temperature, reaction time and the type of used biomass. The value for mass yield can even be as low as 0.45 with energy yield 0.9, when the moisture content of feedstock is 35%. As seen in figure 1, finished torrefied biomass has brown to dark-brown colour, depending on the applied torrefaction conditions and its properties are similar to coal. (Bergman et al. 2005)



Figure 1. Torrefied biomass a.k.a. “bio coal”, before and after densification process. (conBio 2013)

Feedstock for torrefied biomass production includes a large variety of different biomasses. As long as biomass is built from the same lignocellulose polymers, the chemical changes of these polymers during torrefaction are practically similar in terms of property changes. Torrefaction is considered as a slow process, since it requires long residence times of 5 to 15min, compared to other processes presented in this thesis, excluding charcoal production process. In the production of torrefied biomass the occurring decomposition reactions cause the biomass to be completely dried and lose its fibrous structure, therefore biomass can be grinded more easily. Torrefied biomass can

be then densified (pelletised) which leads to very energy dense fuel pellets. The density of torrefied wood is 180-300 kg/m³, but after densification process it can be as high as 750-850 kg/m³. Figure 2 shows simplified process flow sheet of an integrated torrefaction plant. The moisture uptake of finished product varies from 1 to 6%, which is approximately as low as charcoals. (Bergman et al. 2005)

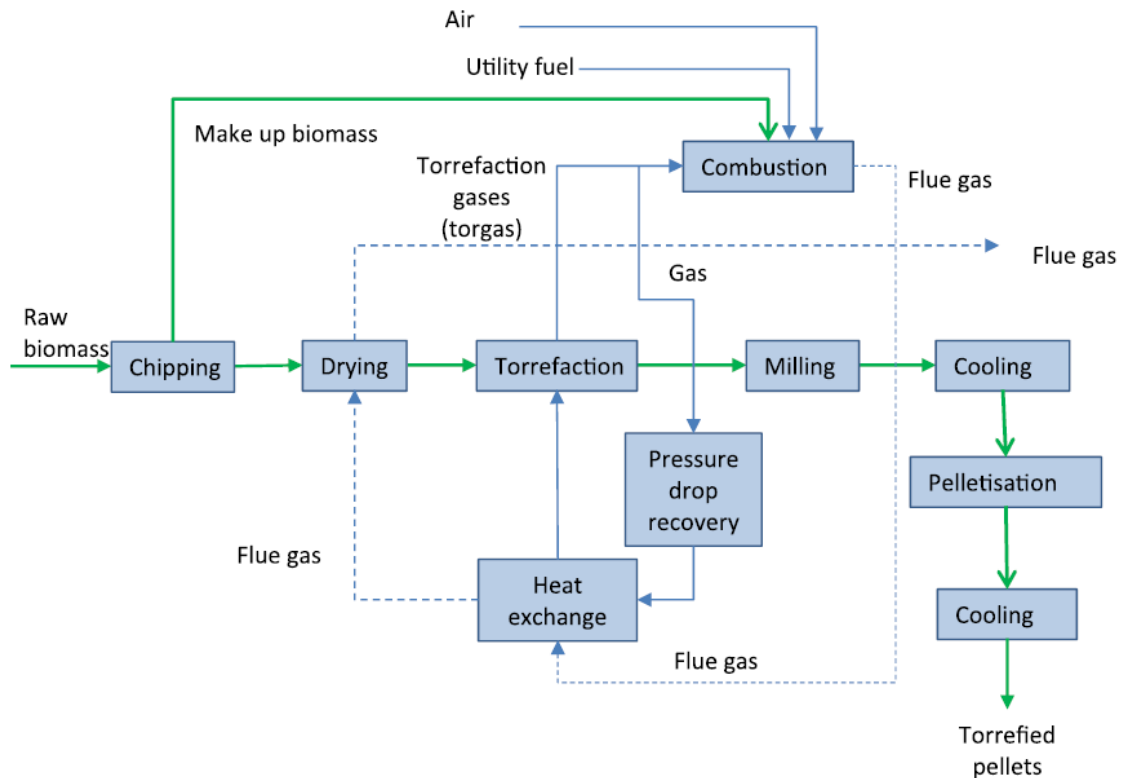


Figure 2. (Batidzirai et al. 2013)

As a result, torrefaction increases the lower heating value (dry) of biomass from 17 to 19 MJ/kg to 23MJ/kg. (Bergman et al. 2005) The production costs for TOPs (torrefied pellets) produced from woody biomass are estimated to be between 2.9 and 4.2 €/GJ(LHV) for production scale of between 50 and 250 kt/year ($\pm 38-48\%$). With future technology TOPs production costs are expected to be around 1.9 to 3.6 €/GJ, pre-learning uncertainties excluded. Torrefaction combined with pelletisation might also help with current logistic issues that exist for untreated biomass. (Batidzirai et al. 2013) (Conversion rate of 1 USD = 0.882 € is used on 18.8.2016)

3.2 Charcoal

Charcoal, as seen in Figure 3, is a bioproduct produced by heating wood in the absence of sufficient air so that full combustion does not happen. Heating causes the woods volatile compounds to be released, which leads to relatively light weight and clean-burning fuel, that consists of 70 to 90% carbon. (Norgate & Langberg 2009)



Figure 3. (The Saint Louis Charcoal Company, LLC 2013)

Charcoal production has several stages. According to Bridgwater A.V. (2012) the residence time of charcoal in the process is long, from hours to days. It begins with wood drying, which takes place in temperature range of 100 to 200 °C, where hygroscopically absorbed water is vaporized. Next step is pre-carbonization, an endothermic phase, which occurs between temperatures of 180-200 °C and 250-300 °C. A portion of the pyroligneous liquid and little amount of non-condensable gases are obtained. The carbonization phase is fast and the reaction takes place in temperatures between 250 °C and 300 °C. Wood loses most of its soluble tar and pyroligneous acid in the carbonization process. The main portion of produced charcoal is produced in final carbonization phase in temperatures above 300 °C. A typical slow pyrolysis arrangement for charcoal production is presented in figure 4. For wood, bark, twigs and leaves feed the yield of charcoal in retort is 13.4% (wet basis). These values are related to retort biomass feed properties, which include 20.0% moisture and 44.4% carbon

contents. The retort yield is higher, up to 23.2 %, if wood only feed is used in the process. (Norgate & Langberg 2009) However, Suopajärvi et al. (2011) suggest that even higher yields of 30 to 35% can be achieved when final temperatures between 450 to 550 °C and increased pressures up to 1.0 MPa are used in the process.

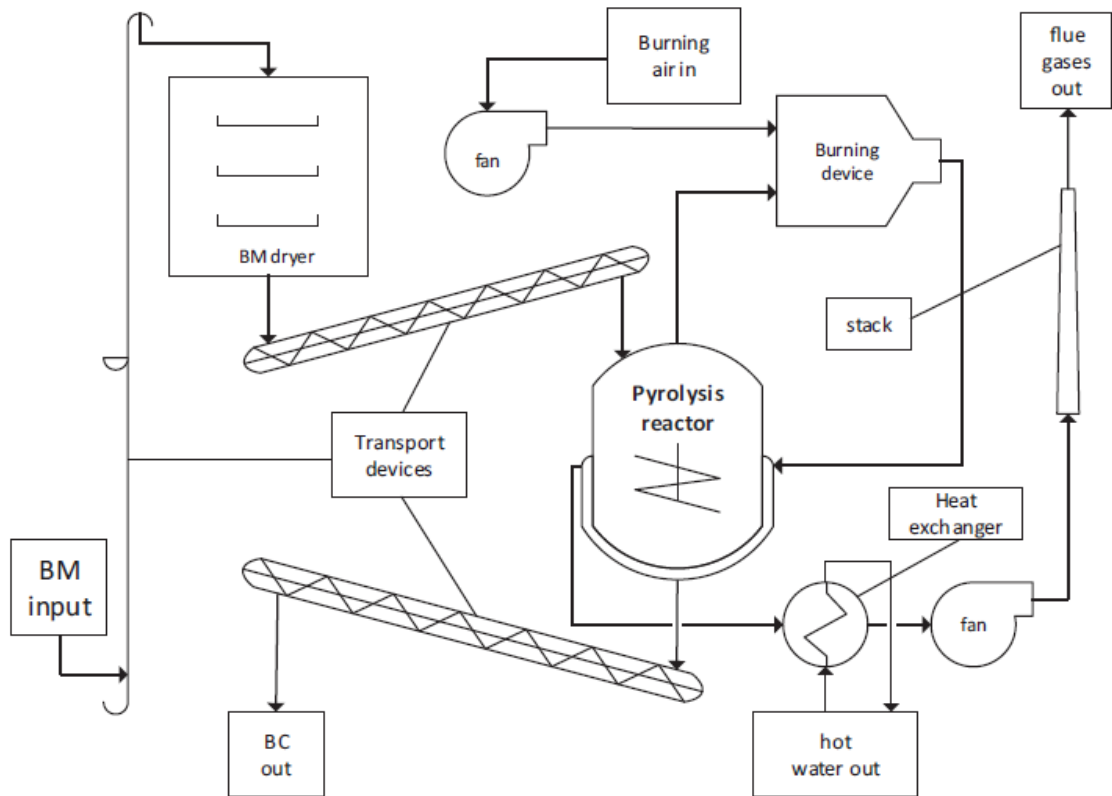


Figure 4. (Klinar D. 2016)

Yields and different properties, such as carbon content of charcoal are determined by pyrolysis temperature used in the process. The total carbon content of the char increases along the rise in pyrolysis temperature such as yield of gas, as can be noted on figure 5. (Suopajärvi et al. 2013)

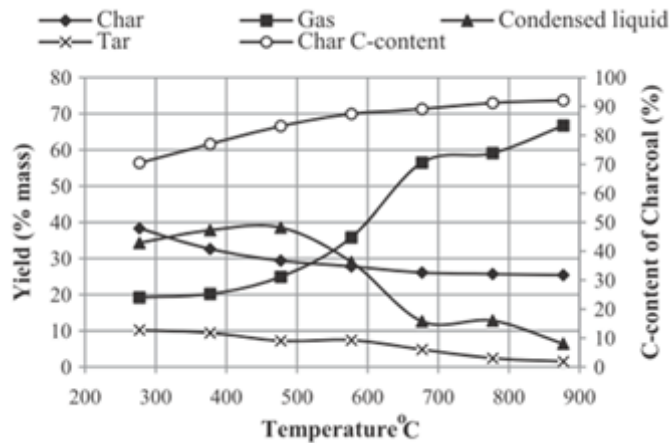


Figure 5. (Suopajarvi et al. 2013)

Currently, charcoal is only utilized in iron and steel industry in Brazil, as it is utilized in small charcoal BF's. Injection rates for charcoal in these furnaces are between 100 to 190 kg/thm. According to the model of Wang et al. (2012), injection rate of 146.7 kg/thm is needed to replace all the PCI (150 kg/thm) used in the BF. Also, BF's CO₂ input could decrease as much as 27% when 100% of the PCI was replaced by charcoal, which could lead to savings in emission fees. (Wang et al. 2012)

When it comes to pricing of charcoal, Norgate & Langberg (2009) mentions its selling price to be US\$386/t (347.9€/t), while pricing of coal is US\$90/t (81.1€/t). It is clear that charcoal is not currently able to compete with coal in terms of economics in steelmaking.

3.3 Bio-SNG

The aim of Bio-SNG production is to convert solid biofuels into gas with high methane content (>95%) that is useable in gas grid feed-in. The process of producing Bio-SNG has five main steps, which are pretreatment of biomass, gasification, gas cleaning, methanation and Raw-SNG upgrading. These main steps form the backbone of the process layout seen in figure 6. (Rönsch et al. 2012)

Biomass pretreatment reduces the water content in biomass, which helps to minimize the exergetic losses in the next gasifier phase. It also improves gasification process

itself, so the process stability is also increased. Conditioned biomass is then gasified at temperatures up to 1,600 °C by adding a gasification agent, such as oxygen or water steam. This results in a raw gas that mainly consists of carbon dioxide, carbon monoxide, water steam, hydrogen and certain amounts of methane. Gas cleaning phase aims to prevent catalyst poisoning and blocking or damaging at other plant components. Impurities such as particles, tars, sulphur, nitrogen, halogen compounds and alkalis have to be removed from the gas. Separation tools include filters and cyclones. Sulphur, nitrogen and halogen compounds are removed by using different absorptive or adsorptive ways, such as alkaline washing, active carbon bed or zinc oxide bed. In the next phase, methanation, carbon monoxide and hydrogen are converted into methane. The reaction can take place in fixed-bed reactor or fluidized-bed reactor. The last step in bio-SNG production is raw SNG upgrading. The raw SNG is dried and cleaned from carbon dioxide and unconverted gas components, such as hydrogen. Cleaning methods include commonly used gas cleaning ways, such as amine or triethyleneglycol based washing systems. These byproducts are then recycled to the process to maximize the process' overall efficiency. (Rönsch et al. 2012)

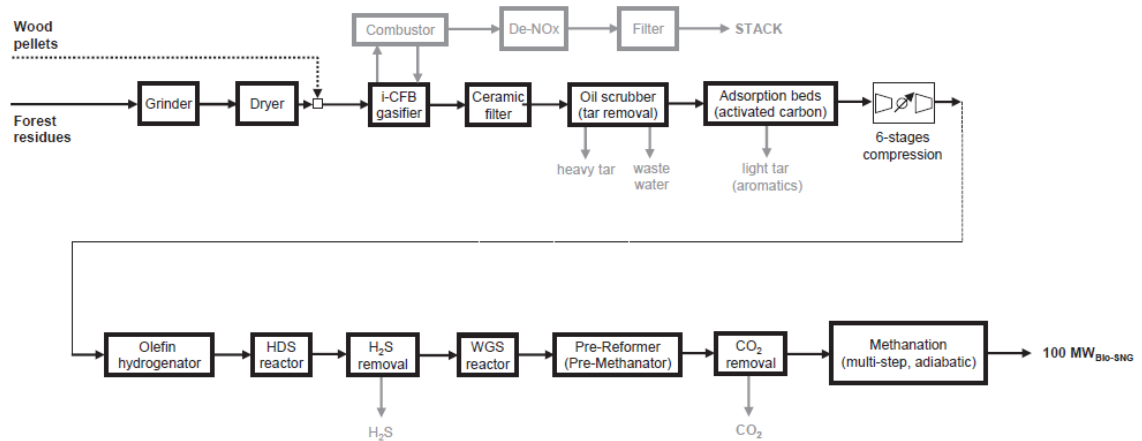


Figure 6. (Haro et al. 2016)

The economic and environmental aspects of Bio-SNG production depends on production plant designs and long term technological solutions. According to Rönsch et al. (2012) long term concepts have better exergetic efficiency compared to short term concepts. Bio-SNG short term concepts' production costs are highest when concept

with a gas turbine or engine are being used, (between 0.10 and 0.17 €/kWh (27.78-47.22 €/GJ)), because of engine and turbine investments. Lowest bio-SNG production costs, 0.09€/kWh (25 €/GJ) are achieved by concepts that transform process heat to electrical energy. For long-term concepts, production costs are between 0.089€/kWh and 0.163€/kWh (24.72-45.28 €/GJ), which are in average lower than short-term concepts costs. Therefore, bio-SNG is not economically competitive, compared to natural gases production costs of 0.02-0.03 €/kWh=5.56-8.33 €/GJ. (Rönsch et al. 2012)

Greenhouse gas emissions from bio-SNG production are lowest on short-term concepts, as steam cycle concept reaches emissions of 17.0g CO₂/MJ. Analyzed long-term concepts show emissions between 18.5g CO₂/MJ and 26.9g CO₂/MJ. Highest greenhouse gas emissions of analyzed concepts are associated with concepts that utilize a gas engine, between 19.4 and 19.7g CO₂/MJ, or a gas turbine, between 25.9 and 26.9g CO₂/MJ. (Rönsch et al. 2012)

3.4 Bio-oil

Bio-oil is product of pyrolysis of biomass. It is also known as pyrolysis oil, bio-fuel oil, pyrolytic oil and liquid wood. Bio-oil is usually in a dark brown organic liquid form and it contains hundreds of organic compounds, such as alkanes, aromatic hydrocarbons, phenol derivatives and small amounts of esters, ketones, ethers, sugars, amines and alcohols. Bio-oils have several uses, as they can be directly used as fuels in boilers or upgraded to produce fuels and bulk chemicals. (Isahak et al. 2013)

Feedstock for bio-oil production includes a large variety of biomass types. Bio-oil can be produced for example from wood sawdust, sugar cane waste, hardwood and softwood from pine tree, rice husks etc. In most cases fast pyrolysis is the preferred regime for process. Other pyrolysis types are used for some biomasses, e.g. slow pyrolysis for plant thistle, steam pyrolysis for potato skin and flash pyrolysis for pinewood sawdust. (Isahak et al. 2013)

Fast pyrolysis is the most effective method to convert biomass into liquid products, yield can be as high as 80% based on dry feed uses. Required conditions for fast pyrolysis process include dry feedstock, small particles (<3mm), short residence times

and moderate temperatures of 400-500 °C. Typical yield values for fast pyrolysis are 60-70% for bio-oil, 12-15% for char and 13-25% for gaseous products. Types of reactors based on fast pyrolysis principle include bubbling fluidized bed (a), circulating fluidized bed (b), both of which are presented in figure 7, rotating cone pyrolyzer, vacuum pyrolysis method and Auger reactor. (Isahak et al. 2013)

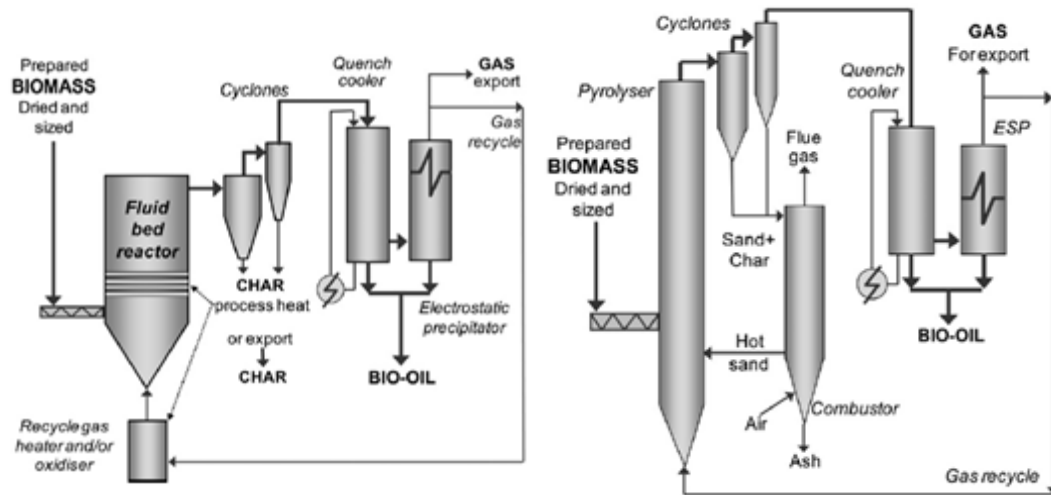


Figure 7. Fast pyrolysis technologies based on a) bubbling fluid bed reactor and b) circulating fluid bed reactor (Bridgwater 2012)

With fast pyrolysis, the best estimated selling price for bio-oil is 8.58 €/GJ to 10.46 €/GJ for a plant with 800 oven-dry tonnes of product per day, depending on char price. (Rogers & Brammer 2012) (6.8 £=8.58 €, 8.3 £=10.458 €, conversion of 1 £=1.26 € is used on 19.4.2016)

3.5 Hydrogen

Annually, about 38Mt of hydrogen is produced worldwide. Most (80-92%) of produced hydrogen is used in oil refineries and in the production of chemicals, such as ammonia and methanol. Other uses of hydrogen include industrial processes, chemical manufacturing and food preparation. Currently, Canada is the largest per capita hydrogen producer (3.4 tonnes per year) and user (2.97 tonnes per year). In future, demand for hydrogen is expected to grow exponentially, as the estimated demand for

hydrogen is predicted to be between 5.9 Mt/year and 6.9 Mt/year in Canada by 2020. (Levin & Chahine 2009)

Ways to produce hydrogen include several different processes, such as electrolysis of water, thermocatalytic reformation of hydrogen-rich organic compounds and biological processes. Currently, the most common ways to produce hydrogen include steam reformation of methane and water electrolysis. Biological production of H₂, biohydrogen, by using microorganisms offers a way to produce renewable hydrogen from biomass. Biomass gasification offers another way to produce hydrogen. Feedstock for hydrogen production includes methane, glycerol, alcohols, polyols, sugars and organic acids for steam reformation and H₂O+electricity for electrolysis of water. Biohydrogen production feedstocks include lignocellulosic biomass for biomass gasification method, which is presented in figure 8, and lignocellulosic biomass and/or lignocellulose hydrolysis products for dark fermentation. Future hydrogen use applications include the use in fuel cell applications, such as portable power and as backup power for telecommunications. (Levin & Chahine 2009)

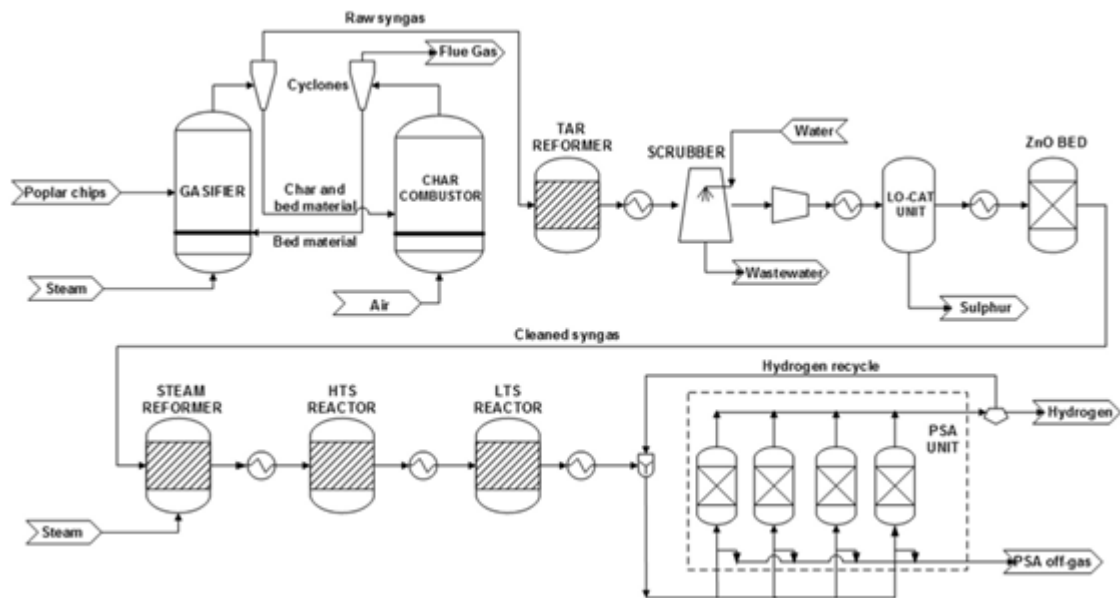


Figure 8. (Iribarren et al. 2014)

3.6 Methanol

Methanol, also known as “wood-alcohol”, is considered to have the best potential of renewable energy sources to contribute for the energy needs of both developed and developing economies in the world. In year 2004, methanol industry generated over \$12 billion/year and employed over 100,000 people, directly or indirectly, worldwide. Methanol production from biomass offers a promising carbon neutral fuel to be used to fuel cell vehicles, as transportation fuel and as a chemical building block. As Amigun et al. (2009) states, one of the main advantages of biomethanol is its low greenhouse gas emissions. The carbon content in biomethanol is primarily from the carbon used in the growing of the feedstock and is only re-released into the atmosphere. (A. Demirbas, 2008)

Production of methanol is done mainly from natural gas, but biomass gasification, seen in figure 9, is a promising alternative to manufacture methanol from biomass feedstock, such as old wood or bio-waste. The biomethanol production is done via gasification and partial oxidation reactions to produce syngas, followed by catalytic conversion into biomethanol. First phase of production is drying and crushing the bio-feedstock into powder. Then, the powder goes through gasification and partial oxidation phases in a temperature of 1250K. This yields a mixture of gases, including H₂, CO, CO₂ and H₂O. Catalytic conversion of the syngas into biomethanol takes place at a pressure of 4-8 MPa. The synthesis that yields biomethanol in the process is $\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}$. (A. Demirbas, 2008)

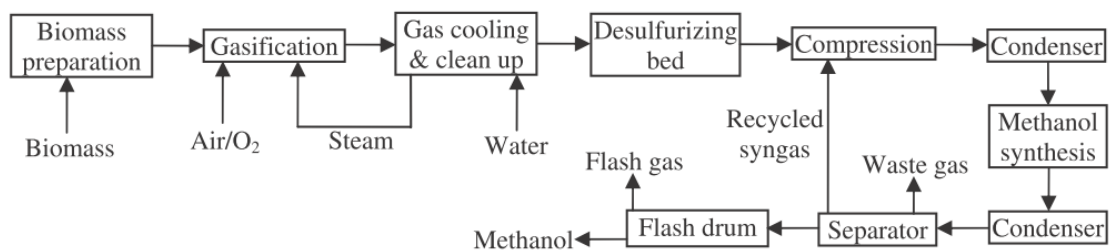


Figure 9. (Sarkar et al. 2011)

The methanol production cost for a 2000 MWth plant capacity in South Africa is evaluated to be 228.8€/ton, when feedstock biomass cost was 0.05€/kg. If biomass price was higher, 0.12€/kg, production cost for methanol was estimated to be 254.26€/ton. Prices converted with an exchange rate of 1€=16.43rand as of 17.4.2016. (Amigun et al. 2009)

3.7 Ethanol

Currently, bio-ethanol is the major bio-automotive fuel. The use of bio-ethanol is expanding fast as a fuel additive and also as a basic chemical. Bio-ethanol can be produced from sugar/starch materials, which is referred as 1st generation bio-automotive fuel or from lignocellulosic biomass, that can be converted into bio-ethanol by gasification-synthesis, gasification-fermentation or hydrolysis-fermentation. Bio-ethanol from lignocellulosic routes is referred as 2nd generation bio-automotive fuel, and its currently high cost is expected to decrease as the feedstock is cheap, abundant and does not compete with different industries, such as food production. One promising way to produce bio-ethanol is the thermo-chemical process, that has been designed and simulated in ASPEN Plus –software. It has been discovered to be a cost-competitive alternative as production related attributes, such as efficient equipment, optimized operation and inexpensive raw material with low pretreatment costs, have been introduced. (He & Zhang 2011)

Bio-ethanol production with thermo-chemical method includes five main steps: biomass pretreatment, gasification, syngas cleaning and conditioning, alcohol synthesis and lastly alcohol separation. In the biomass pretreatment phase the wood chips are screened and metal debris is removed from the biomass with a magnetic separator. Particles that are over 10 mm are fed into a hammer mill for size reduction. Biomass is dried by direct contact with hot flue gas from char combustor and regenerator so that its moisture contents drops from up to 50 wt-% to around 5 wt-%. Gasification takes place after the biomass pretreatment. Indirect dual-bed gasifier is used for the process. Particles, that are separated from the raw syngas are cooled and mixed with water in a cooler and then land filled. The reaction for this thermo-chemical process includes thermal decomposition followed by partial oxidation, reduction and reforming. MgO is added to

increase the ash melting point and to prevent the agglomeration which would result from the interaction of biomass potassium with silicate compounds. The syngas quality depends on several factors: gasifier design, feedstock, gasifying agent, steam to biomass ratio, temperature, pressure etc. For ethanol synthesis, syngas H₂/CO molar ratio should be 1-2. (He et al. 2011)

Impurities, such as tars, sulfurous and nitrogenous compounds, alkali metal species, ash and char, in the raw syngas are threats to ethanol synthesis catalysts and therefore must be removed from the gas. A catalytic reformer is used to crack down tars before the temperature of the gas drops down. Tars are then reformed into additional CO and H₂. The reformed syngas is lead through a cyclone and cooled to 150 °C while the flue gas from the regenerator is sent to a drier through another cyclone. A scrubber and a quench chamber are then used to provide additional cooling and other impurities, such as particulates, residual tars and ammonia are reduced even more. A five-stage compressor is used to compress the gas to 29 bar (43 °C), when NH₃ and H₂O are condensed. After that acid gases, such as CO₂ and H₂S are removed via an amine system. Other sulfurous compounds in raw syngas will be converted into H₂S via H₂-rich syngas and Ni-Mo-based or Co-Mo-based catalysts. A small percentage (about 5 vol.%) of CO₂ is needed for the methanol synthesis catalyst and may also be beneficial for ethanol synthesis. H₂S from the amine unit is pre-heated and oxidized. (He & Zhang 2011)

The cleaned syngas is the compressed and pre-heated to alcohol synthesis conditions of 100 bar and 300 °C. The synthesis lasts for seconds or minutes and the product is then cooled and initially purified to separate out the unconverted gas. In terms of economy and yield, the MoS₂ catalyst is recommended. For alcohols separation, the mixed alcohols are de-gassed, dried and separated into ethanol and higher alcohols. A flash separator is used to separate alcohols from off-gas. The off-gas contains CO₂, small amounts of hydrocarbons and alcohols, which can all be recycled back to the alcohols synthesis reactor. Depressurized alcohols stream is dehydrated with molecular sieve and fed into main distillation column, which is where 99% of the incoming ethanol and methanol are recovered in the overhead, while 99% propanol, 1% ethanol and all of butanol and penanol are located in the bottom stream. The overhead stream is fed into second column to increase the ethanol purity. Methanol is used to rinse adsorbed water

off the molecular sieve in the stream. The produced ethanol and higher alcohols are then cooled and stored. (He & Zhang 2011)

Economy analysis for the thermo-chemical process reveals that ethanol production cost decreases rapidly when plant size increases, as seen in figure 10. Increasing plant size further from 200 MW doesn't provide the same kind of production cost decrease as in the smaller sizes (from 20 to 200 MW). The plant should therefore be built around 200 MW. The production cost of ethanol at this size is around 0.33 €/l. At 1000 MW plant the cost would reach as low as 0.25 €/l. (He & Zhang 2011)

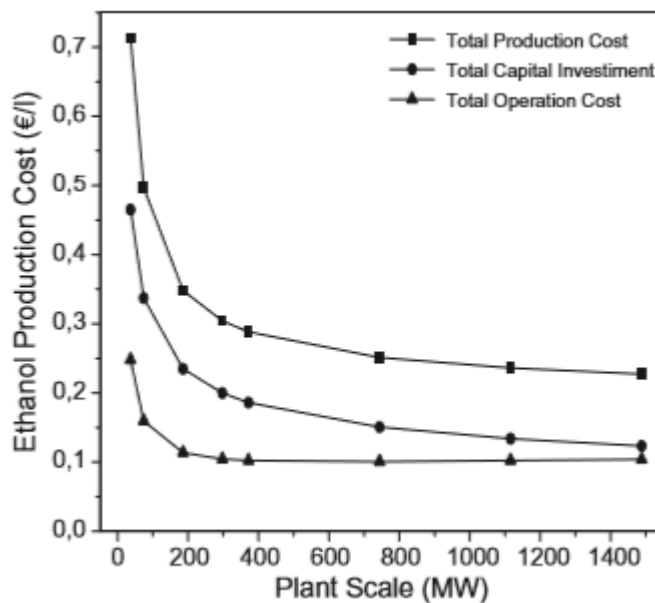


Figure 10. - Ethanol production cost as a function of plant scale (He & Zhang 2011)

4 COMPARISON TO FOSSIL BASED-REDUCTANTS

Currently, one of the main issues of use of biomass-based reductants and energy sources is the economics compared to fossil-based reductants and energy sources. Table 1 provides aggregation of properties and economics of previously addressed bio-products. As the production costs of examined bio-products are compared to traditional fossil fuels, it can be noted that they can't compete in terms of economics, as coal price is stated to be 81.1 €/ton by Norgate & Langberg (2009).

When it comes to comparing competitiveness between different biofuels, table 1 shows that torrefied biomass and bio-oil are the most economical bio-products in terms of production costs. Both of them can also utilize a large variety of different biomass feedstock, which makes them even more appealing compared to the other alternatives.

Bioreductants also offer more environmental friendly way to produce steel. It is estimated that CO₂ emissions from a BF could be reduced by up to 27% when charcoal is being used as PCI replacement. (Wang et al. 2012)

Table 1.

Bio-Product	Feedstock	Capacity (dry tonnes/day)	Technology	Location	Base year	Production cost (€/t, €/GJ)	Reference
Torrefied biomass	Lignocellulosic biomass	300 tonnes/day	Torrefaction + densification	N/A	2013	Between 2.9 and 4.2 €/GJ	(Batidzirai et al. 2013)
Charcoal	Wood products; eucalyptus	N/A	Slow pyrolysis	Western Australia	2006	347.9€/t, 30 €/GJ (selling price)	(Norgate & Langberg 2009)
Bio-SNG	Solid biofuels	N/A	Gasification and methanation	Güssing, Austria	N/A	24.7 €/GJ	(Rönsch et al. 2012)
Bio-oil	Woody biomass and grasses	800 dry tonnes/day	Fast pyrolysis	N/A	2005	8.58 €/GJ to 10.46 €/GJ	(Rogers & Brammer 2012)
Hydrogen	Lignocellulosic biomass and/or lignocellulose hydrolysis products	N/A	Biomass gasification or dark fermentation	N/A	2005	N/A	(Levin & Chahine 2009)
Methanol	Wide range of biomass	23.8 to 4794.5 m ³ /day	Gasification and partial oxidation	South Africa	2008	228.8 €/t, 22 €/GJ	(Amigun et al. 2009)
Ethanol	Wood chips	N/A	Thermo-chemical biomass-to-ethanol process	Forest rich countries, places close to harbors, paper and pulp mills	2010	419.1 €/t (0.33 €/l), 26.8 €/GJ	(He & Zhang 2011)

5 CONCLUSIONS

The use of fossil-fuels in iron and steel industry is a significant greenhouse gas emission cause. This paper examines if it is possible to include low CO₂ emissions in the iron and steelmaking process and regardless stay economically competitive. However, the results indicate that currently, biomass-based reductants would be an effective way to lower greenhouse gas emissions, but the economic aspect is way inferior compared to traditional fossil-fuels.

As demonstrated by Wang et al. (2012), the CO₂ emission reduction from replacing PCI by charcoal in blast furnaces is notable. Low greenhouse gas emissions are the most appealing feature of these bioreductants. If this significant decrease in emissions could be combined with low costs, revolutionary low-emission steel could be produced. Perhaps in the future biomass-based reductants will receive more attention and thereby become more researched and new ways to produce these more environmentally friendly fuels could be discovered and introduced in the industries worldwide. Out of the addressed bio-reductants, only charcoal is currently used in iron and steel industry. However, other economically competitive and environmentally friendly bio-fuels, such as torrefied biomass and bio-oil might be able to have similar use in low-emission steelmaking in the future as technologies and knowledge of these subjects improve.

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