

Lappeenranta-Lahti University of Technology LUT

School of Energy Systems

Master's Degree Programme in Energy Technology

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**TECHNO-ECONOMICAL ASSESSMENT OF UTILIZING
HYDROTHERMAL CARBONIZATION IN PULP AND
BOARD MILL SLUDGE TREATMENT**

Examiners: Professor, D.Sc. (Tech.) Esa Vakkilainen

D.Sc. (Tech.) Katja Kuparinen

Supervisor: D.Sc. (Tech.) Marcelo Hamaguchi

ABSTRACT

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Techno-economical assessment of utilizing hydrothermal carbonization in pulp and board mill sludge treatment

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Hydrothermal carbonization (HTC) is a thermochemical process that is used to convert biomass feedstock into charred matter called hydrochar. The advantage of HTC is its ability to process wet feedstock, which is more challenging through other treatment ways. The produced hydrochar can be used as a biofuel to replace fossil fuels. The HTC pilot project at Stora Enso Heinola fluting mill aims to produce hydrochar from the biosludge generated at the mill's waste water treatment plant. Currently, biosludge is incinerated at the mill's fluidized bed boiler. However, due to its moisture content (13–14%) and low net calorific heating value, it requires support fuel to compensate for the bed cooling. Wet biosludge also causes disruptions at the solid fuel feeding system, resulting in the need of oil burning. Hydrothermal carbonization plant generates savings in fossil fuel and CO₂ emission costs. The investment cost has a major impact on HTC project viability, whereas fixed and variable cost has lesser impact within studied cost range. The HTC investment could benefit from the economy of scale, considering that relative investment costs would be smaller for larger plants.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

School of Energy Systems

Energiatekniikan koulutusohjelma

Mika-Matti Raatikainen

Teknis-taloudellinen arviointi märkäpyrolyysin hyödyntämisestä kartonki- ja sellutehtaan lietteiden käsittelyssä

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Märkäpyrolyysi (hydrothermal carbonization, HTC) on lämpökemiallinen prosessi, jota käytetään HTC-biohiilen valmistamiseen biomassasta. Märkäpyrolyysillä voidaan käsitellä kosteita raaka-aineita, joiden hyödyntäminen muilla menetelmillä on haastavaa. Pilottiprojekti Stora Enson Heinolan flutingtehtaalla kokeilee tehtaan biolietteen hyödyntämistä märkäpyrolyysillä valmistetun biopolttoaineen raaka-aineena. Nykyisin bioliete hävitetään polttamalla. Alhaisesta kuiva-ainepitoisuudesta (13–14 %) ja tehollisesta lämpöarvosta saapumistilassa johtuen liete tarvitsee poltossa tukipolttoainetta ja lisäksi liete aiheuttaa ongelmia kattilan kiinteän polttoaineen syöttölaitteistossa johtaen öljypoltinten käyttöön. HTC-investointi tuottaa säästöjä fossiilisten polttoaineiden ja hiilidioksidipäästöjen kustannusten vähentyessä. Investointikustannuksen vaikutus HTC projektin kannattavuuteen on suuri, käyttökustannusten roolin ollessa vähäisempi. Kokoluokan kasvattaminen voi parantaa HTC projektin taloudellisia edellytyksiä, jos investointikustannuksesta on tällöin mahdollista saada suhteellisesti matalampi.

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ABBREVIATIONS

Roman letters

C	cost, capacity	€, t/a
e	specific electricity consumption	kWh/kg
E	energy (electricity)	MWh
f	CO ₂ default emission factor	tCO ₂ /MWh
h	enthalpy	kJ/kg
I	investment cost	€
m	mass	kg
M	molar mass	g/mol
$q_{m,bs}$	mass flow	kg/s
Q	energy (thermal)	MWh
x	mass fraction	-

Greek letters

α	coefficient of the economy of scale	-
Υ_c	carbon yield	-
Υ_s	solid mass yield	-
ϕ	power	MW

Subscripts

ar	as received
bs	biosludge
c	carbon
CO ₂	carbon dioxide
dry	dry weight
el	electricity
est	estimated
fg	flue gas
fuel	fuel
hc	hydrochar
HFO	heavy fuel oil

new	new
p	peat
pur	purchasing
s	solid
1	original capacity
2	new capacity

Abbreviations

BFB	bubbling fluidized bed
CE	carbon efficiency
CHP	combined heat and power
COD	chemical oxygen demand
HFO	heavy fuel oil
HHV	higher heating value
HTC	hydrothermal carbonization
HTG	hydrothermal gasification
HTL	hydrothermal liquefaction
IPCC	the Intercontinental Panel on Climate Change
IR	internal recirculation
IRR	internal rate of return
LHV	lower heating value
MP	market price
SCWG	super critical water gasification
T	taxes
TOC	total organic carbon
TTP	total purchasing price

1 INTRODUCTION

As we come to 2020s, environmental issues and climate friendly solutions become more relevant than ever. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) published a special report called “Global Warming of 1.5°C”. The report goes through effects of 1.5°C global warming and compares them to a scenario where 2.0°C warming is reached. According to the report (IPCC 2018), human activities have caused approximately 1.0 °C global warming since pre-industrial times. Impacts to many land and ocean ecosystems have already been observed but it does not mean that current or upcoming efforts are pointless. Contrariwise, IPCC (2018, 178–257) recalls for the importance of limiting the planet warming. The report projects that, by limiting the warming to 1.5°C instead of 2.0°C, the sea level rise could be approximately 0.1 m lower by 2100. That implies that up to 10 million fewer people would be exposed to the risks related to sea level rising. Half a degree difference has projected similar influence on land and marine ecosystems. For example, the risk for the terrestrial area to undergo transformation of ecosystem is 50 % lower in 1.5°C scenario compared to 2.0°C. These examples demonstrate how massive impact the limiting of global warming could bring. (*ibid.*)

The energy sector, more specifically the electricity and heat generation market, is responsible over 40 % of global CO₂ emissions (IEA 2019, 5). Realistic scenarios to restrict warming to formerly mentioned 1.5°C with no or limited overshoot requires substantial reduction on CO₂ emissions during near decades (IPCC 2018, 112–113). Against this background, it is not surprising to see studies suggest that CO₂ neutral energy sources, like bioenergy, have potential to play a significant role in the transformation to climate friendly society (Creutzig *et al.* 2015, 930–931).

Biological waste water treatment at pulp, paper and board mills produces wet solid waste called biological sludge or biosludge. Energy-wise, biosludge holds potential for bioenergy production. High water content however makes it challenging to exploit. Incineration is commonly used within mill’s where it is possible, but due to high water content and low net calorific value, combustion of biosludge produces low amount of heat

and often needs support fuel to compensate a temperature drop in the furnace. (Gyllenhammar *et al.* 2003, 28–32; Hagelqvist 2013, 5–10.)

Hydrothermal carbonization (HTC) simulates nature coalification process to convert biomass to a solid, coal-like biofuel. Although the principles were introduced at 1910s, applications and major research date back to recent decades. (Funke & Ziegler 2010, 160–161.) Capability to process wet feedstock provides interesting option for pulp and paper industry to dispose their problematic waste and recover the energy it contains (Wikberg *et al.* 2016, 236–237).

The objective of this thesis is to analyze the economic aspects of HTC utilization at biosludge treatment and assess viability of the HTC plant as an investment for pulp and board mill. Impacts to the mill's other sections, such as power plant and wastewater treatment plant, is considered. The thesis is part of the HTC biofuel project at Stora Enso Heinola fluting mill and the project is used as a reference case during the thesis. Due to schedule established for thesis, field tests could not be implemented. The findings based on data provided by Stora Enso and C-Green and literature in a field.

The thesis begins with survey to the theoretical background of hydrothermal carbonization and its products in chapter 2. Purpose of Heinola biofuel project, parties and technology applied in project will be introduced in chapter 3. Chapter 4 includes calculations about biofuel production rate and fossil fuel savings. Viability analysis and effect of different factors to investment economic outlook will be presented in chapter 5. Finally, conclusions of the thesis will be presented.

2 BACKGROUND

Biomass refers to all organic materials that stem from photosynthesis of green plants. Logging residues, energy crops and animal manure are just a few examples of biomass. It can include a wide range of organic compounds such as cellulose, hemicellulose, lignin, lipids, proteins, sugars and starches. Biomass stores solar energy in the form of chemical energy, which can be released when the chemical bonds between adjacent oxygen, carbon and hydrogen are broken by various biological and thermo-chemical processes. As a fuel, biomass is considered CO₂ neutral as the CO₂ released during combustion is captured through photosynthesis by re-growing biomass (Zhang *et al.* 2010, 969). For a modern energy industry requirements downside of biomass is its heterogeneity in qualities like composition, particle size and moisture content. This is why fuel preparation or pretreatment is often used needed. HTC and carbonization processes in general fits this mold as they convert biomass to more homogenous, coal like material. (Libra *et al.* 2011, 89; Liu *et al.* 2012, 948; IEA 2017, 28–29.)

2.1 Carbonization and char production

Carbonization is “a process by which solid residues with increasing content of the element carbon are formed from organic material usually by pyrolysis in an inert atmosphere” (International Union of Pure and Applied Chemistry 2014, 212). In nature, biomass inherent coalification takes time from hundreds (peat) to hundred million (black coal) years. Temperature and pressure which buried organic material exposes result in chemical and physical changes in biomass residues structure and elemental composition. Carbonization processes that are used for biomass processing strive to similar result in significantly shorter time scale (Libra *et al.* 2011, 89; Flores 2014, 167–168.)

Thermochemical conversion process is a necessity when producing charred matter. Depending on the raw material and targeted end product, there are different conversion methods to choose from. Pyrolysis is an umbrella term for processes where biomass is decomposed under the influence of heat in a gaseous or liquid medium, without any further reactants. Processing temperature and exposure time determine the yield of end

products. A few different conversion processes are described in following sections. (Libra *et al.* 2011,90–92.)

When it comes to charred material production, one must pay attention to the wide-ranging terminology of this field. A general term for solid residue of pyrolysis is char. Fitzer *et al.* (1995, 484) describes char as “a solid decomposition product of a natural or synthetic organic material”. Often used demotic term for material like that is charcoal. Usually charcoal is perceived to mean products used in cooking or as a fuel, which is why term biochar is used to distinguish charred material that is used in soil carbon sequestration or soil amelioration. To stand out from biochar produced by conventional “dry” pyrolysis, the solid residue of hydrothermal carbonization is called hydrochar. This term is used regardless of the application. (Hagemann *et al.* 2018, 1–2; Libra *et al.* 2011, 90–92.)

2.1.1 Dry Pyrolysis

Pyrolysis is a thermo-chemical process where hydrocarbons of organic material is decomposed by heating in absence of oxidizing agents or other reactants. In pyrolysis large hydrocarbon molecules of biomass, such as cellulose in Figure 2.1, decomposes into comparatively smaller molecules, which leads biomass conversion to solid, liquid and gaseous residue. By setting pyrolysis temperature and residence time, it is possible to control ratio of forming process residues. Depending on the targeted yield, the pyrolysis temperature can range from 400°C up to around 800°C and residence time from seconds to hours or days. If time, t_{heating} , required to heat biomass to pyrolysis temperature is longer than the characteristic pyrolysis reaction time, t_r , process is called slow pyrolysis ($t_{\text{heating}} \gg t_r$). Conversely, in the fast pyrolysis, the heating time is shorter than the reaction time ($t_{\text{heating}} \ll t_r$). Pyrolysis process is also an essential reaction step in combustion. (Basu 2018, 155–161.)

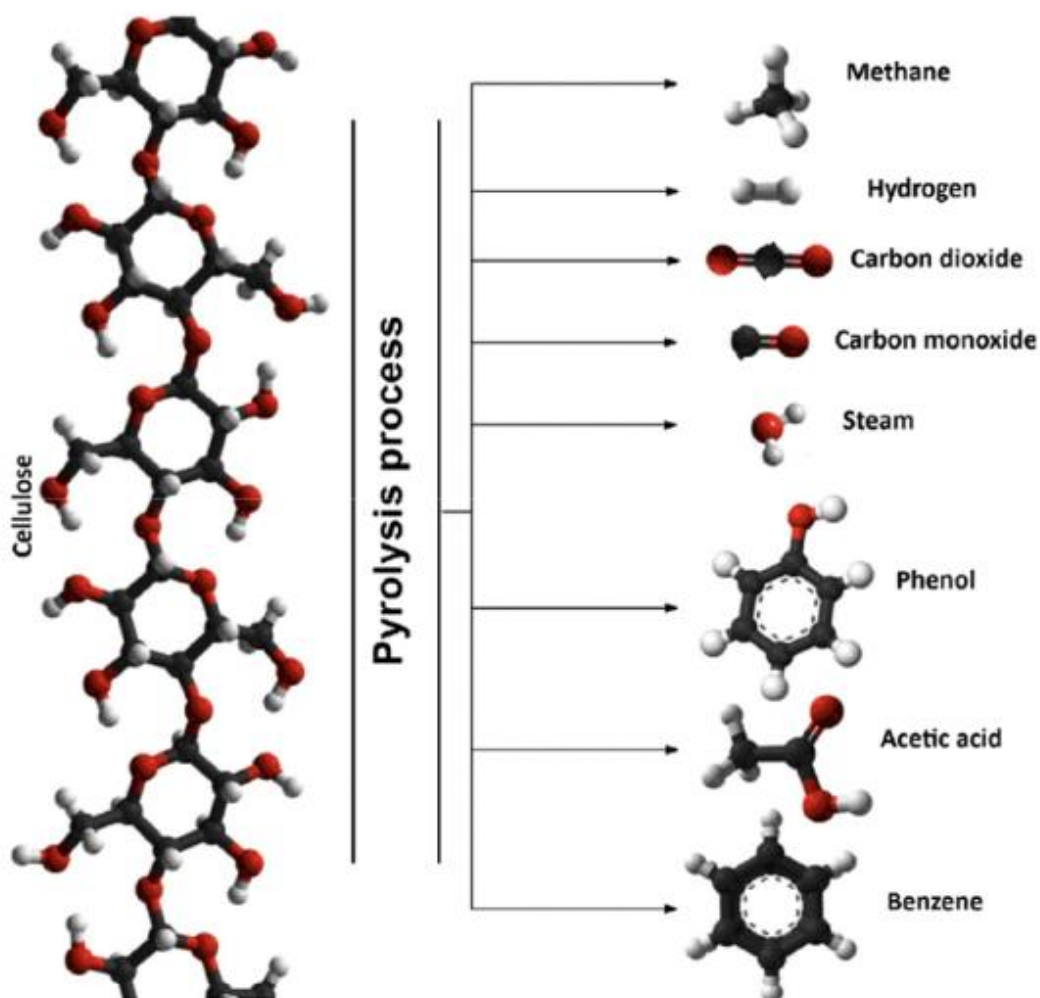


Figure 2.1 Decomposition of large hydrocarbon molecule under pyrolysis process (Basu 2018, 156).

Since ancient times pyrolysis is used to produce charcoal and tar-like substances. For that specific purpose, slow pyrolysis is proper method. Temperature in slow pyrolysis is around 400–500°C. Moderate heating rate combined with long residence time is preferred in biochar production since yield of solid material is higher than in fast pyrolysis. The yield of biochar in slow pyrolysis is usually 35–40% of raw biomass weight. Slow pyrolysis is relatively simple process and suitable for small scale biochar production. In modern solutions, forming non-condensable gases are combusted to provide heat, which improves process energy efficiency. (Libra *et al.* 2011, 91; Manyà *et al.* 2018, 115–116.)

While slow pyrolysis is used in biochar production, fast pyrolysis aims to maximize the share of liquid product. This liquid is called pyrolysis oil or bio-oil. Bio-oil consists mainly of hydrocarbon-based compounds, such as hydroxyaldehydes and -ketones, sugars and dehydrosugars, carboxylic acids and phenolic compounds. The water content can be up to 20 wt.%. The temperature in fast pyrolysis around 500 °C, but it could be higher if goal is to produce pyrolysis gas instead of bio-oil. High heating rate combined with short (< 3 s) residence time leads increased liquid production. (Basu 2018, 161–164.) Yield of bio-oil is typically around 75 wt.%. Division between slow and fast pyrolysis has not been carved in stone and there is even an option of intermediate pyrolysis, where heating rate and reaction temperature are between slow and fast pyrolysis setpoints. (Libra *et al.* 2011, 90 –92.)

2.1.2 Torrefaction

Like pyrolysis, torrefaction is a thermo-chemical treatment used for improving biomass properties as a fuel. The torrefaction process is sometimes called as mild pyrolysis, since it includes the very first decomposition processes of pyrolysis. In torrefaction biomass is thermally treated at 200–300°C by a relatively long time, generally around one hour. Low processing temperature levels makes hemicellulose of biomass to decompose, but more stable biopolymers like lignin and cellulose undergo only minor structural changes. (Bergman *et al.* 2005, 13.) Torrefaction aims to maximize energy density with reduced oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios. Torrefaction also retains most of volatiles in solid, whereas in pyrolysis volatiles disengages to gaseous phase. (Basu 2018, 97.) As Figure 2.2 demonstrates, mass of torrefied biomass is typically 70% of raw material mass, rest 30% converts to torrefaction gases. The gases contain 10% of raw material energy content, leaving 90% to solid torrefied biomass. (Bergman *et al.* 2005, 13.)

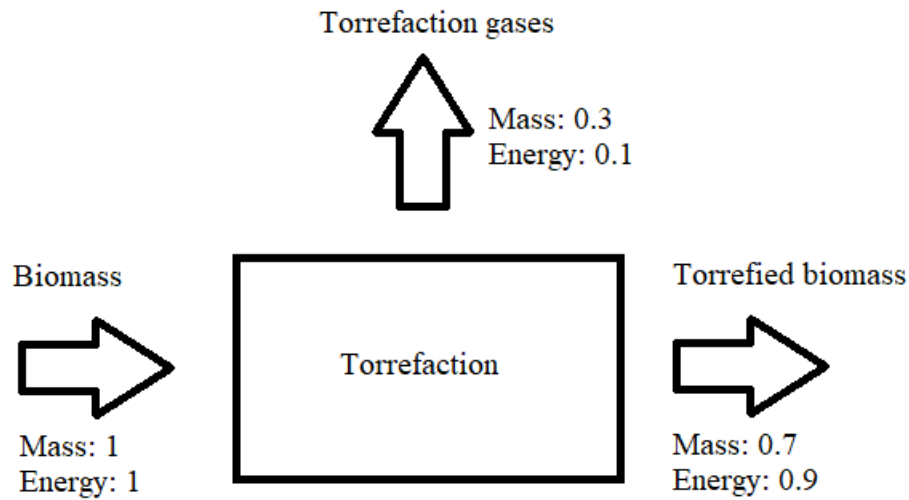


Figure 2.2. Mass and energy balances of torrefaction process (Adapted from Bergman *et al.* 2005, 13).

Torrefied biomass can be used as a fuel either in small, decentralized or residential, heating systems. It can be also co-fired with coal in large coal fired power plants. It is also suitable fuel for gasification. (Basu 2018, 93.) Torrefied biomass could be processed further by pelletization to gain higher mass and energy density, better handling properties and limited dust formation (Bergman 2005, 17–18).

2.1.3 Gasification

In a similar way to pyrolysis and torrefaction, gasification is thermo-chemical process that includes thermal decomposition of hydrocarbon feedstock. It differs from previously mentioned processes by requiring a medium such as steam, air or oxygen. A medium, also called as “agent”, reacts with solid carbon and large carbonaceous molecules and converts them into lower molecular weight gases. (Basu 2018, 211–214.) According to Basu (*ibid.*) main steps of typical gasification process are:

1. Preheating and drying
2. Thermal decomposition
3. Gasification of char and gaseous components

The product gas consists mainly of hydrogen, carbon monoxide, carbon dioxide and methane. If air is used as an agent, product includes also inert nitrogen from air. That is why air gasification gives product gas with lower heating value compared to steam or oxygen gasification. Gasification process requires high temperature (~ 800 °C) with 10–20 second residence time. Yield of gas is up to 85%, rest of raw material ends up char and liquid or tar-like residue. (Libra *et al.* 2011, 91–92.)

2.1.4 Hydrothermal carbonization

Hydrothermal carbonization process uses water as a reaction medium for converting biomass into charred material known as hydrochar. The temperature in HTC process usually ranges from 180 to 250°C. The biomass residence time in HTC reactor varies between 1 to 12 hours, though some sources suggest even longer time. Yield of biochar is 50–80% dry weight. (Libra *et al.* 2011, 92; Krylova & Zaitchenko 2018, 94.) Usually reaction pressure setting is autogenic with the water saturation pressure corresponding to the reaction temperature. As the presence of water is essential part of HTC, moisture of the raw material is not a concern. That gives HTC an advantage compared to pyrolysis or torrefaction, where drying of the biomass is significant energy-intensive part of process. (Kambo & Dutta 2015, 363.) The following chapters will provide more detailed review of hydrothermal carbonization. Table 2.1. contains the summary about process conditions and product yield of processes presented in chapters 2.1.1–2.1.3.

Table 2.1. Comparison of process conditions and product distribution in wt.% for some thermo-chemical biomass conversion methods. Values are approximation and can vary depending on the source. (Libra *et al.* 2011, 92; torrefaction: Bergman *et al.* 2005, 13.)

Process	Temperature [°C]	Vapor residence time/ processing time	Product distribution [wt.%]		
			Char	Liquid	Gas
Slow pyrolysis	400	Hours to week	35	30	35
Fast pyrolysis	500	1 s	12	75	13
Torrefaction	200–300	1 h	70	0	30
Gasification	800	10–20 s	10	5	85
HTC	180–250	1–12 h	50–80	5–20	2–5

As Table 2.1 shows, temperature level in HTC is low compared to other introduced conversion methods. Yield of liquid and gaseous residue is moderate, as HTC aims to hydrochar production.

2.2 Process conditions and chemical reactions in hydrothermal carbonization

Hydrothermal carbonization process was first introduced by German chemist Friedrich Bergius in 1913. Bergius made experiments to produce hydrogen gas from coal by using high pressure (200 atm), moderate temperature (300–600 °C) and water as a medium. When he substituted coal with peat, it was found that the residue in the autoclave resembled a soft natural coal. Analysis of this “artificial coal” showed that its carbon and hydrogen content compared well with natural bituminous coal. (Stranges 1984, 651–652.) Later Bergius was awarded with Nobel prize for his work on the development of high-pressure methods for chemical reactions (Bergius 1932), but HTC did not receive major interest until early 2000s, when it was noted to be effective method for conversion of wet biomasses and hydrochar discovered as a potential source of nanostructured carbon material (Titirici & Antonietti 2010, 103–104; Krylova & Zaitchenko 2018, 94).

2.2.1 Process parameters

The term “reaction severity” is often used to describe process conditions of HTC. Increasing temperature and longer residence time lead to higher reaction severity. A higher reaction severity produces hydrochar with high carbon content but decreases theoretically the yield of the solid product. (Funke & Ziegler 2010, 162.) A typical HTC process operates in the temperature range of 180–250 °C. The residence time varies for different feedstocks and it is often a compromise between hydrochar yield and quality. The literature proposes residence times from 1 to 12 or up to 72 hours. It has been observed that temperature is the most decisive factor to a product characteristic, but processing parameters such as residence time, water to biomass ratio (solid load) and pH also affect the hydrochar properties. (Funke & Ziegler 2010 167–170; 162–167; Jain *et al.* 2016, 794; Libra *et al.* 2011, 92–94.)

Hydrothermal carbonization process uses subcritical water for conversion of biomass to a carbonaceous product. During the process, water acts as a solvent, but also as a catalyst that facilitates hydrolysis and cleavage of lignocellulosic biomass. (Jain *et al.* 2016, 790–791.) As Figure 2.3 demonstrates, higher temperature but still subcritical water pressure is used in another hydrothermal conversion process, hydrothermal liquefaction (HTL), where goal is to produce bio-oil. Also, supercritical conditions are applied in hydrothermal treatment. Hydrothermal gasification (HTG) or super critical water gasification (SCWG) produces mainly methane or hydrogen, depending on the process parameters. (Kambo & Dutta 2015, 363; Libra *et al.* 2011, 92.)

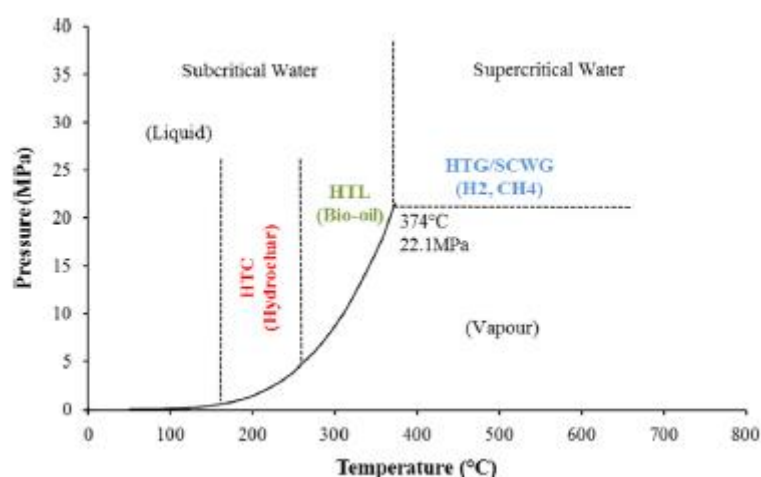


Figure 2.3. Operating areas for different hydrothermal processing methods in temperature-pressure phase diagram of water (Kambo & Dutta 2015, 363).

Hydrothermal carbonization is an exothermal process. Once activated, it is relatively easy to perform chemically. Another advantage compared to other converting techniques is high efficiency for carbon fixation, as carbon efficiency is close to 1. Figure 2.4 provides simplified comparison between carbon efficiency and stored combustion energy in some biomass refining processes. In real life, the process is not so straightforward as biomass contains also more complex carbonaceous molecules than glucose, like hemicellulose, that have their own decomposition methods. (Titirici *et al.* 2007, 788.)

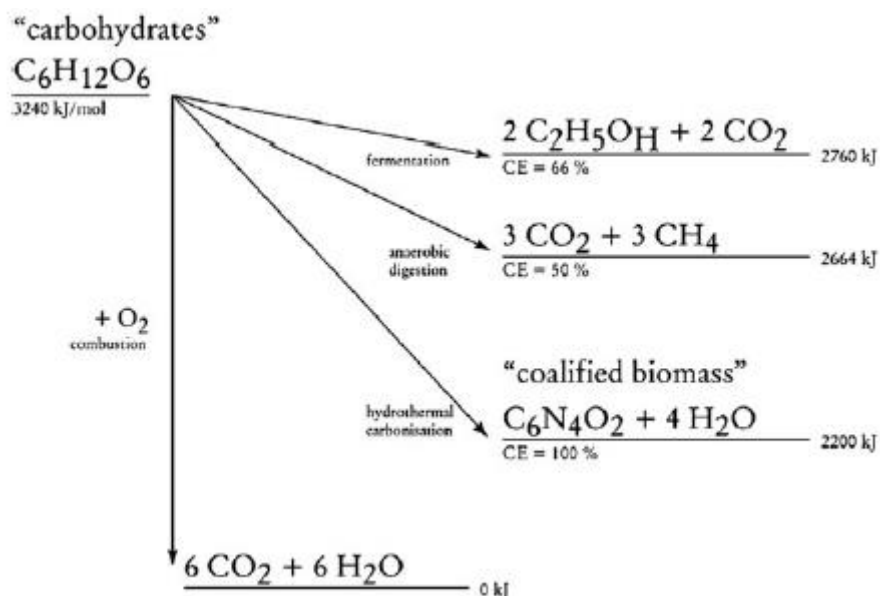


Figure 2.4. Comparison of carbon efficiency (CE) and stored combustion energy of common biomass processing techniques. (Titirici *et al.* 2007, 788).

2.2.2 Reaction mechanisms in hydrothermal carbonization

Hydrothermal carbonization of lignocellulosic biomass is a complex combination of chemical reaction, that have similarities with dry pyrolysis. Due to the intricate nature of the process, the reaction network is not perfectly known yet. The mechanisms identified as stages of reaction, are hydrolysis, dehydration, decarboxylation, condensation, polymerization and aromatization. They are not clear-cut consecutive reaction steps, but more a parallel network of ongoing reactions. (Libra *et al.* 2011, 94; Funke & Ziegler 2010, 163).

According to Libra *et al.* (2011, 94), the mechanism that initiates a hydrothermal decomposition process is hydrolysis. It is a reaction where water reacts with cellulose or hemicellulose, breaking ether and ester bonds in the macromolecule resulting in large number of products including soluble oligomers. With time, these oligomers further hydrolyze into more simple mono- or disaccharides, like glucose. (Coronella *et al.* 2014, 281– 282.) At HTC conditions hydrolysis of hemicellulose starts at 180 °C, while

degradation of cellulose takes place in range from 200 °C to 230 °C. Lignin is the least reactant component of lignocellulosic biomass in HTC conditions and remains relatively stable at 200–260 °C. (Coronella *et al.* 2014, 278– 282; Funke & Ziegler 2010, 163; Reza *et al.* 2013, 162.)

Chemical dehydration and decarboxylation of hydrolyzed material occurs after hydrolysis (Krylova & Zaitchenko 2018, 95). Dehydration can be either chemical or physical process. Chemical dehydration happens due to the elimination of hydroxyl groups (-OH), whereas decarboxylation causes a partial elimination of carboxyl groups (-COOH). Dehydration and decarboxylation contribute to carbonization by lowering the H/C and O/C atomic ratio of the biomass. (Coronella *et al.* 2014, 282–283; Funke & Ziegler 2010, 164.)

Dehydration and decarboxylation of macromolecules produce intermediate compounds such as 5-hydroxymethylfurfural, anhydroglucose and furfural, that are highly reactive for polymerization, condensation and aromatization. These reactions enable that a linear polymer like cellulose can be converted to a cross-linked polymer similar to lignin. It is likely that condensation, polymerization and aromatization reactions, specifically aldol condensation, mainly characterizes formation of the hydrochar during HTC. Biochar hydrophobicity is also a result of condensing fragments within the biomass matrix. (Coronella *et al.* 2014, 284; Funke & Ziegler 2010, 164–165.)

Figure 2.5 illustrates simplified comparison between hydrothermal carbonization and dry pyrolysis reaction pathways. Processes have some similarities in their pathways and according to Libra *et al.* (2011, 94–95) there likely occurs to a certain extent of hydrolytic reactions in dry pyrolysis and some dry pyrolytic degradation reactions during HTC.

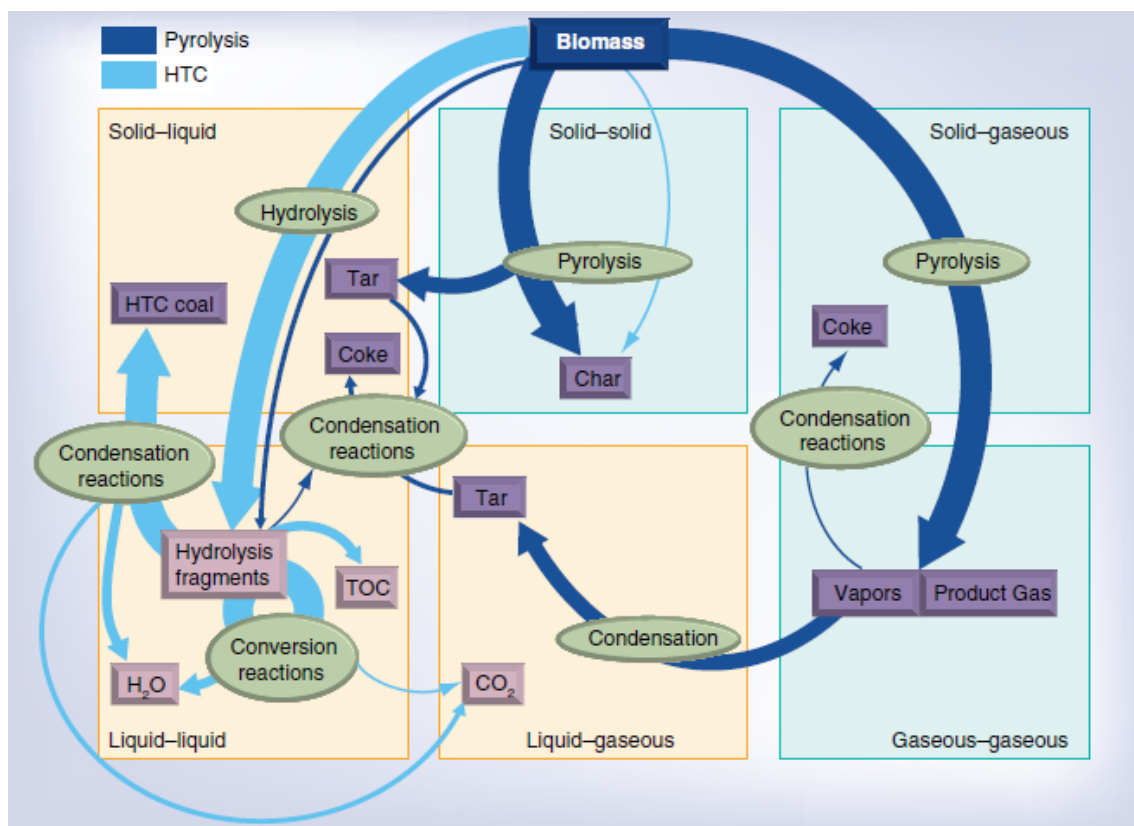


Figure 2.5. Simplified comparison of HTC and dry pyrolysis reaction paths, governing reaction phases and products (Libra *et al.* 2011, 95).

2.3 Products of hydrothermal carbonization

Even though main product of hydrothermal carbonization is solid hydrochar, HTC process produces also liquid and gaseous residues. The yields of solid, liquid and gaseous products depend on both process parameters and feedstock. (Funke & Ziegler 2010, 170.)

2.3.1 Liquid component

Water plays important role in HTC as a solvent and reactant, but at the same time it is also produced as a result of biomass dehydration. Even though focus on HTC process is on the solid yield, amount of liquid residue cannot be disregarded. Due to the decomposition reactions, the process water, later referred as filtrate, contains substantial number of organic and inorganic substances, many of them potentially valuable chemicals. If they are not recovered, these substances might become notable loss. (Funke

& Ziegler 2010, 171.) For example, utilizing organic rich waste waters for anaerobic biogas production has been recognized as a potential route to energy recovery (Villamil *et al.* 2017, 450; Wirth & Mumme 2013; 1).

The liquid residue from the HTC is often called as filtrate. It contains both dissolved organic and inorganic materials and it is the primary medium for carbon loss in HTC process (Funke & Ziegler 2010, 171–172). Organic compounds in filtrate includes organic acids, such as acetic- and glycolic acid, furfurals, phenols and hydrolyzed sugars (Kambo 2018, 1184; Libra *et al.* 2011, 95; Mäkelä *et al.* 2018, 655; Ross 2018, 20). Wirth & Mumme (2013, 1) suggest typical total organic carbon (TOC) content of HTC filtrate ranging from 5 to 20 g/l and up to 40 g/l when filtrate is recycled. The chemical oxygen demand (COD) of filtrates organic compounds usually ranges from 10 to 40 g/l. The filtrate contains also nitrogen and phosphorous compounds that are commonly considered undesired substances in waste water as they untreated contributes to water system eutrophication. In anaerobic waste water treatment system, they can however be valuable as nutrient for microbial activities. (Mäkelä *et al.* 2018, 657; Pietiläinen & Räike 1999, 7.)

Depending on the process conditions, the amount and composition of filtrate can vary even when the same feedstock is used. As process temperature increases, the yield of liquid residue rises. Parmar & Ross (2019, 6–7) researched different filtrates from HTC of agricultural residue, sewage sludge, municipal solid waste and vegetable, garden and fruit waste. They showed that the intensity of correlation could change depending on raw material. Higher temperature also increases filtrate TOC yields (Mäkelä & Yoshikawa 2016, 181; Parmar & Ross 2019, 11.), which is logical considering that increasing reaction temperature agitates decomposition reactions. (Funke & Ziegler 2010, 167–168) However, an experiment by Mäkelä *et al.* (2018, 656) indicates that biological degradability of the organic matter improves at higher temperatures. The study was made by using chemical sludge from pulp mill as raw material. Parmar & Ross (2019, 12–13) states that the increasing solid load adds filtrates TOC and COD content, but biological degradability decreases.

As we go from laboratory to industrial scale HTC plants, economic and environmental issues become more relevant and themes such as energy and water consumption are closely contemplated. Filtrate could be *e.g.* recycled in HTC process to reduce water consumption and wastewater volume. It has been also suggested to be an efficient method for heat recovery. Organic acids lower liquid pH, which could catalyze hydrolysis and decarboxylation further when using recycle filtrate. (Kambo *et al.* 2018, 1182; Mäkelä *et al.* 2018, 655).

2.3.2 Gaseous component

Gaseous compound formed during HTC consists mainly of CO₂, with small amounts of CO, CH₄, H₂ and traces of other hydrocarbons. Although CO₂ is the main component of the gas, all CO₂ formed by decarboxylation reaction is not in gaseous form but solved in water. The amount of CO₂ solved in water can be as high as the amount present in gaseous phase.

It is noted that the amount of gaseous product increases as reaction temperature rises. From the energy usage perspective, it is favorable that the heating value of hydrochar is maximized. Decarboxylation reactions take place for that purpose by removing oxygen from the feedstock and thus increasing the production of CO₂. On the other hand, there are applications such as carbon sequestration, where keeping high rate of feedstocks carbon in the hydrochar is wanted. This means limiting decarboxylation and CO₂ formation. It should be noted that the amount of carbon lost in gaseous form is low compared to the carbon loss on the non-recovered waste water. (Funke & Ziegler 2010, 171–172.)

2.3.3 Solid hydrochar

The hydrochar chemical characteristic differ from raw biomass as it approaches lignin or sub-bituminous coal chemical and elemental structure. Regarding chemical bonds and elemental composition, hydrochar resembles more closely natural coal than charcoal produced by dry pyrolysis. The H/C and O/C ratios of the initial biomass are reduced due

to dehydration and decarboxylation processes during HTC, reaching values close to those of natural coal, whereas dry pyrolysis produces typically lower atomic ratios. Changes in atomic ratios are often visualized in van Krevelen diagram, shown in Figure 2.6. (Libra *et al.* 2011, 95.)

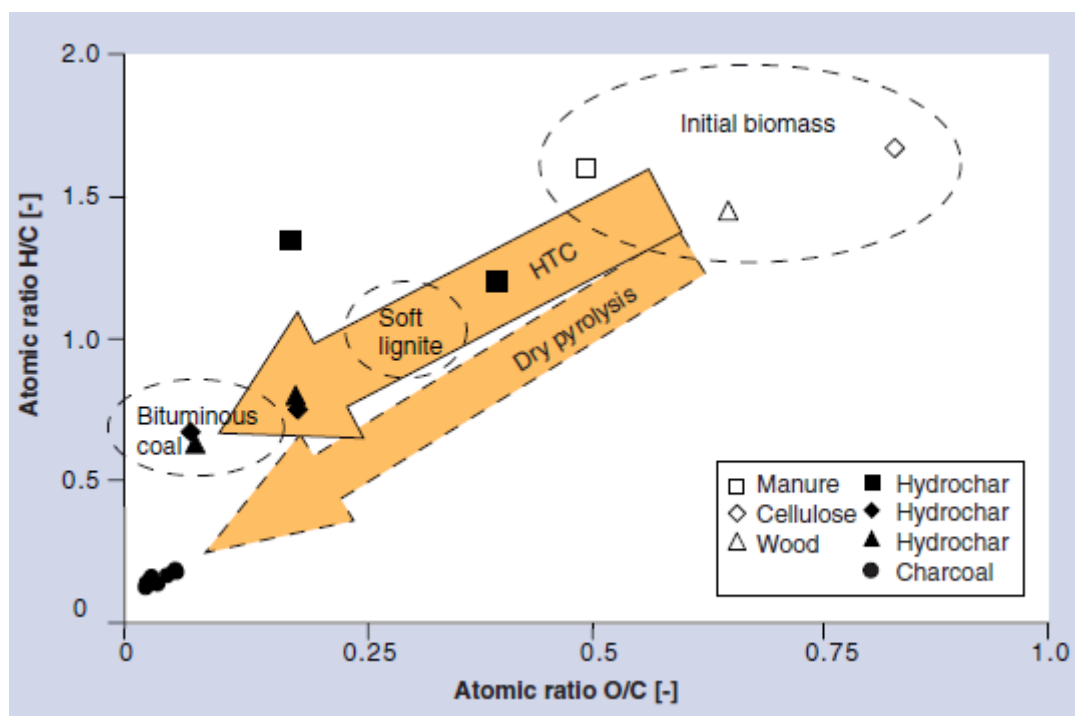


Figure 2.6 Development of H/C and O/C ratios of cellulose, wood and manure in hydrothermal carbonization. Typical ratios for raw biomass, soft lignite and bituminous coal are illustrated for comparison, as well as development of atomic ratio in dry pyrolysis. (Libra *et al.* 2011, 96.)

Reflecting the carbon content, the higher heating value (HHV) of lignin is greater than in hemicellulose, cellulose and extractives. As hemicellulose and cellulose degrades more easily under hydrothermal treatment, the decrease in total O/C ratio results in higher HHV. In addition, compounds like 2,5-HMF, degradation products of cellulose and hemicellulose, that have relatively high HHV, also augment HHV of hydrochar. Setting the process temperature is a compromise between quality (carbon content & HHV) and quantity (solid mass yield). Low temperature leads to high mass yield with lower carbon content, since high temperature has opposite effect on solid residue. (Kambo & Dutta 2015, 366–369.)

The filtrate recycling effects on hydrochar properties. Experiments by Kambo *et al.* (2018, 1187–1188) and Stemann *et al.* (2013, 144–145) shows that filtrate recycling produces hydrochar with lower H/C and O/C ratios. On the other hand, Catalkopru *et al.* (2017, 91–92) did not find any notable decrease in H/C and O/C ratios in their experiment and suggested that this may be caused by differences in raw material and HTC process parameters. All the three above mentioned experiments giving corresponding results on the impact of recycling to hydrochar mass yield, showing that it increases when compared to HTC without filtrate recycling. Increased mass yields are suggested to be the result of dissolved organic matter carbonization and condensation reactions (Weiner 2014, 2167–2168). Kambo *et al.* (2018, 1188) and Catalkopru *et al.* (2017, 91–92) reports 5–10 % and 6–11 % increase, Stemann *et al.* (2013, 145) found lesser increase. Table 2.2 shows the impacts of filtrate recycling to hydrochar properties in above mentioned experiments.

Table 2.2. Hydrochar properties presented with / without filtrate recycling. Values in O/C and H/C columns are molar ratios. (Adapted from Catalkopru *et al.* 2017, 91–92; Kambo *et al.* 2018, 1187–1188; Stemann *et al.* 2013, 144–145)

O/C	H/C	Solid mass yield	Energy yield (from raw biomass)	Raw material	Authors
0.33/0.34 ^{**}	1.14/1.13 ^{**}	74% / 64% ^(*)	88.3% / 76.6%	Grape pomace	Catalkopru <i>et al.</i>
0.34/0.39 ^{**}	1.05/1.14 ^{**}	57% / 52% ^(*)	78.3% / 68.6%	Orange pomace	
0.43/0.40 ^{**}	1.24/1.23 ^{**}	62% / 53% ^(*)	76.8% / 68.4%	Poultry litter	
0.70–0.90/ 0.85 ^(*)	0.30–0.60/ 0.80 ^(*)	57% / 47% ^(*)	80% / 65% ^(*)	Miscanthus	Kambo <i>et al.</i>
0.3/0.4 ^(*)	1.0/1.1 ^(*)	61% / 60%	81.9% / 77.0%	Poplar wood chips	Stemann <i>et al.</i>

* Values are from figures presented in Catalkopru *et al.* (2017, 91), Kambo *et al.* (2018, 1186) and Stemann *et al.* (2013, 144).

** Calculated by using elements mass fractions presented in Catalkopru *et al.* (2017, 91).

The polymeric composition of biomass material has a direct impact on the physiochemical properties of the hydrochar. During HTC processing biomass undergoes a series of chemical reactions that modifies its surficial structure and properties. Improved surface area, porosity and extensive aromatic features are typical for both hydrochar and biochar produced via dry pyrolysis, but there are structural arrangements and surface functionalities that differs significantly between chars. Hydrochar is researched as a raw material for activated carbon and nanostructured materials and that is when porosity and surface area become crucial factors. (Kambo & Dutta 2015, 366–368; Titirici & Antonietti 2010.)

For environmental purposes, it is essential to know the heavy metal content of hydrochar. The literature presents dissimilar results about heavy metal distribution in HTC. Reza (2013, 133–134) shows that HTC treatment can significantly limit hydrochar heavy metal concentration compared to raw lignocellulosic biomass. On the other hand, Liu *et al.* (2018, 284–285) founds increment in heavy metal concentration when using sewage sludge as raw material.

2.4 Hydrochar as a fuel

There are several potential applications for hydrochar produced by hydrothermal carbonization. Early studies focused primarily on soil amendments purposes. Scale of potential applications is nonetheless wider, including energy production, carbon sequestration and biomaterial solutions among other things. (Kambo & Dutta 2015, 369). In this thesis, the focus is on energy issues, with hydrochar being considered as a fuel.

As mentioned in chapter 2.3.3 hydrothermal carbonization converts biomass properties closer to the characteristics of natural coals. Raw material for the HTC is usually some sort of waste biomass. More specifically, HTC seems suitable for biomasses with high moisture, as water is essential part of HTC process and, thereby, there is no need for biomass pre-drying. (Libra *et al.* 2011, 92; Mäkelä *et al.* 2018 654–655). In addition, chemical changes during HTC makes biomass easier to be mechanically dewatered

(Lundqvist 2020a). Wet sludges, for example, are usually problematic waste to handle (Gyllenhammar 2003, 27–28).

2.4.1 Energy content

As an energy carrier, hydrochar has several superior properties compared to raw biomass and lower moisture content being one of them. Chemical dehydration removes water from biomass during HTC, but hydrochar is still in wet state when leaving the process. That is why physical dewatering is used to reduce moisture content of the hydrochar before fuel usage. Compressing, filtering and thermal drying are amongst method used for water removing. Because of the chemical changes during HTC reactions, the moisture content of the hydrothermally pretreated material can achieve value less than 50 % just by compression. (Kambo & Dutta 2015, 363). Water removal increases fuel gross heating value, but as stated in chapter 2.3.3, the hydrochar HHV also exceeds values of original biomass (Kruse *et al.* 2013, 517). Compared to biochar produced via dry thermal pretreatment with same temperature and even longer residence time, HHV of hydrochar is noted to be higher (Kambo & Dutta 2015, 369; Reza *et al.* 2014, 232). According Kambo & Dutta (2015, 369), a possible explanation is that 5-HMF, which is reaction product of HTC, has a relatively high HHV. Increased heating value contributes to higher energy density. Even though hydrochar yield is usually 50–80 % of the raw biomass weight, the hydrochar contains about 80–95 % of the original feedstock energy. (Libra *et al.* 2011, 92; Reza *et al.* 2014, 229).

2.4.2 Storage and handling

Heterogeneity is a typical feature for many biomasses, and it should be considered in biomass fuel usage. HTC treatment produces very homogenous material which facilitate the handling and fuel feeding. (Krylova & Zaitchenko 2018, 98). For untreated biomass, the storage can be problematic due to its hydrophilic nature. Untreated biomass is prone to biological decomposition and problems related to it, such as fungus formation and spontaneous ignition. (Krylova & Zaitchenko 2018, 98; Reza 2013, 116). The hydrophobic nature of hydrochar is consequence of reduced number of hydrophilic

functional groups. (Smith *et al.* 2016, 137). Better water resistance allows for longer storage periods without risk of biological degradation (Kambo & Dutta 2015, 369).

After HTC and drying, hydrochar becomes friable and dusting, so pelletization or briquetting can be used to improve handling properties further (Reza 2013, 68). Compared to torrefied biomass, hydrochar is easier to pelletize as in HTC biomass natural binders, mainly lignin, does not lose its binding properties. Binding properties are based on the phenomena called glass transition, which means solid amorphous material transition to a more viscous state in certain temperature. (Reza 2013, 189). In dry torrefaction, the glass transition temperature of lignin likely increases and makes it less favorable for pelletization. (Reza 2013, 189; Puig-Arnavat *et al.* 2017, 1647).

2.4.3 Inorganics

One possible issue for the biomass combustion is its low ash melting point (Kruse *et al.* 2013, 518–519). This characteristic contributes to furnace slagging and fouling on boilers heat exchangers, which can lead to reduced thermal efficiency, corrosion and problems with ash removal. Alkali metals in ash react with silica to form alkali silicate, which starts melting and softening causing slagging problems. Fouling happens when alkali metals react with sulfur forming alkali sulfate on heat transfer surfaces. HTC allows the extraction of a significant fraction of alkali salts into the filtrate, leaving a more demineralized solid product. (Ross 2018, 9; Smith *et al.* 2016, 139–152). That makes the ash melting point of hydrochar higher than in the raw biomass and possibly comparable to lignin. (Kruse *et al.* 2013, 518–519; Ross 2018, 9).

3 HEINOLA BIOFUEL PROJECT

Heinola HTC-pilot plant is a joint venture of Stora Enso Heinola Fluting Mill and C-Green Technology AB and it is built to the Stora Enso's mill area in the city of Heinola. The trial run of the plant began in early 2020. HTC-plant uses sludge from the mill's wastewater treatment as feedstock. The produced hydrochar is combusted at the mill's power plant, contributing to reducing the fossil fuel consumption. The purpose of the pilot is to test the HTC process on a industrial scale for treating sludges from the pulp and paper industry. Target is to produce CO₂-free biofuel in an energy efficient way to replace fossil fuels. In addition, the suitability and effects of the HTC-filtrate on biogas production are tested. (Southern Finland Regional State Administrative Agencies 2019, 3). As a part of the project, the objective of this master's thesis is to study how HTC could be integrated to the pulp mill in a financially effective way by using Heinola biofuel project as a basis.

3.1 Stora Enso Heinola Fluting Mill

Stora Enso Heinola Fluting Mill is an integrated pulp and board mill that produces semi-chemical fluting (Stora Enso 2020). In addition to pulp and board mill, the mill complex comprises a recovery plant, debarking unit, wastewater treatment plant (WWTP) and combined heat and power (CHP) power plant. As can be seen in the Figure 3.1, fluting board is a material that is used to create wavy structure between two linerboards when manufacturing corrugated board. The main function of fluting is to bring the stiffness that corrugated board requisite and separate the linerboards. (Ek & Mäkeläinen 1983, 529).



Figure 3.1 Corrugated board consists fluting between two liner boards (Seppälä 2018, 5).

Semi-chemical pulp, which is the raw material of the fluting, is produced in integrated pulp mill that employs cooking method called neutral sulfite semi-chemical (NSSC) pulping. Knowing the pulping process is important, as it effects the waste water composition and thus the quality of the sludge. The pulp mill main raw material is debarked and chipped birch, but surplus veneer chips is also used. Semi-chemical pulping consists two main stages: chemical cooking and mechanical treatment. In the chemical stage, the aim is break various bonds between wood fibers by using chemicals and high temperature. Cooking is performed to such an extent that mechanical defibration is possible to perform without causing a significant fiber damage (KnowPulp 2020). NSSC-cooking strive to dissolve lignin of the wood without removing too much hemicellulose, as high hemicellulose concentration is important for reaching enough stiffness in fluting. Cellulose does not usually dissolve much in NSSC-cooking. (Ek & Mäkeläinen 1983, 509).

3.1.1 Wastewater treatment & sludge formation

The wastewater treatment system is closely connected to HTC-project, since the biosludge produced in the mill is used for HTC. In addition, the HTC-filtrate is returned in to treatment. As can be seen in Figure 3.2, WWTP in Heinola mill includes both aerobic and anaerobic wastewater treatment systems, as well as clarifiers that separates solids physically. Mill's wastewater load consists mainly of two major sources. First one is the water from debarking plant, that includes high fiber wastewaters from pulp and board mills' fiber channel. Another main source is secondary condensates from evaporation plant. The WWTP handles also collectable water from certain locations, including the filtrate from sludge handling and mill's domestic supply water.

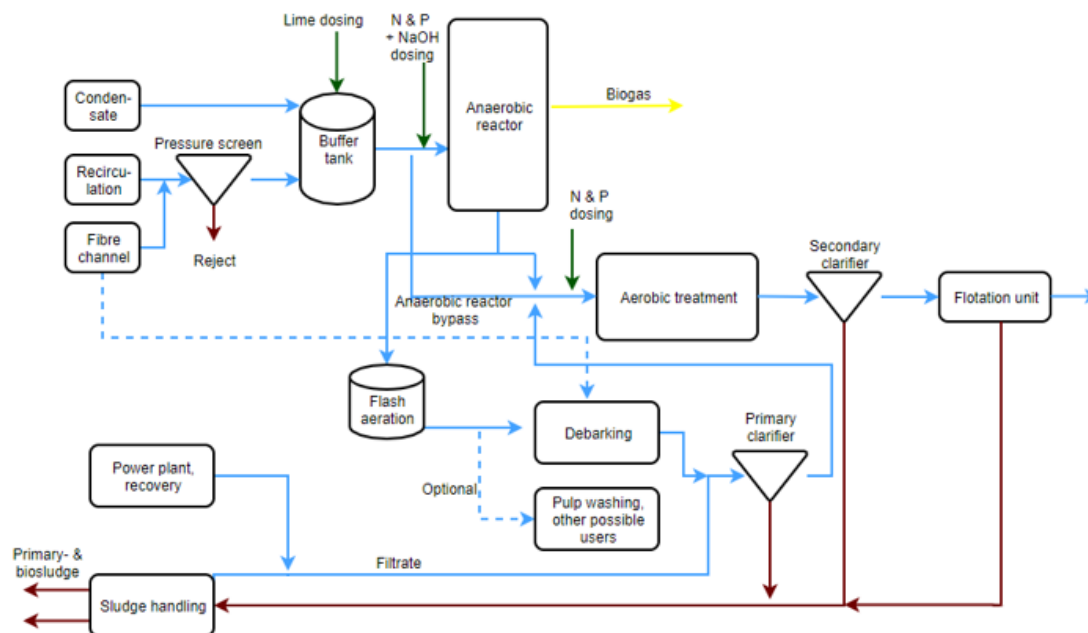


Figure 3.2 Flow diagram demonstrates WWTP's main streams and working principle. Treated water exits system from flotation unit. (Adapted from Southern Finland Regional State Administrative Agencies 2016, 10).

The high fiber wastewaters from fiber channel is discharged to the debarking plant for secondary usage to reduce raw water consumption. From the debarking plant, wastewater first goes to primary clarifier, where the aim is to separate solid fiber and bark particles by sedimentation. This separated residue from primary clarification is called primary sludge (Lohiniva *et al.* 2001, 23–24). According to Thompson *et al.* (2001, 279–280), more than 80 % of suspended solids (SS) can be removed in this stage. The primary sludge undergoes mechanical dewatering, achieving dry matter content of approximately 35–40% (Lohiniva *et al.* 2001, 24).

Condensates from evaporator and board mill recirculation water are treated in the anaerobic reactor, where anaerobic bacteria convert COD load into methane. The anaerobic wastewater treatment can remove 80–90% of wastewater COD-load (van Lier *et al.* 2008, 416). Before anaerobic reactor, phosphorus and nitrogen are added to the wastewater to provide nutrients to the anaerobic bacteria. Also, sodium hydroxide for pH

adjustment is added. Detailed description about the anaerobic reactor and biogas production are presented in chapter 3.1.2.

Wastewaters from anaerobic treatment and primary clarifier are processed further with aerobic treatment. Aerobic treatment is performed in the aeration lagoon, where in the presence of oxygen bacteria converts suspended organic material into biological mass called activated sludge. (van Lier *et al.* 2008, 415; Meyer & Edwards 2014, 324). Secondary clarifier separates the activated sludge and part of the sludge is removed from the process. The rest is recycled in to aeration lagoon. The final separation stage is flotation, where the remaining of biological matters are removed with dispersion water and polymers.

The removed activated sludge from secondary clarifier and the sludge from flotation are called biosludge. The collected biosludge is mechanically dewatered to 13–17% dryness through a decanter centrifuge. The sludge is problematic to handle even after dewatering due to its moisture and rheology. In addition, the strong odor of sludge imposes restrictions for storage. Compared to biological sludge produced in municipal wastewater plants, the biosludge from pulp and paper industry differs due to its relatively high lignin and cellulose contents. According to Meyer & Edwards (2014, 338), the total solids of pulp and paper industry biosludge contains 36–50% lignin and 19–27% cellulose, whereas in municipal biosludge their concentration is 1% or below. The biosludge production in Heinola mill has been 13 000–14 000 ton of wet sludge per year and 16 000 t/a is the maximum estimated capacity. The production of 13 551 t/a biosludge is used as yearly estimate in energy and economic calculations in chapters 4 & 5.

3.1.2 Anaerobic biogas reactor

Anaerobic wastewater treatment is based on bacteria activity that degrades organic material in the absence of oxygen. Anaerobic digestion is an effective method to remove wastewater COD load, but it also enables energy capturing in the form of biogas. (Abbasi *et al.* 2012, 2–4; van Lier *et al.* 2008, 415–416.) In addition to biogas, anaerobic reactor produces granular anaerobic sludge. As Figure 3.3 shows, sludge formation in anaerobic

reaction is lower compared to aerobic reaction. Granular anaerobic sludge has positive market value, so its formation is desirable. (van Lier *et al.* 2008, 415–416).

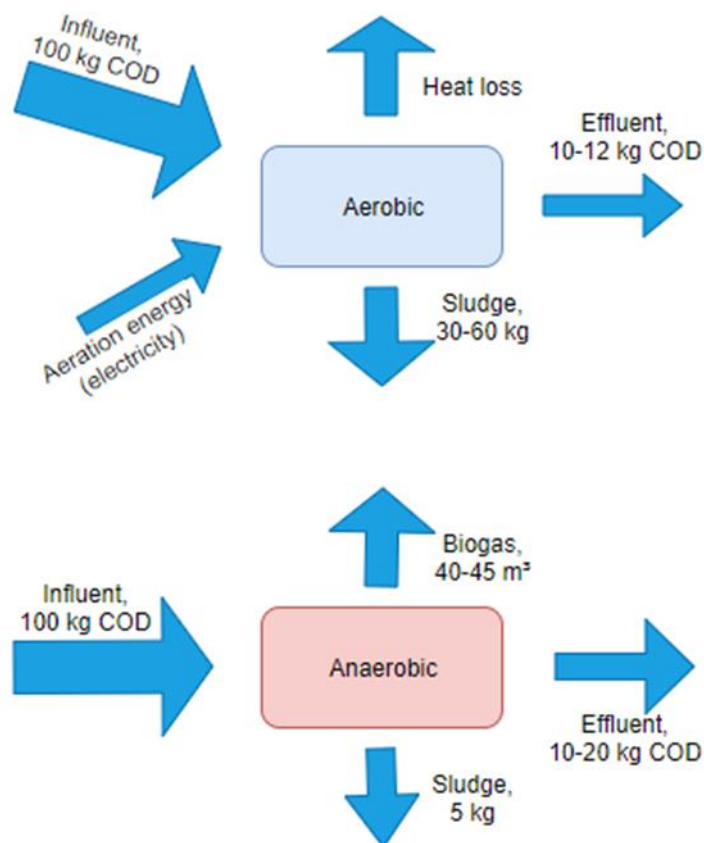


Figure 3.3 Simplified comparison of carbon and energy division in aerobic and anaerobic wastewater treatment. (Adapted from van Lier *et al.* 2008, 416.)

In order to preserve optimal condition for bacterial activity, the bioreactor pH value is controlled by dosing caustic lime and sodium hydroxide. The temperature control is done by adjusting the return condensate temperature. Phosphorous and nitrogen addition are needed before anaerobic treatment, as in-mill streams are often deficient in the nutrients (Meyer & Edwards 2014, 329).

The biogas main component is methane, which accounts for 40–70 vol-% of the produced gas. The rest consist of carbon dioxide, traces of ammonia, hydrogen sulfide and hydrogen. Anaerobic digestion is a multi-stage process that involves hydrolysis,

acidogenesis/fermentation, acetogenesis and methanogenesis. The process steps are performed by bacteria specialized for that conversion reaction. Biogas yield and methane content vary depending on *e.g.* biological consortia and digester conditions. (Abbasi *et al.* 2012, 3–4; van Lier *et al.* 2008, 418). Seppälä (2018, 36) pointed at her master's thesis, that at laboratory conditions HTC filtrate has no inhibitory effect to biomethane potential. Test was performed with wet oxidized HTC filtrate from C-Green's pilot facilities.

As can be seen in Figure 3.4, the anaerobic reactor is an Internal Recirculation (IR)-type. The incoming wastewater is pumped to a standpipe, where a fraction of reactor effluent is mixed with it to control the reactor COD-load. From the standpipe, the influent is conveyed to a mixer chamber at the bottom of the reactor. Anaerobic granular sludge lies at the bottom part of the reactor, where the COD-load is highest. Water flow from bottom to top and smaller granula particles rises upper part of the reactor where they grow and continues COD removal. To provide internal circulation inside the reactor, two circulation pipes convey water from upper part of the reactor to mixer chamber. Treated water goes to standpipe where part is mixed with influent and other part continues to aerobic treatment. Biogas is collected at upper part of the reactor with specific collectors and it is conveyed to biogas repository.

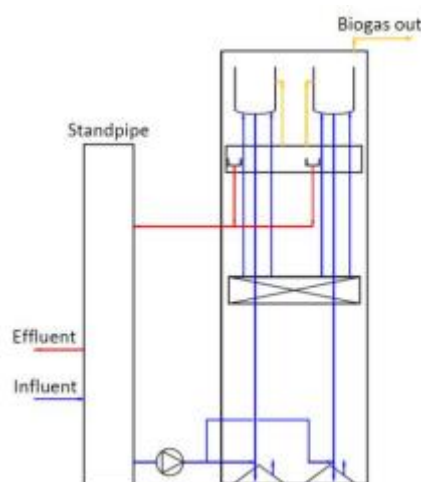


Figure 3.4 IR-type anaerobic biogas reactor. (Southern Finland Regional State Administrative Agencies 2016, 10)

Biogas is combusted in mill's power plant to produce heat and electricity. The produced biogas contributes to reducing the use of purchased fuel, providing therefore supplementary monetary savings. As a biofuel, it also has a reducing effect on mill's CO₂ emissions.

3.2 C-Green Technology AB

C-Green is a Swedish process engineering and cleantech company that produces sludge recycling solutions based on hydrothermal carbonization technology. The company's concept is to manufacture and supply modular designed HTC facilities that are compact and easy to install. (C-Green 2019, 14–15.) C-Green is responsible for the installation and commissioning of the plant. They also operate the process until the Heinola mill personnel is trained for the task.

3.2.1 OxyPower HTC™ plant

Heinola HTC plant is based on C-Green's "OxyPower HTC™" technology. It relies on the wet oxidation of filtrate to produce heat required for the HTC process. Wet oxidation is a water treatment method which removes organic compounds from water by oxidizing them to carbon dioxide and water using an oxidant such as oxygen or air (Bhargava *et al.* 2006, 1221). The exothermic nature of the reaction allows it to be utilized for heat production (Tungler *et al.* 2015, 156). In C-Green solution, the almost pure oxygen is used as an oxidant and it is produced with oxygen generator integrated in HTC plant. Through wet oxidation and heat recovery from filtrate and wet carbonized material, *i.e.* HTC slurry, the C-Green technology is self-sustaining with respect to process heat during continuous operation. An electric heater is used in the process starting phase. (Jakobsson 2019, 7–19). Main flows and process stages are shown in Figure 3.5.

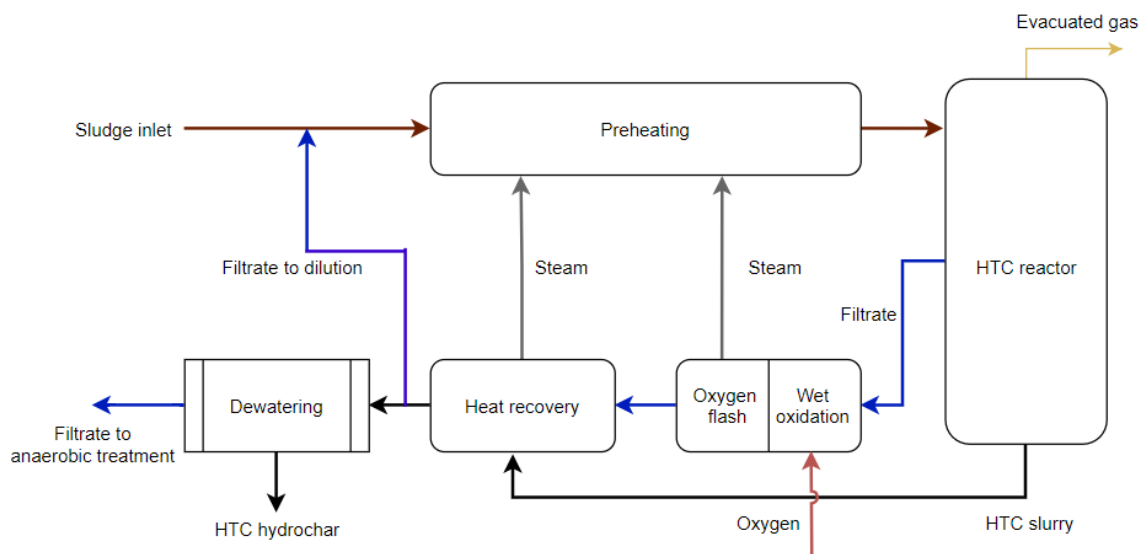


Figure 3.5 Overview of C-Green HTC process (Adapted from Jakobsson 2019, 14).

When using biosludge as a feedstock, incoming sludge dry matter content is approximately 13%. Before the preheating stage, sludge is diluted to 8–9% dryness by using hot filtrate (Jakobsson 2019, 24). The high temperature dilution not only decreases sludge viscosity and facilitates mixing but also serves as first step of sludge preheating, contributing therefore to the heat recovery.

The majority of sludge preheating takes place in multiple pump tanks connected in series. Between pump tanks, the sludge is pressurized step by step and heated by using flash steam generated in cooling tanks and wet oxidation flash tank. When filtrate exits the HTC reactor, it is pumped to the wet oxidation stage. Oxygen is added into the filtrate using a specific oxygen mixer. The oxidation reaction starts immediately, but in order to preserve retention time and maximum amount of reaction heat, the filtrate is conveyed to pressure controlled reactor tank. The reaction heat released increases the filtrate temperature. By lowering the pressure in the oxygen flash tank, part of the filtrate vaporizes. The oxygen flash steam has the highest temperature and pressure of all flash steam produced during the process. Therefore, it is used in last stage of sludge preheating. After the wet oxidation, the filtrate and HTC-slurry are sent to the first cooling tank.

Similarly to pump tanks, cooling tanks are connected in series and vapor is generated by lowering pressure gradually in every tank. (Jakobsson 2019, 27–30.)

HTC reactor is a pressure vessel, where hydrothermal carbonization take place and parts of the organic and inorganic components are dissolved. The feedstock flow in the reactor is maintained through dilution nozzles at the bottom of the reactor. Continuous flow and material recirculating are performed in levels that enables the separation of particle-lean filtrate from the carbonized material. The filtrate is extracted from the upper part of the reactor vessel and conveyed to the wet oxidation stage. HTC slurry accumulates in the lower part of the reactor, from which it is collected and transferred to pump tanks. (Jakobsson 2019, 32–34.)

The physical dewatering is performed with filter press. Settled HTC slurry is pumped to the filter press filtration chambers. Pressurized air is used to compresses the slurry between membrane plates, helping to form a solid filter cake. After compressing, air blowing is used to separate residual free water from cakes. After the drying sequence is over, plates are opened and cakes of hydrochar drops to a container located below the press. The separated filtrate is conveyed to filtrate tank and eventually to the anaerobic wastewater treatment. (Jakobsson 2019, 39–43.)

4 HTC AS A PART OF THE MILL

In this chapter, the influence of HTC on the mill processes and energy balance are evaluated. The main function of HTC plant is to treat biosludge, but its impact extends outside sludge treatment system. As biosludge is currently incinerated in the mill's steam boiler and hydrochar will be used as a fuel too, the HTC plant will mostly affect the power plant operation. The return filtrate from the HTC plant is conducted to the wastewater plant for anaerobic treatment, so the HTC becomes part of the circulation in wastewater treatment system.

Chapter 4.1 focuses on mass flows in HTC plant. The mass balances are based on C-Green's design values and the results are compared to values available in the literature. In chapter 4.2, the energy aspects of HTC are considered. The influence on biogas production and boiler fuel usage as well as HTC plant own energy consumption are studied.

4.1 Mass balance

To get a realistic picture of the energy distribution in HTC, the mass division to different fractions needs to be researched. As mentioned earlier in the chapters 2.2 and 2.3, the share of solid, liquid and gaseous products from HTC depend on multiple factors such as temperature, reaction time and properties of feedstock. In addition to the pure mass, also carbon division must be considered when analyzing HTC energy aspects. Like mass division, carbon division is affected by process considerations. (Catalkopru *et al.* 2017, 91; Funke & Ziegler 2010 170, 162; Libra *et al.* 2011, 92–94).

Cold HTC plant is started by filling it with raw water that is heated with electric heater. As temperature is high enough to perform HTC, sludge feeding to the process is started. It must be taken into consideration that it takes time to replace water in process with diluted sludge.

The sludge is brought into the process with front loader that loads scoops of sludge in a sludge receiving bin. Another incoming element is raw water. Raw water used in the heat

exchangers is not in contact with any fraction of HTC products or raw material. As Table 4.1 shows, the major share of consumed raw water is used in cooling purposes, further exiting the plant via mill's clean water canal. Some smaller raw water consumers are filter press, gas scrubber and pumps that needs sealing water. Gas scrubber uses raw water to wash gaseous compounds generated in the HTC process. The condensate water from scrubber is mixed with leaving filtrate in filtrate tank. (Jakobsson 2019, 12.)

On the exiting side, leaving filtrate is conducted to mill's waste water treatment plant. The hydrochar is collected from the bin underneath the filter press. Gaseous residue of HTC reaction and ventilation gases from various stages of process are treated in a dedicated two-stage gas scrubber before emission to atmosphere. (Jakobsson 2019.)

Table 4.1 Designed mass flows for Heinola HTC plant. Values based on scenario in which 16 000 t/a is treated. (Adapted from Jakobsson 2019, 12–13).

IN [t/h]	
Feed sludge	2,00
Oxygen	0,07
Raw water (Cooling water, filter press wash, sealing etc.)	21,95
NaOH	<0,001
OUT [t/h]	
Dewatered hydrochar	0,33
Filtrate return	2,81
Sewer effluent	0,95
Ventilation gas	0,03
Cooling water return	19,90

The flows in Table 4.1 are based on hydraulic design load of HTC plant's main equipment. In this scenario, the plant could treat at least 16 000 tons wet sludge per year. As Heinola HTC plant is first of its kind, capacity in real life is not known yet. Depending on the sludge water content, it could be realistic to assume that the plant can handle up to 20 000 tons of biosludge per year (Lundqvist 2020a).

4.1.1 Mass yield & hydrochar production

The hydrothermal carbonization process produces solid, liquid and gaseous residues (Funke & Ziegler 2010, 170). Mass yield determines the share of the phase produced per mass of dry feedstock (Lucian & Fiori 2017, 3). In this work, a solid yield of 53% is used to calculate the hydrochar production. The value is based on C-Green's technical data. (Jakobsson 2019, 12). With the 13 551 t/a biosludge production and 13.6% average dryness, the annual dry matter production is 1 843 t/a. The mass of the produced hydrochar m_{hc} is calculated as

$$m_{hc,dry} = Y_s m_{bs,dry} \quad (4.1)$$

where Y_s solid mass yield [-]
 $m_{bs,dry}$ mass of dry biosludge [t]

By using equation 4.1, the estimated annual hydrochar production is 977 t_{dry} which can be converted to 2 171 t/a at 45% dryness. Considering 355 production days per year and 94% plant availability, the hydrochar production rate is 0.27 t/h.

4.1.2 Carbon division

Carbon division between HTC fractions is topic of interest because carbon content influences the quality of products in their usage. For biofuels, the carbon content of generally correlates with the higher heating value (Yin 2011, 1130). Carbon yield describes the mass ratio of the carbon in the product in relation to the carbon in the raw material (Libra *et al.* 2011, 99). Therefore, hydrochar carbon yield could be determined when the solid mass yield and both feedstock and hydrochar carbon content are known. Based on C-Green's pilot results, the dry matter carbon content of the hydrochar and biosludge are 50.9% and 48.4%, respectively. According to Antal & Grønli (2003, 1623), carbon yield can be determined as

$$Y_c = \frac{Y_s x_{c,hc}}{x_{c,bs}} \quad (4.2)$$

where x_c carbon mass fraction of dry matter [-]

With 53 % solid mass yield, the equation 4.2 returns carbon yield of 55.7 %. After stable production is achieved in Heinola, it will be possible to compare the results with values from the pilot tests. It should be noticed, that factors such as residence time, process temperature and feedstock properties affect to the carbon yield (Funke & Ziegler 2010, 162; Libra *et al.* 2011, 92–94).

Another area of interest is the carbon content in the filtrate, as organic matter could be availed to produce biogas in the anaerobic wastewater treatment. This would however require long term trials with the HTC plant to ensure the production of representative samples. Due to schedule established for thesis, this task is left out of the scope for future research.

4.2 Energy aspects

The energy impacts from the HTC plant could be viewed as a balance, where wet biosludge and electricity are considered as influents and hydrochar and COD-rich return filtrate as outcoming flows. The biosludge before HTC treatment contains high amount of water with low net calorific heating value. On the other hand, HTC process produces a biofuel with better fuel value and the energy content of return filtrate could be available for biogas production.

Since in Heinola mill the biosludge is disposed solely by combustion, upgrading its firing properties plays an important role when calculating the HTC project viability. This includes increasing energy efficiency when switching from sludge to hydrochar, but also the related energy saving in form of support fuel. In Heinola case, the potential increase in biogas production is another aspect that contributes to fuel savings.

4.2.1 Fuel value of produced hydrochar

In this study hydrochar is considered as a fuel and it is combusted in Heinola mill's bubbling fluidized bed (BFB) boiler for heat and electricity production. Hydrothermal

carbonization provides an increasing effect on HHV and dry matter content of the treated hydrochar (Fuglesang *et al.* 2015, 32). Increment in dry matter content results to higher as received value of lower heating value (LHV). Hydrochar combustion equate to combustion of a well dried sludge. According to Pipatti *et al.* (1996, 50), sludge can be combusted without support fuel, if its dryness is 35–45% or more. As hydrothermal carbonization produces hydrochar with higher dry matter content than that, it is possible to assume that it can be combusted without support fuel. This enables the hydrochar utilization to partially replace peat. In Heinola power plant, the hydrochar will be co-fired with other fuels. Even if all the produced biosludge is treated via HTC, total hydrochar volume would cover less than 0,8% of boiler fuel usage (Stora Enso 2019).

Elemental analysis of samples from pilot plant reveals decreasing O/C and H/C ratios from biosludge to hydrochar, which is an expected outcome according to literature on the subject (Libra *et al.* 2011, 95–96; Kambo & Dutta 2015, 366). Laboratory tests on Heinola mill's biosludge and hydrochar produced at C-Green's pilot facility in Sweden shows, that on average O/C ratio decreases from 0.49 to 0.34 and H/C ratio from 0.12 to 0.10. Atomic ratios, heating values and elemental composition of analyzed sludge and hydrochar samples are presented in Table 4.2.

Table 4.2 Properties and elemental composition compared between Heinola mill's biosludge and dewatered hydrochar (Adapted from Jakobsson 2019, 9).

		Heinola Biosludge	Hydrochar
Dryness	%	13-17	~ 45
HHV	MJ/kg	20.9	21.5
LHV _{ar}	MJ/kg	0.6	7.8
C	mass-%	48.4	50.9
H	mass-%	5.7	5.1
O	mass-%	23.6	17.2
S	mass-%	2.5	1.5
N	mass-%	7.9	4.6
Cl	mass-%	0.05	0.02
Ash	mass-%	11.9	21.0
O/C-ratio	-	0.49	0.34
H/C-ratio	-	0.12	0.10

Ross (2018, 9) suggests that HTC treatment leads to significant demineralization of the solid material, which reduces fuel slagging and fouling propensity in the boiler. However, it must be noted that mineral extraction is highly feedstock dependent. At Heinola power plant, wet sludge has caused clogging problems in solid fuel conveyor and feeding system. According to Gyllenhammar *et al.* (2003, 22–32) challenges are common with sludge incineration. It is expected that changing sludge to HTC biofuel would mitigate those problems.

4.2.2 Fossil fuel saving

The use of HTC hydrochar in Heinola fluting mill reduces the fossil fuel usage, which is done by reducing the use of support fuel and increasing the sludges net calorific value as fired. In addition, the COD-rich HTC filtrate likely has an increasing effect to biogas production, which can be also fired in. Based on Stora Enso internal calculations, biogas production could end up to 10% higher level than currently (Markkula 2020).

Two primary fuels used in boiler are milled peat with 50% and solid biomass with 44% share in the fuel mix. The biomass consists of mill's own bark and purchased forest fuel. Heavy fuel oil (HFO) is mainly used in situations where solid fuel feeding is inhibited.

Currently, sludge disposal by combustion has an increasing effect to boiler fuel consumption. Biosludge has a small but positive net calorific value, so it has enough energy content to vaporize moisture in it. Vaporized water in flue gas still needs sensible heat to be warmed up. Support fuel is used to compensate the cooling of the furnace due to the wet flue gas (Hagelqvist 2018, 10). By using values from Table 4.2, we can calculate that one kilogram of biosludge fired produces 2.06 kg of flue gas. Stoichiometric reaction calculation is shown in appendix I. Sludge temperature as fired is assumed to be 20°C and the furnace temperature is 850°C. For the energy calculations, 13 551 t/a biosludge production is used as yearly estimate. Fuel power needed to compensate the flue gas heating can be calculated with the equation

$$\phi_{\text{fuel}} = (h_{\text{fg}}(850\text{ }^{\circ}\text{C}) - h_{\text{fg}}(20\text{ }^{\circ}\text{C}))q_{m,\text{bs}} \cdot 2.06\text{ kg}_{\text{fg}}/\text{kg}_{\text{bs}} \quad (4.3)$$

where h_{fg} flue gas enthalpy in certain temperature [kJ/kg]
 $q_{m,\text{bs}}$ biosludge mass flow [kg/s]

If sludge combustion is distributed equally around the year and the boiler runs 8400 h/a, the mass flow to boiler is 0.45 kg/s. When the mole fractions are known, flue gas enthalpies can be estimated from polynomic regression model. In this case, $h_{\text{fg}}(850\text{ }^{\circ}\text{C}) = 1315\text{ kJ/kg}$ and $h_{\text{fg}}(20\text{ }^{\circ}\text{C}) = 27\text{ kJ/kg}$ (Vakkilainen 2020). Using those values in equation 4.1, fuel power of 1.19 MW is needed to compensate for the furnace cooling. That corresponds 9982 MWh fuel consumption annually. If wet biosludge is not combusted, we could save that amount of other fuels.

Hydrochar with increased lower heating value compared to biosludge enables some fossil fuel saving, as it provides more energy even if total amount of combusted material is lower due to mass division between residue phases in HTC process. The increment in provided energy Q compared to current situation can be calculated as

$$\Delta Q = \text{LHV}_{\text{ar,hc}}m_{\text{hc}} - \text{LHV}_{\text{ar,bs}}m_{\text{bs}} \quad (4.4)$$

As can be seen in Table 4.2, the heating values are 7.8 MJ/kg for hydrochar at 45% dryness and 0.6 MJ/kg for biosludge in 13.6% dryness. Annual wet sludge and hydrochar production are 13 551 t/a and 2 171 t/a respectively. According to the equation 4.4, hydrochar combustion produces 8 803 GJ/a or 2 445 MWh/a more energy than wet biosludge combustion. This amount can be reduced from the purchased fuel, if the heat production of the boiler is to be kept constant.

Changing wet sludge to hydrochar would also reduce the oil consumption, since hydrochar will not cause disturbance at the solid fuel handling system same way wet biosludge does. There could be disruptions in the fuel handling system also without wet sludge and oil could be needed for other reasons as well. Therefore, it is very hard to determine when and at what extend the oil combustion is related to sludge incineration.

Based on conversation with the power plant personnel, a rough estimate of the oil saving potential is 20% of boiler total oil consumption (Liikola 2020). That means potentially 700 oil tons saving annually.

The HTC filtrate impact on biogas production could also reduce fossil fuel consumption, as providing more COD to anaerobic reactor should increase biogas production. It is estimated that HTC could increase the production by 10%. (Markkula 2020). In 2017 and 2018, the average biogas production was 12 885 MWh/a. A 10% increase would mean 1 289 MWh/a of extra biogas that could be produced, which means an energy input that could be cut from purchased fuels.

4.2.3 HTC plant energy usage

In the C-Green's HTC concept, external heat energy is not needed when the process is running. Instead, the required heat is generated by wet oxidation and heat recovered. An electric heater is used temporarily during the starting phase. Also dewatering of the hydrochar is carried out with electric filter press, not thermal drier. (Jakobsson 2019, 16; C-Green 2019, 12–14). Pumps, sludge screws and filter press are the main electricity consumers, as well as compressors in oxidant generation. Table 4.3 shows HTC plant's specific energy consumption.

Table 4.3 Electricity specific consumptions. General electricity consumption includes motor drives of pumps and screws, filter press, lighting, space heating etc. (Lundqvist 2020b.)

Position of consumption		Value
Electricity, motor drives etc.	kWh/t _{dry}	304
Electricity, heat generation	kWh/t _{dry}	0*
Electricity, oxidant generation	kWh/t _{dry}	245
Total electricity consumption	kWh/t _{dry}	549
* 400 kW installed power for process starting		

The Heinola mill dry sludge production of 1 843 t/a was calculated in chapter 4.1.1. Based on this production rate and specific electricity consumption of 549 kWh/t_{dry}, plant total electricity consumption would be 1012 MWh/a.

Total electricity consumption of 549 kWh per ton of dry sludge seems to be an advantage when compared to values in other published studies. Fuglesang *et al.* (2015, 30–33) researched hydrothermal carbonization of pulp industry biosludge in AVA-CO2's research facilities. They reported 139 kWh electricity consumption per wet sludge ton, which converts to 818 kWh/t_{dry} with reported the 17% dryness. However, since the research was implemented at a pilot scale plant where steam heating was used Fuglesang *et al.* (*ibid.*) suggests that electricity consumption could be significantly lower in industrial size plant. Lucian & Fiori (2017, 8) used computer modelling to calculate a maximum HTC process electricity consumption of 40 kWh per ton of wet feedstock, which means 114 kWh/t of dry feedstock considering that feedstock's moisture content is 65%, *i.e.* substantially less compared to Heinola mill biosludge.

Wet oxidation technology might provide C-Green an advantage as external heating energy is not needed. Fuglesang *et al.* (2015, 32–33) reported 729 kWh/t_{wet} (4288 kWh/t_{dry}) heat specific consumption without heat recovery. Lucian & Fiori (2017, 8) suggested 310 kWh/t_{wet} (886 kWh/t_{dry}) heat consumption based on their model.

5 ECONOMIC ASSESSMENT OF HTC PROJECT

In this chapter, the economic feasibility of the Heinola HTC plant is researched by calculating both incomes and costs of the project. The target is to find out the viability of the project and study how the different parameters affects the economic outlook. As the Heinola project is used as a baseline case, HTC's financial viability is also examined in other scenarios where different sludge production rates and plant sizes are considered. Key figures such as payback time and internal rate of return (IRR) are used to measure the viability and its changes. To sort out how changes in certain parameter impacts some key figures, sensitivity analysis is performed and visualized through graphs. DataPartner's "Invest for Excel" investment tool is used for the economic analysis. The program returns investment key figures and run sensitivity analysis for certain variables when basic information about project incomes, costs and other parameters are set.

In this project "incomes" are mainly savings gained from incinerating costs and the reduced fossil fuel consumption. Currently, no sludge from Heinola fluting mill is shipped for landfill construction or other external treatment, so there is no savings from disposal fee. When wet biosludge is combusted in the boiler, it causes extra fuel usage by two way. First one is the support fuel that is needed to compensate for the furnace cooling. Calculated in chapter 4.2.2, this energy is not needed when wet biosludge is replaced by hydrochar. The treated sludge contains higher net calorific heating value than biosludge, so it provides higher energy density when fired. More bioenergy is also provided in the form of biogas, as HTC return filtrate potentially increases gas production. In addition, there would be purchased fuel savings from heavy fuel oil as its usage decreases when sludge related fuel feeding problems ends.

To simplify the calculations, it is assumed that support fuel savings and extra energy provide means for cutting only the peat consumption, not from the whole fuel mix. Reducing fossil fuel consumption leads to saving in purchasing, but also it leads to less CO₂-emission payment. In the Heinola case, nutrients of return filtrate such as nitrogen could potentially generate savings in wastewater treatment plant chemical purchasing.

However, without trials it is challenging to determine how much the savings are. Based on Heinola WWTP chemical costs, potential saving would not affect substantially to profitability analysis and it is left outside of scope.

Fuel purchasing cost for the user includes fuel market price and taxes. Heavy fuel oil taxation is based on energy content tax, carbon dioxide tax and strategic stockpile fee. Heavy fuel oil taxation is regulated by the law “Laki nestemäisten polttoaineiden valmisteverosta 1472/1994”. Under Finnish legislation, fuels used for electricity production are non-taxable (1472/1994, 9 §). In CHP-production, the share of non-taxable production should be calculated by a formula given in the legislation. However, for simplification purpose, all the production is considered taxable in this thesis. It should be noted that CHP-production is free from energy content tax (1472/1994, 4 §). Peat taxation is regulated by “Laki sähkön ja eräiden polttoaineiden valmisteverosta 1260/1996”. Peat taxation differs from heavy fuel oil taxation, as “energy tax” is the only tax class for peat. Table 5.1 contains taxes payment for peat and HFO.

Table 5.1 Fuel tax classes for HFO and peat (1472/1994, appendix 30.12.2019/1554; 1260/1996, appendix 1).

Fuel tax		Payment
Heavy fuel oil		
-Energy content tax	[c/kg]	8.56
-Carbon dioxide tax	[c/kg]	18.67
-Strategic stockpile fee	[c/kg]	0.28
Peat		
-Energy tax	[€/MWh]	3.00

For economic calculation purposes, the taxes should be converted to unit €/MWh or alternatively fuel saving from megawatt hours to kilograms. Therefore, the total saved purchasing costs C_{pur} per year can be calculated as

$$C_{\text{pur}} = (TPP_P + T_P)Q_P + (TPP_{\text{HFO}} + T_{\text{HFO}})Q_{\text{HFO}} \quad (5.1)$$

where TPP fuel total purchasing price [€/MWh]

T	taxes [€/MWh]
Q	saved fuel energy [MWh/a]

In addition to purchasing costs, peat and heavy fuel oil combustion create a cost based on CO₂-emissions. The payment is determined by fuel usage and a CO₂ default emission factor. The CO₂ default emission factor for peat is 107.6 tCO₂/TJ and for the HFO, 79.2 tCO₂/TJ (Statistics Finland 2020a). Financial savings from CO₂ emission reduction is

$$C_{CO_2} = (Q_P f_P + Q_{HFO} f_{HFO}) MP_{CO_2} \quad (5.2)$$

where	f	CO ₂ default emission factor [tCO ₂ /MWh]
	MP_{CO_2}	market price of CO ₂ emission allowance [€/tCO ₂]

The costs of a HTC plant can be divided into two categories, variable and fixed costs. Fixed costs include labor and basic maintenance costs, which can be estimated as a percentage of investment cost. The commodities included in variable costs are electricity, raw water and chemicals. Costs of raw water and chemicals are disregarded. The electricity consumption E_{el} in the HTC varies depending on feedstock processing rate and can be determined as

$$E_{el} = m_{bs,dry} e_{el} \quad (5.3)$$

where	e_{el}	specific electricity consumption [kWh/kg]
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The Heinola HTC biofuel project is served as a basis for the feasibility of an industrial size HTC plant when integrated to pulp and board mill. However, it should be pointed out that Heinola project is based on a pilot scale, meaning that information about scalability and ways to improve profitability should be taken into account for more accurate conclusions. To explore different options, the economic analysis is divided into three different scenarios. The first one is the baseline case, which represents the current plans at Heinola mill. The second scenario related to a Heinola type mill with similar biosludge production, but HTC plant is operated at full capacity by importing municipal sludge. The

third scenario considers a larger mill, where the sludge production at Heinola mill and HTC-plant capacity are doubled to evaluate the economy of scale.

5.1 Case 1: Heinola mill

This scenario represents the situation in Heinola. The project's environmental permit for experimental activities states that HTC plant can handle sludges produced at Heinola fluting mill and burn the produced hydrochar at the mill's BFB boiler (Southern Finland Regional State Administrative Agencies 2019, 16). The incomes originate from the energy savings, as presented in chapter 4.2.2. When the biosludge combustion is replaced by hydrochar, support fuel is no longer required and heavy fuel oil consumption decreases. In case the boiler steam production is kept unchanged, the amount of purchased fuel can be reduced. As mentioned before, hydrochar provide higher energy efficiency in the boiler and the additional biogas can also contribute to the share in fuel mix. Fixed and variable costs are calculated as presented in previous chapter.

Investment cost are based on evaluation from C-Green and Stora Enso representatives. As Heinola HTC plant is first of its kind, the investment cost might be higher compared to the situation where more mature technology is available. The estimated investment cost is later referenced as I_{est} . Table 5.2 contains values used in investment calculations.

Table 5.2 Initial values for factors noticed in investment calculations. (1. Jakobsson 2019, 9–11; 2. Markkula 2020; 3. Liikola 2020; 4. Statistics Finland 2020a; 5. Statistics Finland 2020b, 1–9; 6. 1260/1996, appendix 1; 7. 1472/1994, appendix 30.12.2019/1554; 8. Ember 2020)

	Unit	Value
Project basic values		
Investment cost	€	I_{est}
Calculation term	a	15
Discount rate (per annum)	%	7
Income tax	%	20
Biosludge		
Production, wet	t/a	13 551
Dryness ⁽¹⁾	%	13.6
LHV _{ar} ⁽¹⁾	MJ/kg	0.6
Hydrochar		
Production, wet	t/a	2 171
Dryness ⁽¹⁾	%	45
LHV _{ar} ⁽¹⁾	MJ/kg	7.8
Energy saved		
Support fuel (peat)	MWh/a	9 982
Peat replaced by hydrochar	MWh/a	2 445
Peat replaced by biogas ⁽²⁾	MWh/a	1 289
HFO usage reduction ⁽³⁾	t/a	700
	MWh/a	7 856
CO₂ emissions		
CO ₂ default emission factor, peat ⁽⁴⁾	tCO ₂ /TJ	107.6
	tCO ₂ /MWh	0,387
CO ₂ default emission factor, HFO ⁽⁴⁾	tCO ₂ /TJ	79.2
	tCO ₂ /MWh	0.285
Prices, taxes & other costs		
Total purchasing price, peat ⁽⁵⁾	€/MWh	14.00
Taxes, peat (Energy tax) ⁽⁶⁾	€/MWh	3.00
Total purchasing price, HFO ⁽⁵⁾	€/t	450
	€/MWh	40.10
Taxes, HFO (carbon dioxide tax & strategic stockpile fee) ⁽⁷⁾	c/kg	18.95
	€/MWh	16.89
Electricity ⁽⁵⁾	€/MWh	38.00
Fixed costs (percentage of investment cost)	%	4
CO ₂ emission allowance ⁽⁸⁾	€/tCO ₂	25.00

Estimated prices of peat, heavy fuel oil, electricity and CO₂ emission allowances based on 2019 and early 2020 price levels (Statistics Finland 2020b; Ember 2020). By modelling the price trend from 2017 to early 2020, 5% annual increment is added to CO₂ emission allowance price. By using values from Table 5.2, we can calculate annual savings. Savings specified by source are presented in Table 5.3.

Table 5.3 Annual savings denominated in euros in baseline case (Case 1) specified by source. CO₂ emission savings based on calculation term average, as emission price is assumed to increase 5% annually.

Saving or income	€/a
Heavy fuel oil	447 658
Peat	233 226
CO ₂ emission	269 847

Even though the reduction in MWh is higher for peat, the changes in heavy fuel oil consumption cause economic impacts due to its higher cost of use. By utilizing Invest for Excel-program, the profitability analysis for the project is performed. The key figures of the baseline case using values from Table 5.2 values are presented in Figure 5.1.

PROFITABILITY ANALYSIS			
Project description	Case 1: Heinola mill		€
Nominal value of all investments	I_{est}	Discounted investments	I_{est}
Required rate of return	7,00 %		
Calculation term	15,0	years	1/2020 - 12/2034
Calculation point	1/2020	(In the beginning of period)	
Net Present Value (NPV)	679 817	>= 0	
NPV as a monthly annuity	6 029		
Internal Rate of Return (IRR)	9,00 %	>= 7 %	
Modified Internal Rate of Return (MIRR)	7,91 %	>= 7 %	
Profitability Index (PI)	1,14	>= 1	
Payback time, years	12,5	Based on discounted FCF	
Return on net assets (RONA), %	41,0 %	Average 15 years	
Economic Value Added (EVA)	128 050	Average 15 years	
Discounted Value Added (DCVA)	786 076		

Figure 5.1 Key financial figures of the baseline HTC project.

The project with current premises would have an IRR of 9.0% and payback time of 12.5 years. Relatively low IRR and long payback time were expected, considering that a pilot

plant investment cost usually exceeds the costs that could be assumed for a more mature technology at its full potential.

Sensitivity analysis is performed to demonstrate the impacts caused by variation in the input values. Figure 5.2 shows the impact of the total investment cost on the payback time and IRR. In a scenario, where the investment cost is 20% lower than the estimated, a payback time would drop to 9.5 years and IRR would rise to 12.46%. This represents an increase of 38.4% in the IRR and a reduction of 23.6% in the payback time.

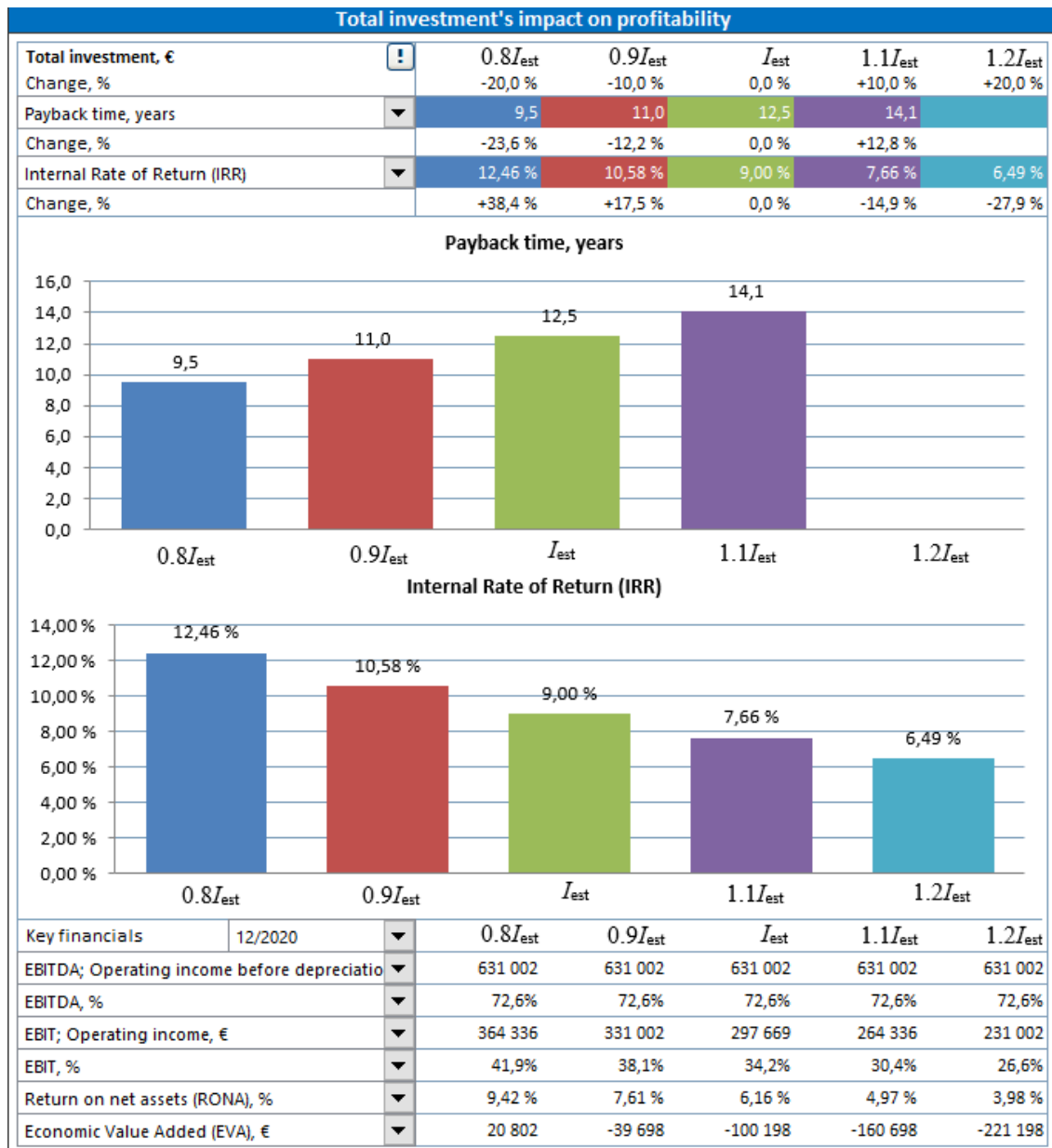


Figure 5.2 Total investment impact on profitability. Key financial figures are calculated when estimated investment costs changes from -20 % to +20 % compared to baseline. Payback time and IRR are presented as bar charts. With 15 years calculating term, over 15 years payback time is not available in the chart.

Table 5.4 presents the impact caused by varying other major parameters. The gains obtained by using HTC depends on the savings from purchased fuel, fuels prices and CO₂ emissions. It is normal for fuel prices to fluctuate, and it is likely that they fluctuate more than +/- 20% that is presented in the sensitivity analysis. Nevertheless, it is possible to

observe how fuel prices might affect to the project outcome. Peat saving potential can vary slightly year by year, as biosludge and hydrochar production is not constant. In addition, field trials to evaluate the impacts of HTC filtrate on the biogas production have not been conducted, which that the prediction of 10% boost in the production in practice is uncertain. The reduction of oil consumption as a support fuel is another matter of uncertainty. Due to high fuel costs of HFO, variation in realized reduction has a significant economic impact. The electricity price also affects the projects viability. Similar to fuel price behavior, the electricity price is prone to fluctuation and the average value during the calculation term is uncertain. Annual fixed costs, including labor and maintenance, are determined as percentage of investment cost. The initial estimation is 4%, but values from 3.2% to 4.8% are considered in the sensitivity analysis. As the HTC pilot project proceeds, the knowledge about manning requirement and regular maintenance become more accurate.

Table 5.4 Impacts caused by different project variables. Original baseline values are shown in column “0%” and impact of +/- 20% variation is presented for every variable. Payback time and IRR are chosen key figures to demonstrate project viability.

Variable	-20%	-10%	0%	+10%	+20%
Peat saved [MWh/a]	10 975	12 347	13 719	15 091	16 463
Payback time, years	14.7	13.5	12.5	11.6	10.9
IRR	7.24%	8.13%	9.00%	9.85%	10.68%
Oil saved [t/a]	560	630	700	770	840
Payback time, years	>15	13.8	12.5	11.4	10.5
IRR	6.75%	7.90%	9.00%	10.08%	11.13%
Peat price, inc. tax [€/MWh]	13.60	15.30	17.00	18.70	20.40
Payback time, years	13.6	13.0	12.5	12.0	11.5
IRR	8.01%	8.51%	9.00%	9.49%	9.97%
Heavy fuel oil price, inc. taxes [€/MWh]	45.59	51.29	57.00	62.68	68.40
Payback time, years	14.9	13.6	12.5	11.5	10.7
IRR	7.08%	8.05%	9.00%	9.93%	10.84%
CO₂ emission allowance price [€/tco₂]	20.00	22.50	25.00	27.50	30.00
Payback time, years	13.7	13.1	12.5	12.0	11.5
IRR	7.93%	8.47%	9.00%	9.52%	10.03%
Electricity price [€/MWh]	30.40	34.20	38.00	41.80	45.60
Payback time, years	12.3	12.4	12.5	12.6	12.7
IRR	9.16%	9.08%	9.00%	8.92%	8.84%
Fixed costs [% of investment]	3.2%	3.6%	4.0%	4.4%	4.8%
Payback time, years	11.6	12.0	12.5	13.0	13.5
IRR	9.83%	9.42%	9.00%	8.58%	8.16%

As can be seen in Figure 5.2 and Table 5.3, the investment cost has the highest impacts on the project financial outcome among the studied project variables. Twenty percent lower investment cost would shorten the payback time by 23.6% from 12.5 to 9.5 years. The IRR would grow by 38.4% from 9.00% to 12.46%. The second most significant variable is the reduction in heavy fuel oil consumption. If the reduction happens to be 20% higher than expected, the payback time would be 15.9% shorter and project IRR 23.6% higher.

The replacement of fossil fuel by hydrochar means that higher peat and heavy fuel oil prices improves the project viability. Table 5.3 shows that heavy fuel oil price cause bigger impacts on the project financial outcome when compared to peat price. A fluctuation of 20% in the heavy fuel oil price could shift the payback time from 14.9 years maximum to 10.7 years minimum. The same fluctuation in the peat price would result in a payback time shifting from 13.6 maximum to 11.5 minimum.

A moderate variation in the electricity price has a low impact on the project viability. There is relative change of only 1.4% in the payback time to either direction if price increases or decreases by 20%. The changes in IRR are also insignificant. The total fixed costs have slightly bigger impacts on the financial outcome. As the sensitivity analysis shows, fluctuation in the project fixed and variable costs has less impact to project viability compared to fluctuation in incomes. Such a finding is expected, since the ratio of investment cost to variable and fixed cost is high.

At the Heinola fluting mill all the produced biosludge is currently incinerated at power plant's BFB boiler. On the other hand, some mills might have option to pay for external partners for disposing the waste sludges. In this case, an HTC plant becomes a more attractive option. Fuglesang *et al.* (2015, 76) calculated a payback time of 4–6 years for an HTC investment at one mill that disposes their biosludge at cost of 400 SEK/t (approx. 37.50 €/t).

5.2 Case 2: Heinola-type mill with option to import sludge

Since the full capacity of the Heinola pilot plant has not been tested yet, the expectation is that it could handle 20 000 tons of wet sludge per year. Considering a biosludge production rate of 13 000–14 000 t/a in the mill, the HTC plant would work only 65–70% of its maximum capacity. In order to utilize the full potential of the plant, an option is to bring sludges from outside the mill to be treated. The sludge could be the nearby town municipal waste or industrial sludge from another mill, as long as it is suitable for the HTC plant. By providing sludge treatment services, it would be possible to produce more

hydrochar and, in addition, increase incomes by charging a gate fee for the imported sludge.

The economic evaluation of this scenario is based on same baseline presumptions as Case 1, but the external sludge is received for the HTC plant to run at full capacity. Therefore, with 13 551 t/a mill own sludge production, it is possible to bring in 6 449 ton of sludge per year. By utilizing the full capacity, extra hydrochar could be produced, which would replace more fossil fuel compared to Case 1. This will result in more savings from fuel and CO₂ emission costs. Due to some uncertainties in anaerobic biogas capacity, biogas production is assumed to be the same as Case 1. It is assumed, that the dryness of the imported sludge is 13.6%, *i.e.* the same as the mill biosludge. With a total of 20 000 t/a feedstock input, the HTC plant would produce 3 204 t/a hydrochar. For the viability calculations 60 €/t gate fee is use as baseline for imported sludge. The fee is based on sludges wet weight. The amount of different savings and incomes are presented in Table 5.5.

Table 5.5 Annual savings and incomes in Case 2 specified by source. Gate fee of 60 €/t is used as basis. CO₂ emission savings based on calculation term average, as emission price is assumed to increase 5% annually.

Saving or income	€/a
Heavy fuel oil	447 658
Peat	271 275
CO ₂ emission	300 998
Gate fee revenue	386 940

As shown in Table 5.5, the revenues from the gate fees become second biggest income after heavy fuel oil savings. The total savings increases 48% when compared to Case 1. As the fixed costs are assumed to stay unaltered, the annual costs increase only by 7.7%. The results of the profitability analysis and project key figures are shown in Figure 5.3.

PROFITABILITY ANALYSIS				
Project description	Case 2: Heinola-type mill with option to import sludge			€
Nominal value of all investments	I_{est}	Discounted investments	I_{est}	
Required rate of return	7,00 %			
Calculation term	15,0	years	1/2020 - 12/2034	
Calculation point	1/2020	(In the beginning of period)		
Net Present Value (NPV)	3 856 132	>= 0		
NPV as a monthly annuity	34 198			
Internal Rate of Return (IRR)	17,39 %	>= 7 %		
Modified Internal Rate of Return (MIRR)	11,16 %	>= 7 %		
Profitability Index (PI)	1,77	>= 1		
Payback time, years	6,9	Based on discounted FCF		
Return on net assets (RONA), %	82,6 %	Average 15 years		
Economic Value Added (EVA)	478 271	Average 15 years		
Discounted Value Added (DCVA)	3 962 391			

Figure 5.3 Financial key figures for HTC investment project in which external sludge importing is in use.

In this scenario, the project viability would increase compared to Case 1. The earnings from the gate fee earnings and the reduction in fossil fuel consumption exceed substantially increased the increased variable cost (electricity). The payback time is shortened by approximately 45% from 12.5 years in Case 1 to 6.9 years. The relative increment in the IRR compared to Case 1 is 93%, from 9.0% to 17.4%. The economic impact of gate fee on the key financial parameters is studied presented in Figure 5.4, with gate fee changing from 48 €/t to 72 €/t.

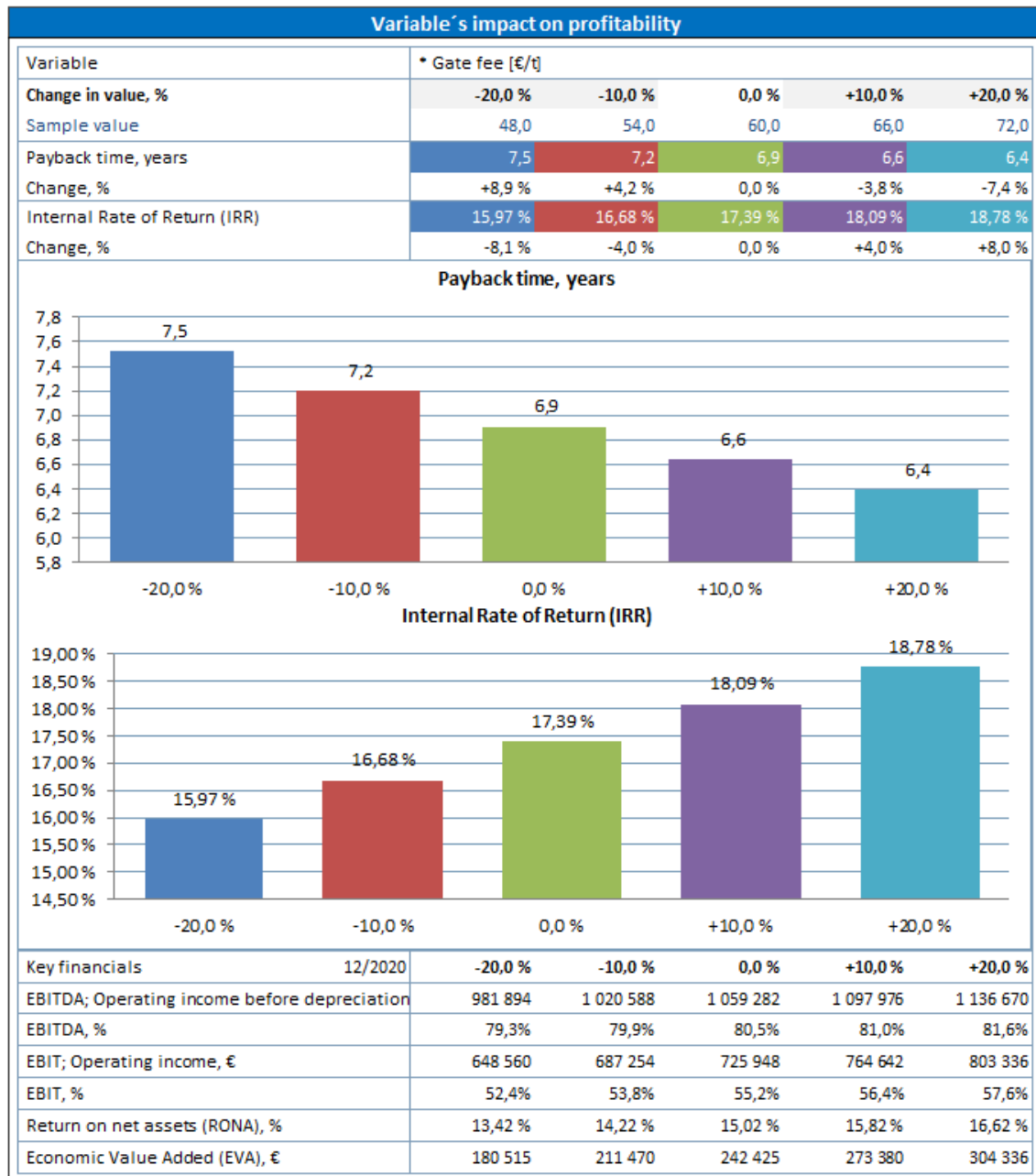


Figure 5.4 Impact of gate fee [€/t] on profitability. Key financial figures are calculated when gate fee changes from -20% to +20% compared to baseline 60 €/t. Payback time and IRR are presented as bar charts.

The changes in gate fee results in the payback time varying from 7.5 to 6.4 years. IRR varies from 15.97% with the lowest studied gate fee to 18.78% when gate fee is at its highest. The impact of the investment cost is also a point of interest in this scenario with

imported sludge. The sensitivity analysis for different investment cost is presented in Figure 5.5.

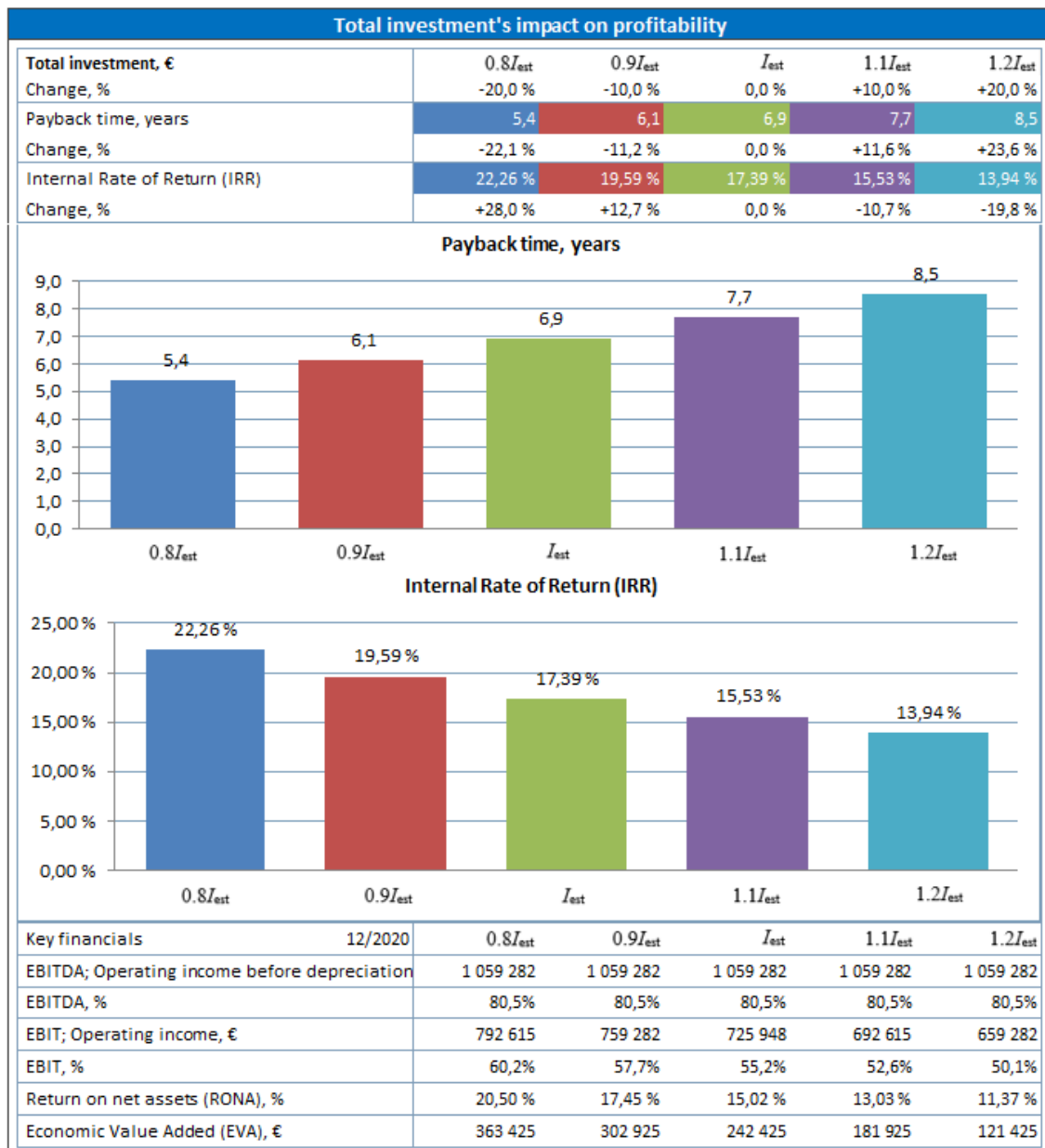


Figure 5.5 Total investment impact on profitability in Case 2. Key financial figures are calculated when estimated investment costs changes from -20% to +20% compared to baseline. Payback time and IRR are presented as bar charts.

The influence of investment cost stays dominant in Case 2. If the investment cost can be reduced by 20% from the current estimated value, the project payback time would decrease by 22.1% from 6.9 to 5.4 years. The IRR would increase by 28.0% from 17.39% to 22.26%. The relative impacts caused by the changes in investment are slightly smaller than in Case 1, but it is still the most significant variable affecting the project financial outcome.

5.3 Case 3: Scaling to double size

One objective of this thesis is to study the economic suitability of HTC to pulp and board mills and what does it take for the investment to be viable. As shown in chapters 5.1 and 5.2, the investment cost has been the predominant factor to the viability when the HTC technology is integrated to Heinola-type mill. In cases 1 and 2, the default HTC plant capacity has been 20 000 tons of wet sludge per year. In order to evaluate how the scale impacts to the HTC project viability, this chapter considers a scenario where the HTC project takes place in a larger mill with the doubled sludge production rate compared to Heinola mill. Therefore, the HTC plant capacity is raised to 40 000 t/a. New investment cost for bigger plant $I_{\text{est,new}}$ is estimated by scaling it to original investment using relationship (adapted from Berthouex 1972, 2111)

$$I_{\text{est,new}} = I_{\text{est}} \left(\frac{C_2}{C_1} \right)^\alpha \quad (5.4)$$

where	C_1	original capacity [t/a]
	C_2	new capacity [t/a]
	α	coefficient of the economy of scale [-]

A typical value for exponent α is 0.6 which was selected to estimate the investment price of double size plant (Berthouex, 1972, 2111). In this case, C_2/C_1 is 2, so the new investment cost equals to the original estimated investment cost multiplied by $2^{0.6}$ or 1.516. Due to economies of scale, larger plant has relatively cheaper investment cost compared to a smaller one.

The Case 3 is based on Heinola-type mill but with double sludge production. In this case all the sludge is also incinerated. The new support fuel saving is calculated using equation 4.3. The fuel energy increment by changing wet sludge to hydrochar is calculated by using equation 4.4. It is also assumed that heavy fuel oil consumption and saving potential in this larger mill is twice as much as in cases 1 and 2, even though this might be overestimated. The biogas potential growth is assumed to be same 10% as earlier scenarios, as there is no certainty about anaerobic reactor conversion capacity. Values used for profitability analysis in Case 3 are presented in Table 5.6.

Table 5.6 Initial values for factors noticed in investment calculations for Case 3. (1. Jakobsson 2019, 9–11; 2. Statistics Finland 2020a; 3. Statistics Finland 2020b, 1–9; 4. 1260/1996, appendix 1; 5. 1472/1994, appendix 30.12.2019/1554;

	Unit	Value
Project basic values		
Investment cost	€	$I_{\text{est,new}}$
Calculation term	a	15
Discount rate (per annum)	%	7
Income tax	%	20
Biosludge		
Production, wet	t/a	27 102
Dryness ⁽¹⁾	%	13.6
LHV _{ar} ⁽¹⁾	MJ/kg	0.6
Hydrochar		
Production, wet	t/a	4 341
Dryness ⁽¹⁾	%	45
LHV _{ar} ⁽¹⁾	MJ/kg	7.8
Energy saved		
Support fuel (peat)	MWh/a	19 973
Peat replaced by hydrochar	MWh/a	4 889
Peat replaced by biogas	MWh/a	1 289
HFO usage reduction	t/a	1 400
	MWh/a	15 711
CO₂ emissions		
CO ₂ default emission factor, peat ⁽²⁾	t _{CO2} /TJ	107.6
	t _{CO2} /MWh	0,387
CO ₂ default emission factor, HFO ⁽²⁾	t _{CO2} /TJ	79.2
	t _{CO2} /MWh	0,285
Prices, taxes & other costs		
Total purchasing price, peat ⁽³⁾	€/MWh	14
Taxes, peat (Energy tax) ⁽⁴⁾	€/MWh	3
Total purchasing price, HFO ⁽³⁾	€/t	450
	€/MWh	40.10
Taxes, HFO (carbon dioxide tax & strategic stockpile fee) ⁽⁵⁾	c/kg	18.95
	€/MWh	16.89
Electricity ⁽³⁾	€/MWh	38
Fixed costs (percentage of investment cost)	%	4
CO ₂ emission allowance ⁽⁸⁾	€/t _{CO2}	25

As the amount of annual feedstock biosludge doubles, the hydrochar production increases at the same ratio. Reduced CO₂ emission are calculated by using equation 5.2. Fixed cost level kept in 4% of the investment cost. The plant electricity consumption is based on specific values presented in Table 4.3. Savings by source are presented in Table 5.7

Table 5.7 Annual savings in Case 3 specified by source. CO₂ emission savings based on calculation term average, as emission price is assumed to increase 5% annually.

Saving or income	€/a
Heavy fuel oil	895 316
Peat	444 548
CO ₂ emission	521 761

The profitability analysis for this case is performed by using Invest for Excel. Calculation term is 15 years. The key financial figures of Case 3 are shown in Figure 5.6.

PROFITABILITY ANALYSIS				
Project description	Case 3: Scaling to double size			€
Nominal value of all investments	$I_{est, new}$	Discounted investments	$I_{est, new}$	
Required rate of return	7,00 %			
Calculation term	15,0 years		1/2020 - 12/2034	
Calculation point	1/2020	(In the beginning of period)		
Net Present Value (NPV)	3 910 205	≥ 0		
NPV as a monthly annuity	34 678			
Internal Rate of Return (IRR)	14,11 %	≥ 7 %		
Modified Internal Rate of Return (MIRR)	10,01 %	≥ 7 %		
Profitability Index (PI)	1,52	≥ 1		
Payback time, years	8,5	Based on discounted FCF		
Return on net assets (RONA), %	67,4 %	Average 15 years		
Economic Value Added (EVA)	515 607	Average 15 years		
Discounted Value Added (DCVA)	4 071 264			

Figure 5.6 Key financial figures of the double size HTC project compared to baseline.

In comparison to Case 1, the key figures such as net present value, payback time and IRR are more favorable as the investment cost is relatively smaller. The payback time is 32% shorter and IRR 57% higher than in the baseline case. Therefore, the economy of scale could potentially be part of the solution to make HTC more compelling technology for pulp and paper industry. As the previously studied cases have shown, investment cost has a great impact on economic outcome. The sensitivity analysis for total investment cost is shown in Figure 5.7.

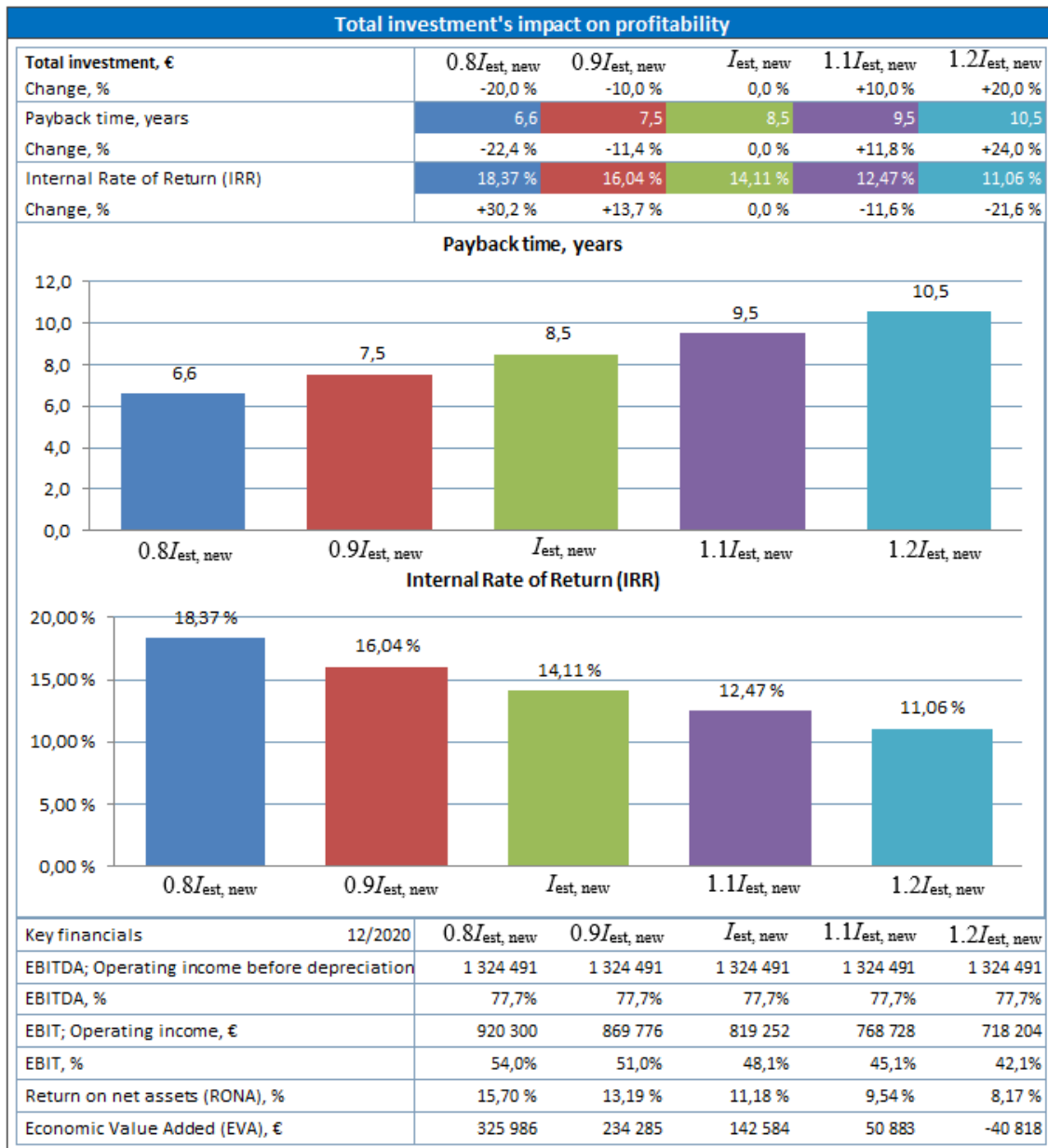


Figure 5.7 Total investment impact on profitability in Case 3. Key financial figures are calculated when estimated investment costs changes from -20 % to +20 % compared to case's baseline. Payback time and IRR are presented as bar charts.

The relative changes in project payback time and IRR are in same range than in Case 1. At the lower end, the payback time is 6.6 years, which is 22.4% lower than in baseline estimation (8.5 years). The IRR starts to approach 20% benchmark, as it is 18.37% in best case scenario.

The premises in this large-scale scenario are better than in Case 1 to make the project viable. For that reason, it is interesting to study how the import of sludge would affect the project economic outcome. Similarly to Case 2, it is assumed a situation where the external sludges are used to achieve full capacity of the HTC plant. Again, this would increase hydrochar production and create opportunity to get incomes from disposal services. When the HTC plant capacity is 40 000 t/a and biosludge production 27 102 t/a, there is possibility to import 12 898 tons of external sludges. At 60 €/t gate fee that means 773 880 €/a of potential incomes. The impact of imported sludge on peat reduction and CO₂ emission are calculated using Equations 4.4 and 5.2. The electricity consumption is bases on Equation 5.3. Figure 5.8 includes the financial key figures for viability using different gate fees.

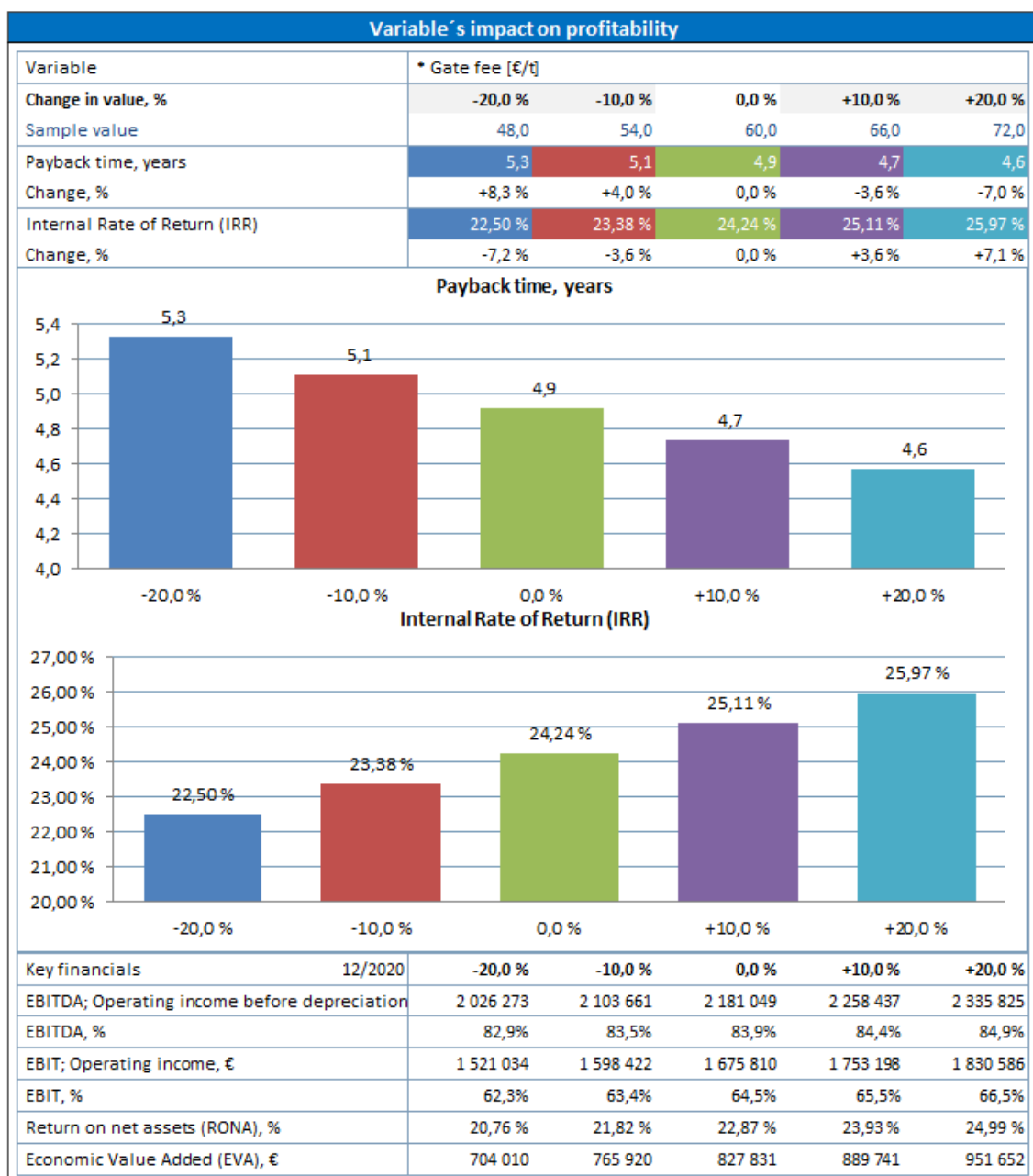


Figure 5.8 Impact of gate fee [€/t] on profitability in Case 3. Key financial figures are calculated when gate fee changes from -20 % to +20 % compared to baseline 60 €/t. Payback time and IRR are presented as bar charts.

As can be seen in Figures 5.7 and 5.8, adding imported sludge in the to Case 3 would improve the project viability. At 60 €/t gate fee, the payback time would be shortened from 8.5 to 4.9 years. The relative change is -42%. IRR would increase by 72% from

14.1% to 24.2%. Considering the studied gate fee values, the fluctuation in the project viability can be seen as moderate. The payback time vary between 5.3 and 4.6 years and IRR between 22.5% and 26.0%. Relative fluctuation in payback time at 48 €/t gate fee is 8.3% and at 72€/a gate fee -7.0% compared to baseline estimate 60 €/t. For IRR corresponding changes are -7.2% and 7.1%. Figure 5.9 shows the impacts on the key financial parameter when the total investment costs are changed for this scenario.

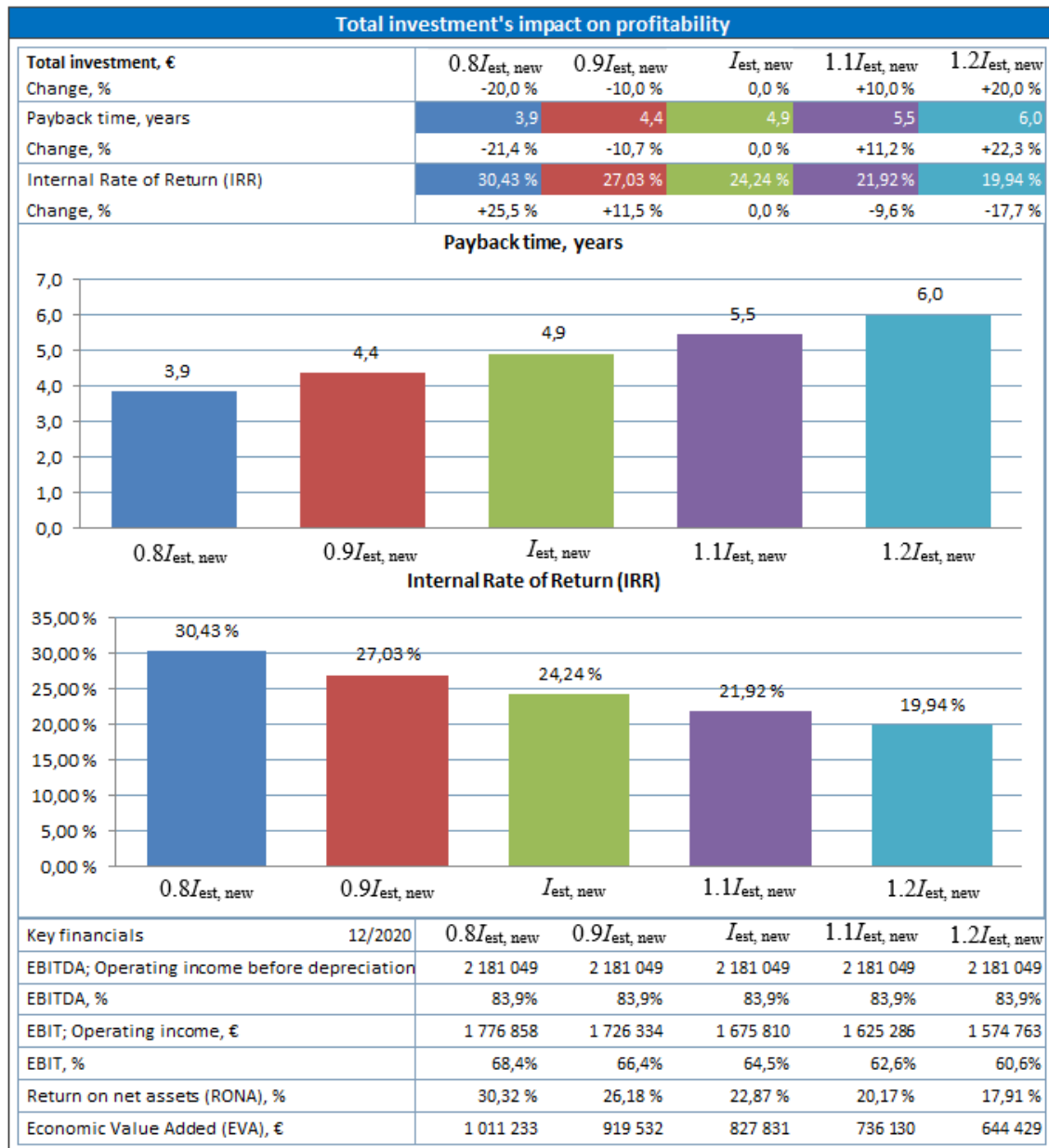


Figure 5.9 Total investment impact on profitability in Case 3 with 60 €/t sludge importing gate fee. Key financial figures are calculated when estimated investment costs changes from -20 % to +20 % compared to case's baseline. Payback time and IRR are presented as bar charts.

By changing the investment cost estimates, the project payback time varies from 3.9 to 6.0 years. The revenues from gate fee have a significant impact on the project viability. Even if the investment cost is increased by 20%, the investment pays itself back quicker compared to scenario where sludge importing is not an option, but investment cost is 20%

less than estimated. In latter scenario, the payback time is 6.6 years, as shown in Figure 5.7. As the key parameters have shown, the scale of economy gives more favorable starting point for viability analysis. Taking this account, it is possible to create a “best case scenario” with two major variables, for example where investment cost decreases by 20% and gate fee increases by 20%. In this case, the payback time would be 3.6 years and IRR for the investment 32.5%.

6 CONCLUSIONS

The biosludge produced at Heinola fluting mill is currently incinerated in the mill's power plant BFB boiler. Combustion of wet sludge requires support fuel and it causes disruptions at the solid fuel feeding system. The utilization of a hydrothermal carbonization technology would result in lower fossil fuel consumption, as the need for support fuel is diminished. This means that peat usage at fault conditions reduce and more bioenergy is provided. In addition, situations when oil is burned would decrease. All these results in lower CO₂ emission and reduced fuel costs.

The economic analyses showed that investment cost is the most significant factor for the project viability. It is worth noting, that total investment costs used in the calculations are estimations based on Heinola pilot plant. When the technology achieves its maturity, it is reasonable to expect lower manufacturing and building costs and thus, lower investment costs.

Sensitivity analysis revealed that the possible reductions in heavy fuel oil usage is another significant factor to the project profitability. The amount of saved peat in megawatt hours was greater than HFO, but the oil higher price and taxation compared to peat makes HFO savings more important. The oil saving significance to the results creates some uncertainties to the analysis, as the amount of saved oil is based on estimation, not measured data. It should be noted that fuel prices used in the calculations are based on 2019 and early 2020 price level. If the oil price stays low during the calculation term, the viability would suffer.

As the researched cases shown, converting the biosludge to hydrochar and using it as a fuel does not provide very intriguing investment project based on Heinola fluting mill situation. However, it does not take away from HTC technology the status of a promising treatment method for problematic wastes. It requires case by case analysis, for example if the mill is in a situation to invest in a new sludge processing technology. Mills with bigger sludge production and bigger sludge disposal costs might benefit more from HTC

in the finance point of view. The economies of scale could potentially reduce the relative investment cost and make the project more viable.

Importing sludges from outside the mill could provide economic benefits, if HTC plant full capacity is not used. However, it would require more work to study how different sludges suits to HTC plant and how practical arrangement would be performed. Under the Heinola HTC plant's current environmental permit for experimental activities, it is not possible to handle sludge flows outside the mill. Nevertheless, it is still noteworthy path for future research and upcoming projects.

7 SUMMARY

Purpose of this thesis was to research HTC technology energy aspects and feasibility in pulp and paper industry by using Heinola HTC pilot plant as a reference. Heinola HTC biofuel project is interesting pilot case, because it provides opportunity to study industrial scale HTC plant in a real-life operating environment. C-Green's wet oxidation utilizing HTC plant is trailblazer on its field and future findings will be intriguing. For this study, field tests did not manage to implement for schedule reasons, but results based on data provided by Stora Enso and C-Green, findings from C-Greens pilot facilities and literature in a field.

Hydrothermal carbonization has raised interest due to its ability to process biomasses that are wet and problematic to handle. Solid product of HTC, hydrochar, is a coal-like biofuel, whose dryness, heating value and homogeneity are superior compared to feedstock biomass. At Heinola fluting mill, incinerating biosludge requires support fuels to compensate a temperature drop at the furnace and covering situations when sludge causes disruption at solid fuel feeding system. By replacing the wet biosludge by hydrochar, reduction in fossil fuel consumption and CO₂ emissions are gained. HTC filtrate has potential to increase biogas production, which contributes to fossil fuel saving.

The economic analysis of HTC investment shows that investment cost is the most important factor to project economic outlook, followed by gained fuel savings especially in heavy fuel oil. Impact of HTC plant own energy consumption cost was found to be minor. As the viability of the HTC project is heavily connected to investment costs and incomes, ways to influence those factors are significant. Scaling HTC technology to larger size is beneficial, if economy of scale has a decreasing effect to relative investment cost. Gaining extra revenue by utilizing HTC plant surplus capacity to process municipal or other external sludges was found to be notable method to improve project viability and should be considered if it is technically and accordance with local environmental regulation possible to implement.

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APPENDIX I. FLUE GAS FORMATION IN BIOSLUDGE COMBUSTION

Table I. Combustion reactions of Heinola mill's biosludge.

SLUDGE 1 kg					FLUE GAS				
	M [g/mol]	m [g]	N [mol]	O ₂ -need [mol]	CO ₂ [mol]	SO ₂ [mol]	H ₂ O [mol]	N ₂ [mol]	O ₂ [mol]
C	12.01	65.82	5.48	5.48	5.48				
H ₂	2.02	7.75	3.85	1.92			3.85		
O ₂	32.00	32.10	1.00	-1.00					
S	32.06	3.40	0.11	0.11		0.11			
N ₂	28.10	10.74	0.38					0.38	
H ₂ O	18.02	864.00	47.96				47.96		
Ash		16.18							
Total O ₂ -need				6.51					
Excess air coefficient = 1.2									
N ₂ from excess air (3.77*6.51*1.2)								29.43	
O ₂ from excess air (6.51*(1.2-1))									1.30
Total					5.48	0.11	51.81	29.82	1.30
Mol-%					6.19	0.12	58.53	33.69	1.47
Mass [g]					241.13	6.79	933.27	837.90	41.60

By adding together all flue gas components, total flue gas production is 2.06 kg_{fg}/kg_{bs}.