LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
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OPTIMIZATION OF BIOMASS-FIRED POWER PLANT BY UTILIZING REAL-TIME FUEL STORAGE MODEL

Examiners: Professor, D.Sc. Risto Soukka
Laboratory engineer, Lic.Sc. (Tech.) Simo Hammo

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
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Optimization of biomass-fired power plant by utilizing real-time fuel storage model

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Keywords: biomass, power plant, optimization, FUELCONTROL ® Storage model

This master's thesis was assigned by the Inray Oy Ltd to study the optimization opportunities of the power plant by utilizing the real-time storage model developed by the company. The aim of the study was to verify the performance of the storage model at Järvenpää's power plant by studying different factors of the storage model. Another purpose was to make a tool for implementing the elemental analysis of the fuels to the model.

The thesis consists of a literature review and an experimental section. Concepts such as characteristics of the solid biofuels and recycled fuels, multifuel operation in the power plants and the issues related to the biomass combustion caused by the fuels were presented in the theory. In the experimental section the fuel stream that was unloaded from the storage silos was sampled and compared to the storage model according to the composition and the moisture of the fuel mixture. The results indicates that the storage model corresponds well to the fuel stream unloaded from the storage model according to the studied factors. The elemental analysis of the fuel was implemented to the storage model by calculating fuel indexes and the use of them was demonstrated.

The research concluded that the storage model can assist the plant by providing real-time information for plant operators and automation system about the quality of the fuel. The model can be used to prevent problems due to fluctuations in the fuel quality and to facilitate the control of the combustion process. The storage model has potential to short- and long-term fuel supply and cost optimization as well as plant daily operation, maintenance, and consumable utilization optimization.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
School of Energy Systems
Ympäristötekniikan koulutusohjelma
Sustainability Science and Solutions

Jenni Partti

Biovoimalaitoksen tuotannon optimointi hyödyntämällä reaaliaikaista varastomallia

Diplomityö

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132 sivua, 12 taulukkoa, 50 kuvaa, 6 liitettä

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Tämän Inray Oy:n tilaaman diplomityön tavoitteena oli tutkia voimalaitoksen optimointimahdollisuuksia hyödyntämällä yrityksen kehittämää reaaliaikaista varastomallia. Tutkimuksen tarkoituksena oli todentaa varastomallin paikkansapitävyys tutkimalla eri tekijöitä. Toinen tavoite oli kehittää työkalu, jonka avulla polttoaineiden alkuaineanalyysit voidaan lisätä varastomalliin.

Diplomityö koostuu teoriasta ja kokeellisesta osasta. Teoriaosuudessa esiteltiin kiinteiden biopolttoaineiden ja kierrätyspolttoaineiden ominaisuuksia, monipolttoainevoimalaitosten toimintaa ja biopolttoaineiden poltosta aiheutuvia ongelmia ja niiden syitä. Kokeellisessa osassa varastosiiloista purettavasta polttoainevirrasta otettiin vertailunäytteitä, joita analysoitiin ja verrattiin varastomalliin reaaliaikaisuuden, polttoaineseoksen koostumuksen ja kosteuden suhteen. Tämän tutkimuksen valossa voidaan todeta, että varastomalli vastaa hyvin varastosiiloista puretun polttoainevirran suhteen. Polttoaineen kemiallisten ominaisuuksien lisääminen varastomalliin toteutettiin laskemalla niille polttoaineindeksit, joiden toimivuus demonstroitiin.

Varastomalli voi auttaa voimalaitosta tarjoamalla reaaliaikaista tietoa laitoksen työntekijöille ja automaatiojärjestelmälle polttoaineen laadusta. Mallin avulla voidaan ennaltaehkäistä polttoaineiden laatuvaihteluista johtuvia ongelmia ja helpottaa polttoprosessin säätöä. Varastomalli parhaimmillaan mahdollistaa lyhyen ja pitkän aikavälin polttoaineen hankinnan ja kustannusten optimoinnin sekä laitoksen päivittäisen käytön, ylläpidon ja polttoaineen käytön optimoinnin.

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Mikkeli, 31st of October 2021
Jenni Partti

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LIST OF SYMBOLS

Symbols

%	percent
ar	as received
db	dry basis
ds	dry solids
M	moisture content
m^3	cubic meters
$Q_{p,net,d}$	net calorific value at constant pressure on a dry basis, MJ/kg
$Q_{V,gr,d}$	gross calorific value at constant pressure on a dry basis, MJ/kg

Abbreviations

BFBC	Bubbling fluidized bed combustion
BFB	Bubbling fluidized bed
CFBC	Circulating fluidized bed combustion
CFB	Circulating fluidized bed
CHP	Combined heat and power
DSC	Distributed control system
EU	European Union
FB	Fluidized bed
GCV	Gross calorific value
GHG	Greenhouse gas
GUI	Graphical user interface
MC	Moisture content
NCV	Net calorific value
SRF	Solid recovered fuel

Chemical compounds

CO_2	Carbon dioxide
HCl	Hydrochloric acid
HF	Hydrofluoric acid
H_2S	Hydrogen sulfide
K_2CO_3	Potassium carbonate
K_2SO_4	Potassium sulfate
KCl	Potassium chloride
KPO_3	Potassium metaphosphate
KOH	Potassium hydroxide
NaCl	Sodium Chloride
NO_x	Nitrogen oxide
P_2O_5	Phosphorus pentoxide
P_4O_{10}	Phosphorus pentoxide
PCDD	polychlorinated dibenzodioxins
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_x	Sulfur oxide

1 INTRODUCTION

1.1 Background

The threat of energy crisis caused by climate change has highlighted the importance of developing renewable energy options with low greenhouse gas (GHG) emissions and carbon dioxide (CO_2) neutrality. Political declarations and actions in response to these demands provide considerable drivers for the ongoing development of renewable energy sources. The European Union´s 2030 Climate and Energy Framework target scenario strives toward to mitigate GHG emissions and increase the share of renewable energy to 32% (European Commission). The actions that will assist Finland to achieve the targets set in both the Government Programme and those of EU for 2030 to achieve a reduction of 80-90% of GHG emissions by 2050 is described by The National Energy and Climate Strategy of Finland to 2030 (Anttila et al. 2018; Huttunen 2017, 13). Finland has committed itself to increasing the share of renewable energy in energy end-energy consumption to more than 51% by 2030 (Ministry of Economic Affairs and Employment of Finland 2019, 47)

The most important sources of renewable energy used in Finland are hydropower, bioenergy, wind power and ground heat (Official Statistics of Finland 2020). Most significant source of bioenergy is wood-based energy, which is based on residues and by-products of forestry or forest industry, including sawdust, bark, other industrial wood residues, as well as forest chips made from logging residues and early thinning wood (Alakangas et al. 2016, 65; Koponen et al. 2017, 29-30). Bioenergy can also be produced from biodegradable and municipal waste and side streams of agriculture and industrial production (Ministry of Economic Affairs and Employment of Finland). Wood-based energy is a preferable solution since it is classified as CO_2 neutral. That is, the tree absorbs as much carbon dioxide as it releases when combusted. (Berndes et al. 2016, 8; Norton et al. 2019.) The energetic utilization of woody biomass is mostly focused on combustion due to being the most advanced and market-proven application (Obernberger & Biedermann 2013, 343). Energy plants are either combined heat and power (CHP) plants or heating plants in Finland (Ranta et al. 2017).

The drive toward distributed generation is emerging, owing mostly to falling costs of wind and solar photovoltaics, as well as advancements in battery-based energy storage. However, while wind and solar are leading the way, they are not the only distributed energy resources that are progressively playing a role in the developing energy environment. Fuel flexible plants that can burn biomass alone or a combination of solid fuels and waste to create both heat and electricity for high fuel efficiency are also becoming more common, particularly for community district heating or industrial installations. These multi-fuel plants use renewable fuels and are completely dispatchable, addressing the intermittency and energy storage concerns that wind and solar plants experience. (Sumitomo SHI FW 2018.) The variability that wind and solar power add to the energy market is offset by the generation of conventional CHP (Jegoroff, 2020).

There are many reasons apart from environmental benefits for utilizing wood fuels for heat and energy purposes. Domestic fuels produced and used regionally have significant regional and national economic benefits by providing local people with business and job opportunities across the procurement chain, from harvesting to transporting, storing, and processing woody biomass for energy. (Väätäinen 2018, 9). Due to domesticity and sufficient availability, increasing the share of biomass as an energy source will in principle improve security of supply if it replaces imported fossil fuels with closely available energy sources (Pöyry Management Consulting 2019, 27). Furthermore, energy wood extraction from forests can be considered as a part of sustainable and effective forest management, therefore enhancing wood production for industrial purposes (Koponen et al. 2015, 4; Väätäinen 2018, 9)

The achievement of all the above-mentioned targets will not be straightforward. Aside from industrial residues, the transition from fossil fuels to renewables needs more biomass that can be derived directly from the forest. The availability of energy wood is mainly affected by the wood market situation, meaning the number of regeneration and thinning operations and forest management work. (Huttunen 2017, 40.) The supply of energy wood is sensitive to the cycles of the forest industry (Tahvanainen & Anttila 2011). The availability of wood is largely dependent on forest industrial residues. Only parts of the wood that are not suitable for forest industry are collected from the forests as energy wood. (Pöyry Management

Consulting Oy 2019, 29.) The increasing use of wood-based fuels is restricting the feedstock availability over time and varying and increasing prices are among the issues already detected (Khan et al. 2008). Competition for wood fuel is further intensifying as energy companies are on the same track. Heat production in large cities of Southern Finland, which is so far strongly based on coal, is being reformed to be bio-based among other solutions. For example, large-scale heating plant using forest biomass as their main fuels have been built in Vantaa, Lahti and Naantali (Vantaa Energia; Lahti Energia; Turun Seudun Energiantuotanto) and are being built in Helsinki metropolitan area and Tampere (Helen, Tampereen Sähkölaitos Oy). The potential of wood energy is good in Finland, but its supply varies strongly regionally due to unevenly distributed resources across the country (Ranta et al. 2012). As seen in the Figure 1, fuel demand is highest in southern, western, and central Finland, while the most abundant forest resources are centered in eastern and northern Finland (Ranta et al. 2012; Tahvanainen & Anttila 2011). That is why wood is imported to Finland because it expands the supply area, especially in plants near the coast and the eastern border and offers energy plants advantages in price competition and diversification of supply chains (Pöyry Management Consulting Oy 2018, 25). In the end, the actual supply potential is determined by the forest owner’s willingness to sell energy wood (Ranta et al. 2017).

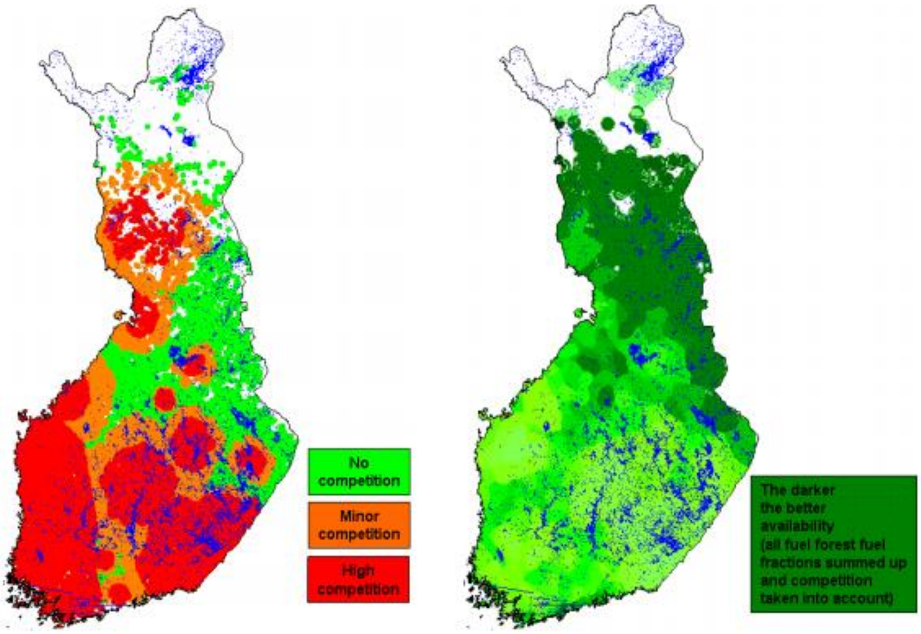


Figure 1. Competition of biomass is showed at the left map and the biomass availability after competition is showed at the right. All types of forest biomass are considered. (Ranta et al. 2012)

According to the Ranta et al. (2017) the price development of energy wood is determined by demand and supply factors that vary by location and season. Furthermore, national policy regulations, EU policy and sustainability criteria for biomass fuels, have a temporal impact on price developments. The factors affecting the demand and supply of energy wood, as well as the fuel price, is presented in Figure 2. The competitiveness of wood-based solid fuels is affected by various incentives, prices, and taxes of competing fuels such as peat and fossil fuels, and the price of emission allowances (Ranta et al. 2017). The most significant recent drivers set by the Finland’s parliament is a decision to ban the use of coal in 2029 and the incentives package for district heating companies giving up coal by 2025 to motivate the abandonment of the use of coal (Banning the use of coal Act 29 March 2019/416: Ministry of Economic Affairs and Employment 2019). The use of peat also decreases due to the EU's tightening emissions trading system and the Finland’s government decision to almost double the peat tax from the beginning of 2021 (Ministry of Finance 2020). These are further contributing the shift from coal and peat to biofuels and recycled fuels.

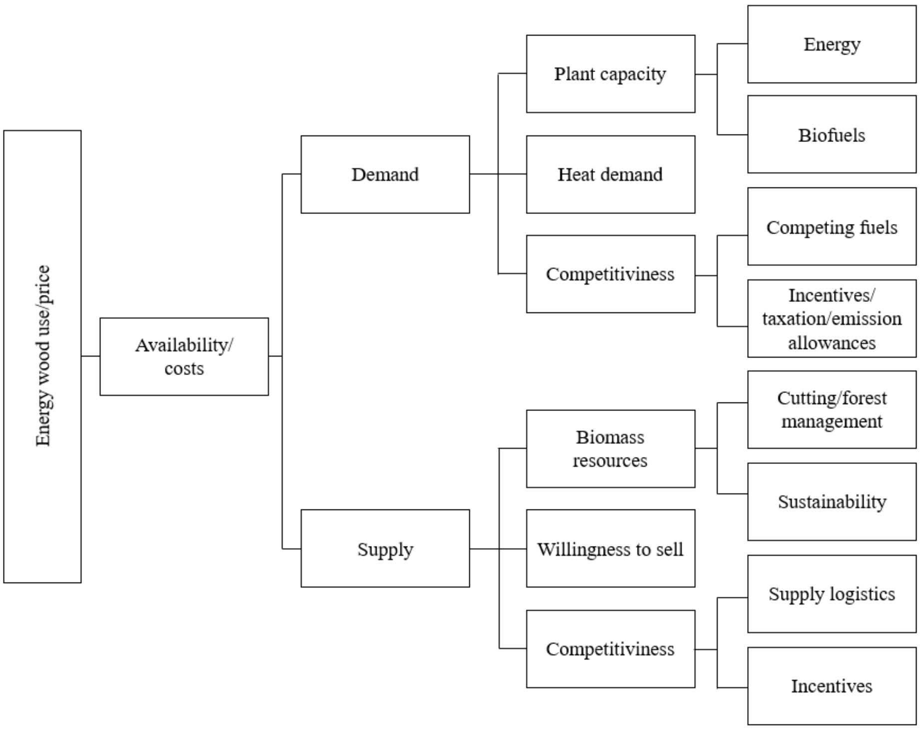


Figure 2. Factors affecting the energy wood use and price (adapted from Ranta et al. 2017)

The main factor affecting the utilization of forest biomass is heat demand (Ranta et al. 2017). There is clear seasonal variation of district heating production in both the demand and the supply of the fuels, but there is also annual variation due to the climate and prevailing weather (Gadd & Werner 2013; Ranta et al. 2017). A typical seasonal variation in heat load pattern in Finland is reflected in Figure 3, with low heat loads during summer and high heat loads during winter. (Finnish Energy, 2020). Due to this, variations in fuel quality, especially moisture content, are increasing. The cold winter months illustrate the need for a wide variety of fuels to guarantee the security of supply of heating (Gadd & Werner 2013).

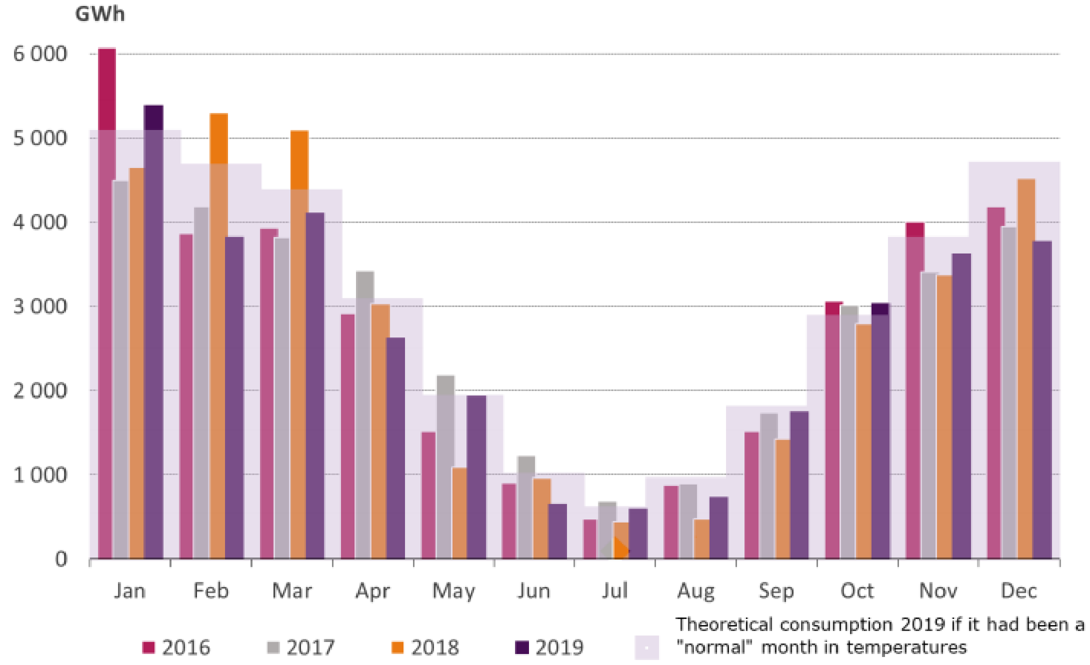


Figure 3. Monthly district heat demand in 2016-2019 (Finnish Energy, 2020).

Since prices for wood-based biofuels have risen and prices are expected to rise further, waste-derived fuels are becoming an important contributor to the energy resource and efficiency agenda (Kinnunen et al. 2019; Lesar et al. 2018; Velis et al. 2013;). In addition to benefits of green energy, they are widely available and inexpensive (Kinnunen et al. 2019). Due to the Finnish law restricts the disposal of biodegradable and other organic waste in landfills (Government Decree on Landfills, 2 May 2013/331), incineration is an appealing option for matters that are unsuitable for further use. The production of recycled fuels is now an important part of Finnish waste management, and it provides a considerable amount of waste materials for efficient utilization in energy recovery (Official Statistics of Finland, 2020b). The combustion of recycled wood is also increasing, since it is considered carbon dioxide neutral energy source, but is less expensive compared to forest fuels (Lesar et al. 2018). Co-firing is also a preferable alternative since domestic fuel's supply security of investigated Finnish CHP-plants is primary dependent on the use of multi-fuel boilers that are fuel flexible and by decentralized fuel supply, according to the Karhunen et al. 2015. To satisfy the energy price, increasing energy demand, and biomass supply while transitioning from fossil fuels, a broad spectrum of renewable fuels must be used for energy.

A solid fuel fired power plant's production cost split is given in Figure 4. The variable and fixed operation and maintenance cost is 25% of the total cost and capital cost account the other 25% (Valmet). According to the study of IRENA (2012) and Valmet (2019) the fuel cost has the largest share (40-50%) of total production cost. Therefore, the power plants are constantly optimizing fuel procurement by striving to use the cheapest fuels for the benefit of their customers. The goal is to produce as much heat as possible at an affordable price. However, there is a clear link between the fuel price and the difficulty of combustion: lower-cost fuels are more complicated to combust (Valmet, 2019).

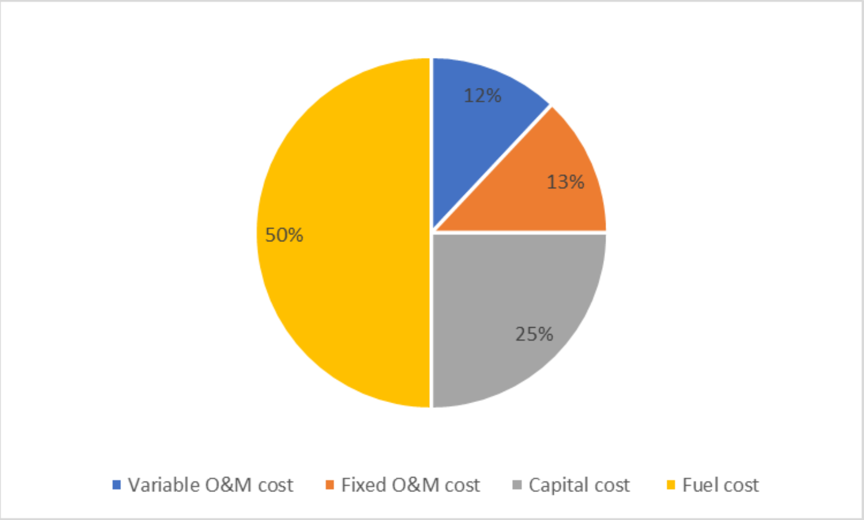


Figure 4. The production cost split of a solid fuel fired power plant (Valmet 2019)

Apart from the availability, logistics and cost issues, wood and waste fuels' utilization remains challenging for several reasons. Generally, the problems start to occur when the quality of the fuel decreases. The special features of biofuels are low calorific value, high moisture content and high volatile matter content. In addition, biofuel ash is rich in alkalis. There specially exist drawbacks with utilizing waste-derived fuels because they contain harmful substances, such as heavy metals, for the boilers. These characteristics of biofuels and waste fuels create issues that must be addressed in the design and process control of the power plant. (Hämäläinen et al. 2003.) The formation of deposits on thermal surfaces, sintering and agglomeration of the fluidized bed, and high-temperature corrosion of thermal surfaces are the most serious issues in the fluidized bed combustion of biofuels (Hagman et al. 2013). Alkali compounds, in particular, have a high corrosion rate increasing maintenance costs and reducing production efficiency for the power plants (Henderson et al. 2006). Corrosive-related maintenance is estimated to account for 10% of a plant's annual operating and maintenance costs (Valdez et al. 2012). According to Henderson et al. (2006), a full set of superheaters for a 100 MW combined heat and power boiler costs well over a million euros. As a result, the durability of superheaters is a significant element in determining long-term production costs. Unscheduled downtime caused by malfunctioning superheaters are also extremely expensive. (Henderson et al. 2006).

Moreover, Jegoroff (2020) states that although CHP-plants offer the opportunity to burn new types of bio-based fuels and thus directly reduce the use of fossil fuel, the facilities are designed to run smoothly or at least as expected. Rapid load changes and fuel changes can strain equipment materials, produce additional emissions, and degrade energy production efficiency (Jegoroff, 2020). Furthermore, as a result of the increasing share of intermittent renewable energy generation, flexibility demands have increased for boiler-based energy production, requiring faster ramp rates and lower permitted minimum load (Huttunen et al. 2017)

1.2 Goal and scope

This Master Thesis is done for Inray Oy Ltd. Inray provides fuel quality measurement systems utilizing advanced X-ray technology to enhance the performance of energy production, bio-refineries, and pulp mills (Inray). The Smartflex project aims to the development of smart monitoring and control tools for controlling power plants in quickly evolving circumstances and prolonging the lifespan of the plants while still maintaining high productivity and low emissions in a consistent manner. The project also aims to provide power plants with solutions to their requirements of flexibility, as the wind and solar energy supply fluctuations require traditional CHP plants to be more adaptable. Monitoring and control tools are developed to provide plant operators with real-time process knowledge and instructions for optimum plant performance. The tools, at best, ensure the plant's high performance, low emissions, and good condition under varied conditions. The SmartFlex project is funded by Business Finland, which includes VTT, Fortum Power and Heat Oy, Sumitomo SHI FW Energia Oy (SFW) and Pinja Oy. (Jegoroff, 2020.)

As a part of the SmartFlex-project the same companies are also working on parallel projects to develop own applications. Developed by Inray Oy, FUELCONTROL ® Storage is a real-time storage model for solid fuel management in biopower plants. The storage model has been developed since 2015 and is currently being demonstrated at Vantaa Energy's Järvenpää power plant.

The goal of this master thesis is to verify the performance of the storage model and investigate how the storage model can be used to improve the boiler's overall performance. The following questions can be used to describe the scope.

- Does the composition of the output fuel of the storage silos correspond to the fuel composition of fuel samples?
- Is the storage model consistent and real-time compared to the output fuel stream of the storage silo?
- Does the moisture of the fuel samples correspond to the data provided by the X-Ray 2 and storage model?
- How elemental analysis of the fuel can be implemented to the storage model?
- Can the storage model be used to improve the performance of the plant?

This thesis is divided into theoretical and empirical sections. The theoretical part goes over the physical and chemical properties of the most common biofuel and recycled fuels used in power plants, the multifuel operation in plants and the adverse effects and technical challenges of the boiler caused by the biofuels. The description of the Järvenpää plant, its processes and the testing environment including the FUELCONTROL ® -system and storage model are presented in the empirical section. Following that, the test drive plans for the verification of the storage model are introduced, as well as the results are analysed. The empirical section will conclude with the report’s conclusions and summary.

Process data about the boiler and combustion process is beyond the scope in the experimental section the thesis. The regulation of combustion process, the efficiency of the plant, operating and maintenance costs caused by a corrosion, or the emissions and their reduction are not used to prove the performance of the storage model. The optimization opportunities of the storage model are only discussed in the conclusion. The verification of the chemical composition or the energy content of the fuel mixture are also beyond the scope.

2 PHYSICAL CHARACTERISTICS AND CHEMICAL COMPOSITION OF FUELS

The physical characteristics and chemical composition of the solid biofuels used have an impact on the entire process of energetic use of solid biofuels (fuel supply, combustion system, gaseous and solid emissions) (Obernberger et al. 2006). In this chapter, the chemical fuel composition and important physical characteristics of fuel are discussed. The majority of the characteristics are quality-relevant factors, as they can affect the emissions formation and thermochemical processes or determine the use of the produced slag residues or ash (Hartmann 2013, 1423). As a result, the relevance of each of the presented fuel parameters is addressed individually below.

2.1 Physical properties of solid biofuels

2.1.1 Calorific value

The calorific value of the fuel is arguably the most significant characteristic since it affects how much energy can be generated as well as the theoretical achievable combustion temperature. For the calorific value, a distinction is made between the gross and net calorific values. Both definitions are provided, and the differences between them are explained. Gross calorific value (GCV) is described as the quantity of heat generated when one unit of mass of fuel is completely combusted and the outputs cool to a temperature of 25 °C (Alakangas et al. 2016, 27; Hartmann 2013, 1433-1436). As the GVC is determined, it is assumed that the water produced by the combustion of the hydrogen in the fuel, as well as the water retained in the fuel are liquid after combustion (Alakangas et al. 2016, 27). The energy needed to evaporate water during combustion is accounted for in the net calorific value (NCV). (Hartmann 2013, 1433-1436.)

The calorific value of a fuel is influenced not only by its chemical composition, but also by its content of additional heat-consuming components such as ash content and moisture. The moisture content of the biomass has the greatest impact on its net calorific value. Considering moisture content varies greatly, fuel comparisons are usually conducted on a dry matter basis. (Strömberg 2006, 26-27) A correlation exists between actual calorific value and moisture content, as it can be seen from the Figure 5.

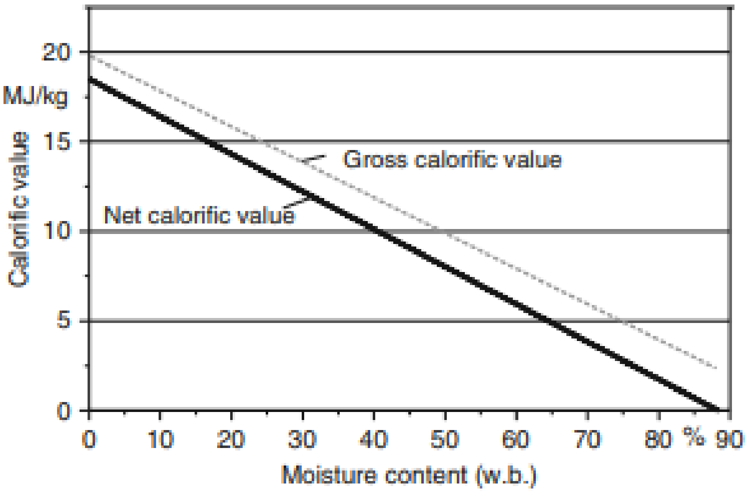


Figure 5. The difference in gross and net calorific value as a function of moisture content (Hartmann 2013, 1434).

The ash content has an impact as well. The typically small range of ash content in fuels results in a very minor influence of calorific value. The quantity of energy in a given load may be determined using the moisture content and calorific value of the fuel. The calorific value influences its suitability for combustion in various boilers.

2.1.2 Moisture content

Moisture content causes a major impact on the combustion efficiency of thermal and power plants (Jahkonen et al. 2012). The quantity of water that can be removed from a fuel under certain conditions is referred to as moisture content. It is generally proportional to the total mass, which includes water. Moisture has a significant impact on the fuel mass and the combustion temperature that may be achieved given thermodynamic circumstances. Moreover, the fuel’s storability is affected. (Hartmann 2013, 1439-1441.) Using formula 1, the moisture content can be determined from the wet weight.

$$M_{ar} = \frac{m_2 - m_3}{m_2 - m_1} x \, 100 \qquad (1)$$

In which

M_{ar} = moisture content as received [w-%]
m_1 = weight of the empty tray [g]
m_2 = combined weight of the tray and the sample before dying [g]
m_3 = combined weight of the tray and the sample after drying [g]

A high moisture content can cause the combustion temperature to be reduced while increasing the flue gas volume, which displaces heat transfer from the furnace to the convection area. Due to the altered heat transfer, the higher gas volume may also result in a reduction in boiler power output. (Strömberg 2006, 27)

2.1.3 Ash content and ash melting properties

The ash generated by thermal combustion is the solid inorganic residue left over, and as a concept, it is distinguished by a broad range of macro- and micronutrients that remain after combustion (Hartman 2013, 1440-1441; Singh et al. 2020, 17). It may come directly from unpolluted fuel, or it could originate from mineral pollutants entrained throughout the supply chain, such as during harvesting, comminution, transport, and storage (Hartmann 2013, 1440-1441).

The ash composition of a fuel impacts both the environment and the furnace’s technical design. The ash percentage of a fuel is critical to how well it functions in a particular plant. Higher ash content in fuel may result in more particle separation demands or higher particle emissions. Special technical solutions for de-ashing and cleaning heat exchanger surfaces may also be required. (Hartmann 2013, 1441.) Additionally, high ash content raises the costs of the ash handling system as well as the disposal of the ash produced (Strömberg 2006, 27).

The physical characteristics of the ash are altered as a result of induced reactions during thermochemical conversion. In the fire bed, depending on the temperature, phenomena such as sintering, or even total melting of ash particles might occur. This can lead to serious technical drawbacks in the conversion plant, and it must be considered while designing the combustion process. The melting behaviour of ash is determined by the ash components and is thus directly connected to the fuel composition. As a result, ash melting behaviour is mentioned as one of the fuel-specific characteristics. (Hartmann 2013, 1441.)

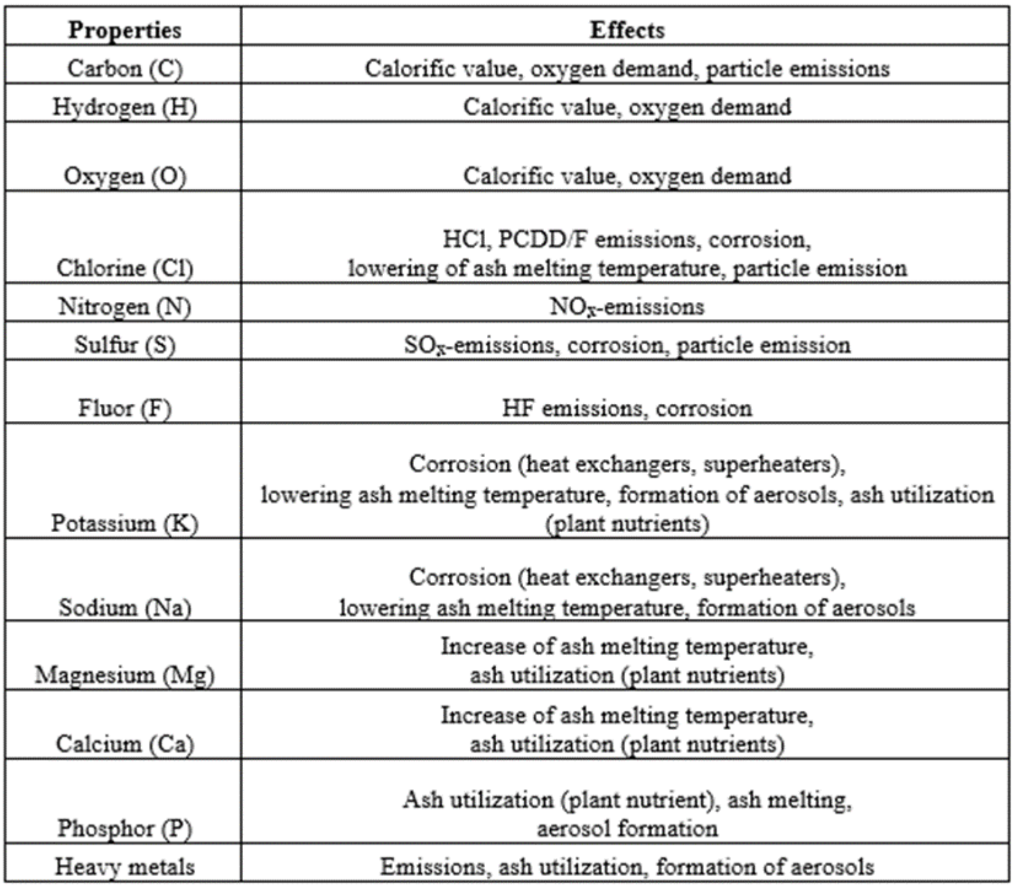
2.1.4 Volatile matter

Volatile matter contains all of the products formed during pyrolytic decomposition of dry organic material under specific heating conditions. The amount of volatile matter influences the burning profile, reactivity, and emissions, among other things. The volatiles content has a significant impact on how the fuel behaves during combustion. The volatile matter content enables conclusions to be drawn about the gas build-up during gasification or the length of the flame during combustion. (Hartmann 2013, 1437.) As a result, it is an important feature for furnace design. A fuel with a high volatile content, for example, will have a combustion process that includes mostly of heating, gasification, and combustion in the gas phase (Strömberg 2006, 27). Additionally, increasing the rate of secondary air flow and the furnace’s combustion space may be required to guarantee a suitably long residence time of the larger gas volume produced (Hartmann 2013, 1437; Strömberg 2006, 27). Combustion of low volatile-content fuels, on the other hand, will occur mostly in the solid phase on the surface of fuel particles or in the fuel bed. (Strömberg 2006, 27)

2.2 Chemical properties of solid biofuels

The chemical combustion-relevant properties of solid biomass fuels are presented in Table 1. They are further discussed in the following chapter.

Table 1. The effect of elemental composition in Fuels (adapted from Hartmann 2013, 1424; Obernberger & Biedermann 2013, 346)



Properties	Effects
Carbon (C)	Calorific value, oxygen demand, particle emissions
Hydrogen (H)	Calorific value, oxygen demand
Oxygen (O)	Calorific value, oxygen demand
Chlorine (Cl)	HCl, PCDD/F emissions, corrosion, lowering of ash melting temperature, particle emission
Nitrogen (N)	NO_x-emissions
Sulfur (S)	SO_x-emissions, corrosion, particle emission
Fluor (F)	HF emissions, corrosion
Potassium (K)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilization (plant nutrients)
Sodium (Na)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols
Magnesium (Mg)	Increase of ash melting temperature, ash utilization (plant nutrients)
Calcium (Ca)	Increase of ash melting temperature, ash utilization (plant nutrients)
Phosphor (P)	Ash utilization (plant nutrient), ash melting, aerosol formation
Heavy metals	Emissions, ash utilization, formation of aerosols

The carbon and hydrogen have an effect on its heating value by increasing it while oxygen decreases it (Grier 2014, 204; Khan et al. 2008; Nanda et al. 2014). The nitrogen dioxide (NO_x) emissions are mainly caused by the oxidation of the chemically bound nitrogen in the fuel (Obernberger & Biedermann 2013, 346). According to Sommersacher et al. (2011) the increase of NO_x emissions happens as the N content of the fuel increases, whereas the rate of fuel N conversion to NO_x decreases. The presence of chlorine in the fuel influences the formation of the gaseous hydrochloric acid (HCl), chlorine gas (Cl_2) or alkali chlorides, such as potassium chloride (KCl) and sodium chloride (NaCl). Due to subsequent cooling of the flue gas in the boiler, a substantial share of the Cl condenses as salts on the heat exchanger surfaces on the fly ash particles in the flue gas. The Cl release is therefore relevant element concerning gaseous HCl emissions, aerosol and deposit formation and corrosion risks. The sulfur causes primarily gaseous sulfur oxide (SO_x) emissions and alkaline and alkali earth sulfates. As a result, understanding the release of S is essential for aerosol emissions, gaseous emissions, and deposit formation. (Sommersacher et al. 2011.) Ash deposits, which are caused by Cl and S, mainly consists of alkali metal salts such as potassium sulfate (K_2SO_4) and KCl. Furthermore, Cl and S interferes with the flue gas's dew point, affecting condensation in heat exchanger and flue gas cleaning. (Obernberger & Biedermann 2013, 346-347.)

According to Strömberg (2006, 32), the form of Cl is able to change from gaseous HCl to salts and vice versa. As previously noted, it may also be a component of damaging organic compounds. The way Cl is bounded determines the shift to larger compounds in the supplied fuel. Since the toxic substances are low in volatility, they can be discovered in ash, particularly fly ash. (Strömberg 2006, 32.)

Sulfur, on the other hand, has a weak proclivity to form toxic organic compounds. In the absence of oxygen, sulfur will form hydrogen sulfide (H_2S), resulting in a sub-stoichiometric combustion. During the formation of sulfide (S^{2-}), H_2S may be bound to alkaline ash. Ash containing either metal ions or a strong alkaline ash and reducing environment are required for this formation to happen. Metal ions with a high affinity for H_2S, such as Cd, Hg, Pb, and Zn, are required. Under oxidizing conditions, primarily SO_2 and smaller amounts of sulfur trioxide (SO_3) are produced. Both compounds can react with alkali metals to form salts. Since SO_2 is a weaker acid, it bonds the alkali more loosely. A desulfurization step is necessary if the fuel involves a significant amount of sulfur. This normally extracts the HCl as well. If the sulfur is oxidized to SO_3, it can be removed. Usually, sulfur is collected from the flue gases after the combustion in boiler. (Strömberg 2006, 33)

Ash-forming elements can occur in various forms (soluble ions, associated to organic matter, minerals) in biofuels, which influences the behaviour of fuel ash. The interactions between compounds containing chlorine, sulfur, aluminium silicate and alkaline substances control the rate of deposits forming in biomass combustion. NaCl or KCl are example of high-risk chlorine compounds. These alkaline chlorides, on the other hand, can react with sulfur and aluminium silicate compounds to produce HCl. (Aho et al. 2010)

$$2MCl(g) + SO_2(g) + \frac{1}{2}O_2(g) + H_2O(g) \rightarrow M_2SO_4(s) + 2HCl\ (g)$$

Where M denotes an alkali metal, for example K or Na (Aho et al. 2010; Shao et al. 2012)

The presence of Pb, K, Na and Zn increases the risk of ash-forming elements being emitted during combustion, and thus the formation of deposits and aerosol. However, during combustion the concentration of these elements in the ash vapors formed is not equal to the concentration of these elements in the fuel because the gaseous atmosphere, chemical interactions with other elements (e.g., Si), and the combustion temperature all have a significant effect on the release activity. (Obernberger & Biedermann 2013, 347.)

Since potassium (K) is found in considerably higher amounts in most biomass fuels than other aerosol-forming elements, the release of K is the most important factor in the aerosol emissions formation. K in a fuel during combustion is either retained in the condensed phase of ash particle or released into the gas phase (Mason et al. 2016). Sorvajärvi et al. (2014) concludes that in the temperature range above 727 °C (1000 K) majority of the potassium in the gas phase are in the form of K, KCl or KOH, as these species stay stable in the gaseous phase at such temperatures. Jöller et al. (2007) and Knudsen et al. (2004) concludes that in the temperature range of 500-1500 °C, most of the potassium released to the gas phase consists of potassium hydroxide (KOH) and KCl. In this temperature range, less K is released as K_2SO_4 and potassium carbonate (K_2CO_3). Variety of factors influence the release of K.

The occurrence of phosphor in the flue gas is causing the formation of aerosols and deposits, mostly by the formation of potassium metaphosphate (KPO_3), phosphorus pentoxide (P_2O_5 and P_4O_{10}). If the fluor is presence in the fuel, it may have effect on hydrofluoric acid (HF) emissions and corrosion. The ash melting point temperature is increased by magnesium and calcium. Regarding of the ash-forming elements, non-volatile elements (Si, Mg, Ca, Fe, Al) semi-volatile elements (P, Mn), and rather volatile elements (K, Na) can be distinguished. Rather and semi-volatile elements are partially released from the fuel to the flue gas and interact with other elements in the flue gas, such as S, Cl or CO_2. (Hartmann 2013, 1430-1433; Obernberger & Biedermann 2013, 346.) Minor ash-forming elements, such as Zn, Pb, Cd, Cu, Cr, Co, Ni, Mo, As, Sb, Hg, Tl, are particularly of concern in order to prevent problems associated with excessive gaseous and particle-bound heavy metal emissions, as well as regarding the utilization of ash. Furthermore, the formation of heavy metal chlorides in ash deposits can significantly decrease the melting point of the ashes, resulting in increased depositions and corrosion. (Obernberger & Biedermann 2013, 346.)

2.3 Solid wood fuels and mixed fuels

Fuels described in this chapter are forest fuelwood, industrial wood residue, recovered wood and mixed fuels, since they are the most used biomass-mass based fuels in Finland. Classification of fuels is done according to Statistics Finland's Fuel Classification 2021. According to the statistics presented by Ylitalo (2020), the contributions from the solid wood fuels are equivalent to a total of 20,5 million solid cubic metres in heating and power plants in 2019. The consumption of different solid wood fuels is given in Figure 6. A more detailed overview of the various fuels is provided in order to comprehend and clarify the features and issues connected with each fuel.

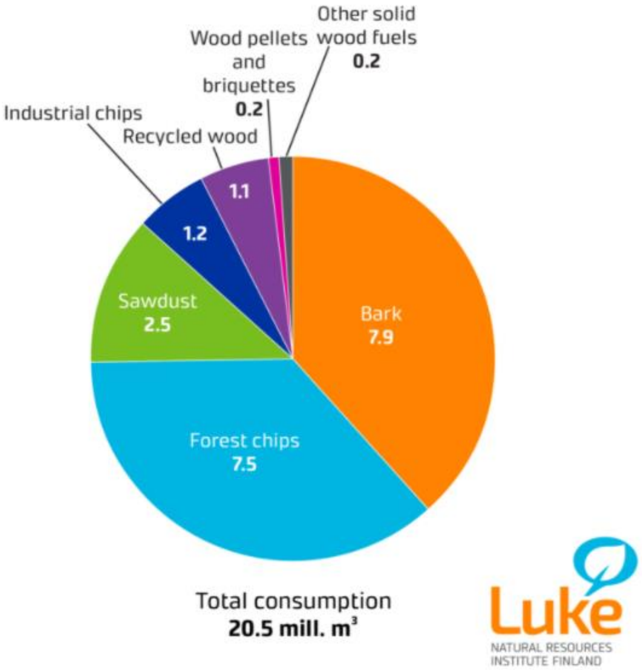


Figure 6. Solid wood fuel consumption in heating and power plants in 2019 (mill. m^3) (Ylitalo, 2020).

2.3.1 Forest fuelwood

Generally, forest fuelwood is produced from raw wood that was previously unused for any other purpose by using a mechanical process (Alakangas et al. 2020, 9). Wood materials or stems that do not yet meet the quality requirements or dimensions for industrial roundwood are used to generate energy and heat. Poor-quality and small sized delimbed stems and whole woods are typically utilized for energy purposes during pre-commercial thinning or early thinning of young stands, regeneration, and final felling in wooded areas. By-products rejected for industrial use, such as treetops, foliage, living and dead branches, off-cuts of stems, roots, and stumps are utilized for energy purposes, which are formed from regeneration felling and felling linked to stemwood harvesting. (Väätäinen 2018, 9). Forest chips can be made from delimbed stem and whole tree as well as from forest residue and tree stumps and roots.

Wood has the ability to bind water from its surroundings while also releasing water into the air. According to the temperature and humidity circumstances, the humidity of the wood evolves towards equilibrium moisture, where the amount of volatile and binding water is equal. Moisture in wood is always changing as circumstances change in nature. The rate and direction of change are determined not only by the circumstances, but also by the moisture content of the wood. (Janhunen et al. 2012)

The moisture content of forest fuels varies considerably depending on source, the season and the time between supply and combustion (Alakangas et al. 2016, 58). According to Strömberg&Svärd (2012, 58) the mixture of 40-60% moisture content is common, and up to 75% moisture content has been reported. The moisture content of wood-based fuels varies and is normally in the range of 40-55%. Problems occur mainly at high or varying moisture levels. (Strömberg&Svärd, 2012, 58.) Due to high moisture content, they have a lower heating value compared to fossil fuels. Higher moisture content typically leads to operational issues in the boilers, with process instability and higher CO and VOC emissions (Svoboda et al. 2009). More detrimental to the combustion process than the high moisture content is the variation of the moisture content of the fuel, which can substantially reduce the efficiency of the boiler, as the boiler's control values, and the combustion process must be changed as the fuel’s moisture content varies (Helynen & Flyktman 2004). Bed temperature variation due to moisture fluctuations in the fuel is a problem, as in an increased risk of bed sintering. Power plants have increased the frequency of bed sand replenishment and mixed moist and dry fuels to tackle the issues (Orjala et al. 2003).

High proportion of fine particles can also cause problem, since they fly up and burn higher up in the furnace or in the fluid bed. It can cause accelerating corrosion due to a combination of coatings, elevated temperature and reducing environment due to low presence of oxygen and a high carbon monoxide level. The risk increases in BFB boilers as the temperature in the superheaters is higher. This might cause significant tube damage and steam leaks in the long term. Wood fuels can cause alkali (particularly potassium) and chloride-induced operational problems. (Strömberg&Svärd 2012, 58.) While the levels of potassium and chlorine are comparatively low in wood-based fuels, they cause issues because wood lacks the compounds found in peat and coal that protect the boiler (Alakangas et al. 2016, 190). Calcium is the most common elements that forms ash in wood fuels (Obernberger & Biedermann 2013, 346). The majority of biofuels have a high level of volatiles (Strömberg 2006, 27)

Despite having a low ash content, solid biofuels typically include highly undesirable ash constituents (chlorine and potassium) that promote corrosion. Furthermore, the resultant ash frequently has a low melting temperature. (Vakkilainen 2017, 212)

2.3.2 Industrial wood residue

Industrial wood residue consists of by- products from mechanical forest industry and pulp and paper industry, such as bark, sawdust, and wood residue chips, as well as other types of industrial wood residue (Alakangas et al. 2020, 9; SFS-EN 17225-1:2021, 15). The bark contains the bark generated in the commercial timber by different debarking techniques. The sawdust includes sawdust, cutter chips and other fines produced by the board mills and the pulp industry. Industrial wood chips include chips made from sawmill surface boards and strips, other wood waste produced by further processing of sawn timber, as well as compensating pieces from board mills, veneer, and similar waste wood. (Alakangas et al. 2020, 8-10.)

2.3.3 Recycled wood

The definition and terms of recycled wood are not always globally consistent and may vary by source. In some contexts, the terms recovered wood (Statistics Finland, 2020) and used wood (SFS- EN ISO 17225-1:2021) have been used to describe this material. Furthermore, the phrases waste wood or wood waste may be encountered, although these terms are rather problematic because they indicate that the item should be categorized as waste. Even when the term waste appears in the title, this is not always the case. (Alakangas et al. 2015.) The term recycled wood is commonly used in Finnish statistics and trading. Therefore, this thesis will employ the term recycled wood.

In the classification of recycled wood fuels, no residual products from felling or by-products of wood processing are considered, only clean wood classifies as a solid biofuel, or discarded wood, or wood product, such as new constructions' wood waste, wood packaging and pallets utilized for previous commercial applications with no prospect of reuse or recycling is included (Alakangas et al. 2014, 10-14; SFS-EN 17225-1:2021, 15; Statistics Finland 2020).

The four categories of decommissioned wood are categorized A, B, C, and D. Solid biofuels are classified into two categories: A and B and are covered by the standard SFS-EN ISO 17225-1 and are not subject to the waste incineration regulation. Wood residue, which composition includes more organic halogenated chemicals and heavy metals than natural wood but does not contain wood preservatives, falls into Category C. Such wood waste belongs to recycled fuels (SFS-EN 15359) and is subject to the standard of the Waste Incineration Regulation. Wood treated with wood preservatives, such as pressure impregnated wood, is a hazardous waste and it is classified as Category D. Only recycled wood classified as A and B are discussed more in depth since these fuels are allowed to be combusted in CHP-plants. Recovered wood in categories A and B does not consist of more heavy metals or halogenated compounds compared to natural wood. (Alakangas et al. 2014, 12-14.)

In principle, the combustion behaviour of recycled wood derived from clean used wood and used destruction wood, as well as pallets, is comparable to that of clean wood. Recycled wood is occasionally relatively dry, its NCV might appear to be higher than that of typical fresh wood fuels (Alakangas et al. 2015). However, since recovered wood has previously been used for various purposes, it is often contaminated. Processing recycled wood is tightly monitored by recycling companies, however, certain non-wooden elements (metals, plastic, stones, cardboard, paper, cardboard) and various surface treatments chemicals, including as paints, lacquers, and siccatives can occur in a mixture of recycled wood (Alakangas et al. 2015; Edo et al. 2016; Strömberg & Svärd, 2012, 66).

The increased quantities of heavy metals in interaction with potassium and chlorine accelerate the production of deposits in the boiler as well as corrosion (Alakangas et al. 2015; Kinnunen et al. 2019). Additionally, the combustion of recycled wood generates ash that can be more problematic compared to clean wood (Alakangas et al. 2015; Strömberg & Svärd 2012, 71-72). As mentioned before, the impact of finer fractions when utilizing recycled wood has been a recognized issue. Also, with finer fractions occurs incomplete combustion, which results in the emission of unburned material along with the ash. (Strömberg & Svärd 2012, 71-72.) Further issues with recycled wood are caused by metal objects of zinc, brass and aluminium in the fuel increasing the risk of plugging primary air openings (Alakangas et al. 2015). The requirements of bed material change in FB boilers increases to prevent sintering when a recycled wood has a high share in fuel mixture. This happens as the contamination in the recycled wood lowers the melting temperature of the ash and bed material, resulting in sticky particles. (Strömberg & Svärd, 2012, 71-72.)

2.3.4 Solid recovered fuels

Solid recovered fuels consist of fuels made from sorted dry solid waste from communities, businesses, or industry. Refuse-derived fuel (RDF) was the most often used term in technical literature before solid recovered fuel (SRF) was introduced. SRF is clearly differentiated from RDF, even though the terms RDF and SRF are sometimes used interchangeably to represent the same waste derived fuel. The main distinction is that SRF is produced in accordance with standards, whilst RDF is not (Nasrullah 2015, 2-4).

All fuels which combustion has been formally sanctioned and proved technologically possible and controlled, which risks can be minimized, and which are cost competitive are potential choice for energy producers. The economic drawbacks need to be considered since adding SRF to the fuel mix can cause the modifications to fuel reception and handling, as well as technical risks resulting from variations in the quality of these fuels. In order to provide a clean and efficient combustion process and not to risk the plant's efficient operation technologically, environmentally and/or economically, it is essential to acknowledge the characteristics of SRF. (Alakangas et al. 2016, 153)

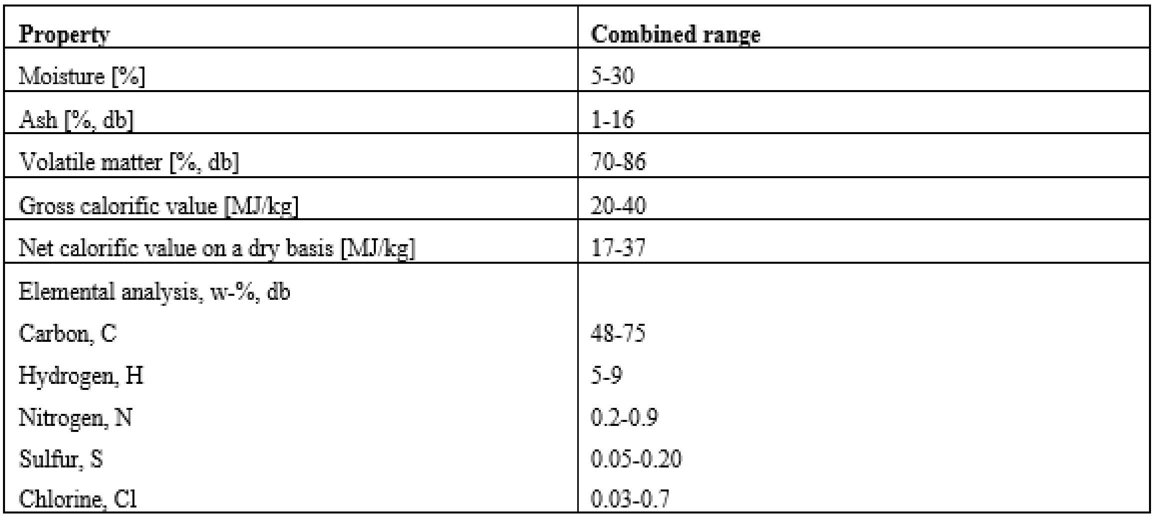
Solid recovered fuel (SRF) is generally obtained from non-hazardous waste after it has been processed, homogenized, and improved in quality so that it may be traded between producers and users (Rada & Ragazzi, 2014). It is intended to be utilized as a source for energy recovery in existing heat and power plants alongside other thermal processes (Alakangas et al. 2016, 151). A variety of waste streams are used to produce SRF, for example production specific waste, municipal solid waste (MSW), commercial and industrial waste (C&IW), construction and demolition waste (C&DW), as well as some other source-separated processed dry combustible fractions (Velis et al. 2013; Ragazzi & Rada 2012; SFS-EN 21640:2021, 8-9). Mechanical treatment (MT) or mechanical biological treatment (MBT) facilities is used to generate the SRF in Europe. Biowaste, metals, stones and PVC-containing plastic have been mechanically separated. (Rada & Ragazzi, 2014.)

Most SRFs are composed of a variety of waste components which can lead to problems for the boiler because chlorine, metals, and other harmful substances impact the combustion and the ashes. In case of high proportion of plastic in SRF the lower moisture content and higher calorific value is achieved due to hydrogen and carbon concentrations. On the contrary, wood in the fuels result a higher moisture content and a lower calorific value. PVC in the fuels result a higher chlorine concentration. Consideration must be given to the possibility of high-temperature corrosion caused by the chlorine component of the fuel at high steam superheating temperatures associated with power generation. Furthermore, the possibility of boiler fouling must be considered, since SRF can contain a higher Na, P and Al concentrations compared to other fuels. Heavy metals have an effect to the emissions and restrict the usage of ash. Furthermore, SRF can affect the melting behaviour of ash of fuel mixes. (Alakangas et al. 2016, 153-154)

The inclusion of household foil items and aluminium in construction trash raises the proportion of aluminium. The most serious issue in terms of combustion is metallic aluminium. Despite having a low melting point, aluminium is difficult to oxidize. In some cases, aluminium in fuel has caused boilers to get blocked. Furthermore, SRF may consists of lead compounds that are extremely fouling and corrosive. When compared to solid biofuels, the concentrations of some heavy metals (Cu, Cr, Zn, and Pb) in filter ash often rise significantly. (Alakangas et al. 2016, 153-154)

The recycled fuel is commonly drier than biofuels, so the capacity of flue gas condenser is lowered, and less condensation water is generated. When a moister biofuel is used with recycled fuel, the capacity of the flue gas condenser and the volume of condensation water remain constant. Overall, the properties of SRF vary broadly, as seen in Table 2.

Table 2. The properties of SRF vary depending on the source of the raw material and the composition of the material (Alakangas et al. 2016, 154)



Property	**Combined range**
Moisture [%]	5-30
Ash [%, db]	1-16
Volatile matter [%, db]	70-86
Gross calorific value [MJ/kg]	20-40
Net calorific value on a dry basis [MJ/kg]	17-37
Elemental analysis, w-%, db	
Carbon, C	48-75
Hydrogen, H	5-9
Nitrogen, N	0.2-0.9
Sulfur, S	0.05-0.20
Chlorine, Cl	0.03-0.7

3 MULTIFUEL OPERATION AT POWER PLANTS

3.1 Industrial Combustion Technologies

Boiler is defined as a steam generator that utilize combustion as its main heat source. The commonly used fluid is water, which is converted to steam by the hot flue gases produced during the process of combustion in heat engines, which convert heat to work. (Vakkilainen 2017, 1-2). The fuel is combusted in the boiler's combustion chamber, often known as a furnace (Basu et al. 2000). Biomass combustion technologies include fluidized bed, fixed bed, and pulverized fuel combustion systems (Obernberger & Biedermann 2013, 351). The basic principles of these technologies are presented in Figure 7. Bubbling fluidized bed (BFB) and circulated fluidized bed (CFB) are introduced more in depth. Figure 8 presents the schematic of a common CFB boiler and the locations of the different components of the boiler.

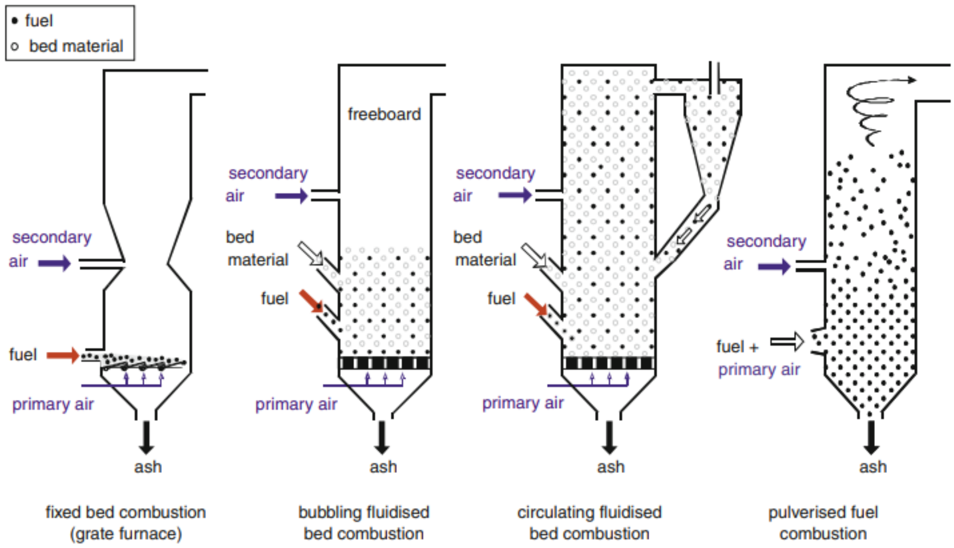


Figure 7. Combustion technologies for biomass. (Obernberger & Biedermann 2013, 351)

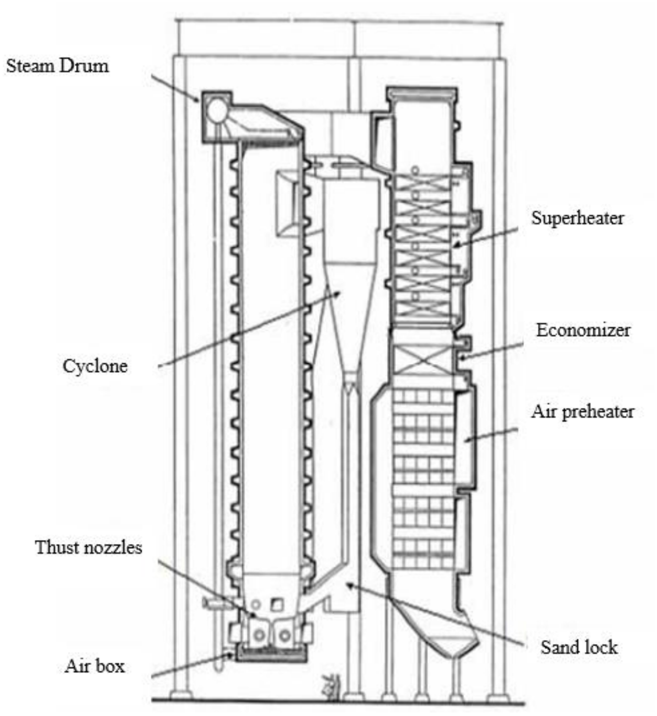


Figure 8. An overview of a CFB boiler (Storesund 2015, 265).

3.1.1 Bubbling fluidized bed combustion

In a boiler with BFB combustion, the combustion of fuel occurs with a bed material, usually made from sorbents, fuel ash or sand that is fluidized (Basu 2015, 6; Storesund 2015, 264; Vakkilainen 2017, 213). In FB boilers biofuel particle mass fraction constitute only 1-5 % of the total mass of all bed solids (Basu 2015, 6; Vakkilainen 2017, 213). Combustion air is supplied through a large number of nozzles in the bottom of furnace. The boiler is designed so that the speed in the furnace is so high that fuel and bed material are fluidized. (Storesund 2015, 264.) As the air is blown through a layer of bed material, the bed becomes completely suspended and begins to behave like a fluid as air velocity increases. When the temperature of the furnace rises, so do the gas velocities. At the bottom of the boiler, the fuel is injected with bed material. (Vakkilainen 2017, 213.) Constant interaction with hot solid particles results in the combustion of fuel. The BFB and CFB boiler can be distinguished as the two main types of FB combustion (Storesund 2015, 264; Vakkilainen 2017, 1-2).

A schematic of typical BFB boiler is shown second from the left in Figure 7. The primary air is introduced evenly through nozzles to the bottom of the boiler. As the fluidizing velocity exceeds the minimum fluidizing velocity, the gas that is not necessary to fluidize bed flows through it as bubbles. (Vakkilainen 2017, 213-214.) In BFB boilers, the air velocity is adjusted so that the fuel and bed material expand to a certain level. Only the finest particles leave the bed and are separated in a dust separator after the boiler. (Storesund 2015, 264.) There is a clear surface level where the bubbling bed ends and the free space above bed, called freeboard, starts (Basu 2015, 9). In BFB boilers, part of the combustion occurs in the freeboard with an increased temperature as a result (Storesund 2015, 264-265).

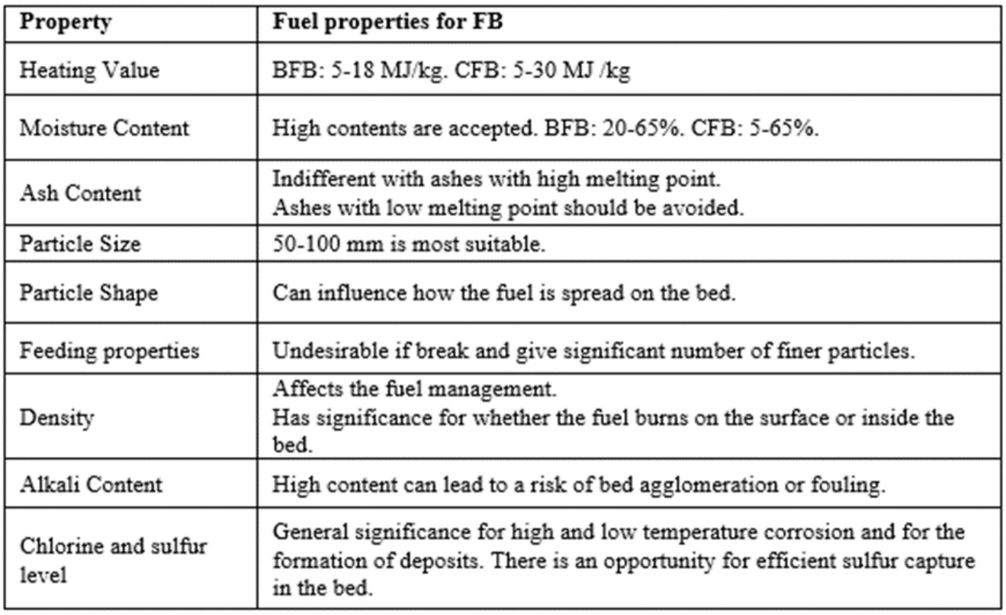
3.1.2 Circulating fluidized bed boiler

A schematic of common CFB boiler is shown in Figure 7 second from the right. In CFB boilers, the air velocity is so high that fuel and bed material follow the air flow (Storesund 2015, 264). The fuel, together with the bed material, is introduced into the furnace’s lower section and is fluidized in the gas flow. Some of solids exits with the flue gases, due to the high-velocity combustion gas. That’s why they are collected with a cyclone and recirculated back to the boiler. (Basu 2015, 5-7.) The finest particles accompany the flue gases and are separated in a dust separator after the boiler (Storesund 2015, 264). The primary combustion air is let in through an air distributor or grate at the furnace surface. In order to complete the combustion, secondary air is entered at some height above the grate. (Basu 2015, 5-7.) Since the bed solids are well blended in the furnace’s height, the stable bed temperature in the range of 800-900 °C is achieved (Vakkilainen 2017, 222).

The advantages of FB combustion include the ability to use mixture of fuels simultaneously, simple, and inexpensive sulfur removal by limestone injection, high combustion efficiency and low NO_x emissions. BFB and CFB boilers are very fuel flexible and a wide variation of solid biofuels with a large variation is moisture content or ash content can be utilized. The CFB does better in terms of environmental performance. FB boilers are suitable for dealing challenging fuels because they are not too sensitive to variation in fuel composition and performs at a low steady temperature. The bed heat capacity aids in dampening the effects of changes in fuel quality. (Vakkilainen 2017, 212)

As non-combustible materials in the fuel can get stuck at the bottom and interfere the fluidization, boilers can only handle limited amounts of them. Fuel must go through pre-treatment in order to remove the metal and other non-combustible parts from the fuel thus reducing the risk of disturbances. Fuels that contain ash with a low melting point entail an increased risk of sintering of bed material. (Storesund 2015, 264.) Table 3 lists further essential fuel properties for FB combustion. The fuel flexibility of the CFB boiler is one of its key features: various fuels can be combusted simultaneously (Basu 2015, 8)

Table 3. Important fuel characteristics for different kinds of combustion technologies (Strömberg & Svärd, 2012, 22)



Property	Fuel properties for FB
Heating Value	BFB: 5-18 MJ/kg. CFB: 5-30 MJ /kg
Moisture Content	High contents are accepted. BFB: 20-65%. CFB: 5-65%.
Ash Content	Indifferent with ashes with high melting point. Ashes with low melting point should be avoided.
Particle Size	50-100 mm is most suitable.
Particle Shape	Can influence how the fuel is spread on the bed.
Feeding properties	Undesirable if break and give significant number of finer particles.
Density	Affects the fuel management. Has significance for whether the fuel burns on the surface or inside the bed.
Alkali Content	High content can lead to a risk of bed agglomeration or fouling.
Chlorine and sulfur level	General significance for high and low temperature corrosion and for the formation of deposits. There is an opportunity for efficient sulfur capture in the bed.

3.2 Supply chain of the fuels

The objective of supply chain of fuels is to generate a biomass fuel from diverse biomass resources that fulfils the criteria of the combustion plant in terms of fuel quality and fuel prices (Van Loo & Koppejan 2008, 54). According to Rentizelas et al. (2009) common biomass supply chain is made up of a series of distinct operations. The following actions are necessary to supply woody biomass from its point of origin to a power plant:

- Harvesting the wood fuels from conventional forestry includes felling, extraction, processing, and comminution of the wood. Depending on the material and local conditions, the type of production processes and order sequence might vary.
- Handling and transporting wood fuels to a location where road transport vehicles may be employed is also required. After transporting the wood fuels to the roadside, it must be loaded onto road transportation vehicles for delivery to the power plant, where the fuel in unloaded from the vehicles.
- Long-term storage of wood fuels is required since many wood fuels have seasonal variability as they are harvested at a certain time of year yet are used at the power plant all year. Additionally, fuel must be kept in the plant to ensure fail-safe operation. The storage location might be at the forest site, power plant or an intermediate location.
- All of the procedures required to manufacture an improved wood fuel from a harvested biomass resource or various types of waste wood are included in fuel pre-treatment, such as particle size reduction. By processing the wood fuel, the amount that can be supplied and the efficiency with which it can be handled will increase. Processing can occur at any point in the supply chain, although it is most commonly done before road shipment and is often less expensive when combined with harvesting. (Rentizelas et al. 2009)

Supply chains of wood chips vary according to the places of chipping and storage and the modes of transport. Forest chips supply chains can be divided into three main types of fuel main according to the place of chipping. The most common method is roadside chipping, in which the forest fuel storage on the roadside is chipped in connection with the storage and delivered directly from the same location by a truck to the energy plant. The second most common is terminal chipping, in which the fuel of several roadside storages is transferred to a terminal, which is larger than the roadside depot. The wood is later chipped at the terminal and delivered to the plant by the truck. The third solution is in-field chipping. The unchipped fuel is transported by the truck from the roadside directly to the plant where the chipping takes place. Instead of chipping, the term crushing can sometimes be used, as especially in in-field and terminal chipping, the fuel is modified to the size of the pieces required by the plant by crushing. (Korpinen et al. 2019 7; Kärhä, K. 2011)

3.3 Fuel quality measurement

The aim for the power plants is to have fuel of consistent and predictable quality. Therefore, measurements and predictions of quality-related fuel properties throughout the production chain are required. (Alakangas 2020, 26) Better understanding of fuel characteristics is also a solution to improve quality in combustion. The importance of determining the quality of forest chips increases with use. In order to optimize new, more accurate power plant processes, it is important to determine the exact quality of the fuel to be burned and the actual energy it contains. (Fridh 2016, 11-15)

The quality assurance is aimed to strengthen trust in material quality by consistently fulfilling the agreed-upon customer needs, which are typically specified in the delivery agreement, or the supplier's product declaration (Alakangas 2020, 26). The result of measuring the fuel properties for determining trade prices is an effective supply chain management allowing for the selection of the most suitable fuels loads or the creation of mixtures of various types of fuels for the current load on the boiler to achieve a consistent fuel quality (Berg & Bergström, 2020). Handling biofuels is challenging as fuel quality varies, so there is natural need to measure the fuel's quality. The fuel quality measurement is usually carried out as the biomass load is delivered to the heating plant (Fridh 2016, 15.) In many older plants, the determination of fuel moisture is still based on sampling and laboratory analyses. By far the largest error in the moisture determination arises from the sampling, so the aim is always to make sampling as representative as possible. (Alakangas 2020, 28-36.)

3.3.1 Measurement needs

Wood quality measurement procedures are regulated in the Finnish Timber Measurement Act of 2013, which applies to unprocessed thinning wood, logs, and canopy pulp, as well as wood chips made from them. Measuring energy wood is covered by the Timber Measurement Act when the quantity to be measured is volume, mass, or number of pieces. The purpose of the law is to guarantee fairness in the energy wood trade and to safeguard the interests of employees, employers and contractors involved in the supply chain. However, the factory measurement specified in the Act does not require the determination of the energy content of forest chips, but the determination of the moisture and calorific value of the fuel is based on an agreement between the energy plant purchasing the chips and the fuel supplier. In large power plants, the energy content of wood chips is used as the basis for payment for trade, but in small plants it is common for fuel to be paid for the basis of measured solid or bulk volume. Moreover, measurement data is essential for the parties involved in the procurement of forest chips but is also valuable for operational decisions and supply chain development in the fuel supply organization.

3.3.2 Measurements before energy plant

In a supply chain of wood chips, a terminal refers to the area where the chipping or transfer loading phase of a fuel batch is preceded and followed by either a road, rail, or water transport phase. In most cases, the unchipped fuel is transported by car to the terminal from where it continues, also by car, to the power plant. In practice, the terminals are very diverse in terms both of material handling and measurements arrangements. For example, for terminals at the upstream end of the supply chain, the most important feature may be better accessibility than the first roadside storage during the downtime. Correspondingly, terminals in the vicinity of power plants may aim for better security of supply and higher plant efficiency compared to direct roadside chipping chains. A prerequisite for higher efficiency is that the terminal can monitor the quality of the fuel during storage and mix the fuel batches from the different fractions to suit each demand situation. (Korpinen et al. 2019, 14)

The purpose of the terminal largely determines which measurement or evaluation methods are used. In a terminal set up near roadside depots, estimation of the amount of biomass and energy content in the depot are often based on measurements taken at the logging site and along the roadside. Some terminals near power plants may use the terminal’s own bridge scale, from the measured mass with possible auxiliary measurements, for example quick moisture measurements), the necessary information is derived about the main properties of the fuel stored in the terminal. (Korpinen et al. 2019, 14)

3.3.3 Measurement at an energy plant

At an energy plant, the first and last measure of fuel load is usually the weighing of the vehicle with a vehicle scale. If the incoming load is wood chips and is immediately unloaded on a conveyor leading to a storage silo, measures are taken at the same time to determine the moisture and further calorific value of the imported fuel. (Korpinen et al. 2019, 13.) The most common method for determining the moisture is oven-drying based on samples taken from the load, in which sampling, pre-treatment and determination of moisture are most often performed in accordance with standards. Mechanical solutions for sampling have also been developed to speed up the procedure and reduce the influence of the sampler on the measurement result (Alakangas 2020, 30).

The weakness of the oven drying method is its slowness (Korpinen et al. 2019, 14.). In addition to oven drying, the so-called rapid measurement methods can be used where the fuel supplier receives feedback on the moisture content of the delivered load. (Alakangas 2020, 22.) A weakness in sampling-based methods, on the other hand, is the poor representatives of the samples for individual deliveries, when only two increments per 50 m^3 of loose or stacked fuel must be collected during unloading the fuel load (Alakangas 2020, 34). Sampling-based methods can be replaced by continuous measurement methods, where all the chips contained in the load are measured from the material flow of the plant’s fuel conveyor. Currently, the only continuous real-time forest chip measurement application in Finland that is in commercial use by power plants (moisture content is the basis for payment) is Inray Ltd’s FUELCONTROL, where the measurement is based on X-ray scanning, in which the radiation is directed into the material stream and the transmitted radiation is measured (Inray Ltd). Other methods that can be applied to continuous measurement and for which there is a commercial application are optical methods and microwave methods (Fridh, 2016).

4 ADVERSE EFFECTS AND TECHNICAL CHALLENGES OF COMBUSTION

Corrosion, erosion, deposit formation, agglomeration is among the most common boiler problems. They are discussed in further detail in this chapter.

4.1 Corrosion

Corrosion is another challenge during boiler operation, here is it outlined to as corrosion that can take place between the fuel feed and the stack on a flue-gas side (Sandberg et al. 2011; Strömberg&Svärd 2012, 409). Corrosion can occur in a combustion plant on nearly all the metal structural parts in contact with the fuel, combustion air, flue gas or combustion residual products. The risk of corrosion is related to the chemical properties of the fuel. (Strömberg&Svärd 2012, 409) Three different types of corrosion are here covered: corrosion of the furnace, superheater corrosion and low temperature corrosion.

4.1.1 Superheater corrosion

Corrosion on superheaters is often caused by combination of high material temperatures combined with low melting phases of alkaline compound phases and reducing atmosphere, which can happen if the fuel is not completely burned before it reaches the superheater. Four main explanations for the corrosion attacks have been identified: the low efficiency of final combustion, the starting melting point of the ash, imbalances on the steam and flue gas side and the high surface temperature of the superheater tubes. The melting point of ash is determined by the ash composition, where the enrichment of potassium and chloride is particularly important. In addition to the steam temperature, the temperature of the superheater tubes is also determined by the flue gas temperature and the construction of the boiler. (Strömberg&Svärd 2012, 409-410)

One form of superheat corrosion is called coal ash corrosion, which originates from firing of coal. However, when boilers are fed with other fuels the same form of corrosion will also occur. Steel exposed to high temperatures in an oxidizing atmosphere forms a thermodynamically stable oxide layer. In case of a high-alloy chrome steel, the oxide layer will be dense and protective. Chlorine-containing salts such as KCl and NaCl are produced, when fuels with high levels of alkali metals such as potassium and sodium, as well as high levels of chlorine are combusted (Henderson et al. 2006). These salts can break down the protective oxide layer and there is a risk of corrosion. (Strömberg&Svärd 2012, 409-410)

4.1.2 Low temperature corrosion

Low temperature corrosion is caused by sulfuric acid, which is produced by the sulfur in the fuel or additives used during combustion. During combustion, SO_2 is formed and a small part of this SO_2 may be further oxidized to SO_3. As the temperature of flue gas goes below certain temperature, gaseous H_2SO_4 is starting to form due to reaction of SO_3 and water vapor. When the temperature of the sulfuric acid’s dew point is exceeded, the gaseous sulfuric acids tend to form an acid mist or is deposited on cold surfaces. (Vainio et al. 2016.) Low temperature corrosion is reported on components such as the dust filters, air preheaters, flue gas ducts, and economizers (Strömberg & Svärd 2012, 411; Vainio et al. 2016)

Strömberg (2006, 45) and Strömberg & Svärd (2012, 411) express that boiler that burn mixed fuels with high moisture content and low combustion temperatures have had problems, while plants that burn clean, dry biofuels have survived without problems. Analysis of coatings shows that all of them contain substances that are typical of low-melting compounds such as sulfur, chlorine and ammonium (Strömberg, 2006, 45; Strömberg & Svärd 2012, 411). Vainio et al. (2016) indicates that the possibility of sulfuric acid dew point corrosion is relatively low during the combustion of low sulfur biomass. However, co-combustion of biomass and SRF can contribute to the formation strongly hygroscopic $CaCl_2$ (Vainio et al. 2016).

4.1.3 Furnace corrosion

Locally reducing conditions can occur when combustion happens in stages increasing the risk of furnace corrosion, which can occur through a variety possible mechanism but is commonly referred to as CO corrosion. CO corrosion gets its name from the fact that it occurs at high CO levels in the gas, which is a direct outcome of oxygen deficiency. A reaction occurring between carbon and metal surface is probably the most important mechanism in CO corrosion. The carbon in the form of CO or other molecule that contains carbon can be absorbed on the metal surface and there begin to react to form pure carbon. Inclusion carbides are formed when this carbon diffuses into the metals. Carbides are describes as compounds of carbon and metal e.g., Fe_3C, $Cr_{23}C_6$, Ni_3C. This is what happens in CO corrosion where the metal alloy is crushed apart by successive formation of inclusion carbides that form their own grains in the metal structure and eventually burst the surrounding metal matrix. (Strömberg&Svärd 2012, 411-412)

4.2 Erosion

Erosion is associated with material felling caused by a flowing gas or liquid that may but does not have to contain solid particles. Erosion damage occurs due to too high gas velocities against a certain surface and / or too high dust contents in the gas that hits the surface. Strömberg & Svärd 2012, 357.) Erosion damage caused by sand is usual in fluidized bed boilers. Even superheaters in the fireplace are prone to erosion. The tube surfaces in the furnace and the cyclones are exposed erosion, as well as the cyclone´s central pipes and tubes, which are placed in bed material. (Storesund et al. 2015, 265.)

4.3 Formation of deposits

There are two main sorts of deposits that can be recognized.: slagging and fouling. Fouling is referred to layers of materials (ash) deposited on the boiler’s convection heat surfaces. When vaporized inorganic elements condense on ash particles and heat surfaces at cooler temperatures, deposition occurs. Slagging occurs when partially fused or completely molten deposits on convection surfaces or the furnace walls are revealed to primarily radiant heat. The partially melted or fused pieces after fly ash depositions has started to melt on heat exchanger surfaces is describes as slag. Slagging and fouling in the radiative sections of steam boilers can lead to decreased heat transfer rate and thus boiler capacity. (Khan et al. 2008; Obernberger&Biedermann 2013, 370-371)

4.4 Agglomeration

Agglomeration happens within the bed itself which is where the particles of the bed tend to be stick together into larger particles (Morris et al. 2018). The fuel’s inorganic alkali components, primarily Na and K, can often react with bed material to form low-melting silicates resulting agglomeration (Bartels et al. 2009). The creation of a melt on the surface of the bed material increased its stickiness, causing an increasing number of particles to bind together and form larger agglomerates (Scala 2018). The formation of agglomerates can cause partial or even total de-fluidization of the boiler (Bartels et al. 2009; Brus et al. 2005; Morris et al. 2018)

Due to sintering this agglomerate may be further reinforced, a process in which the melting of particles and the fusion of agglomerates into large, hardened structures is contributed by high, localized temperatures. This is commonly referred to as coating-induced agglomeration. As enough silica and alkali metals are present in fuel ash to create eutectic melts, the term melt-induced agglomeration is commonly applied. (Morris et al. 2018)

4.5 Load changes

As the load on an FB boiler varies, so do the fuel and air supply. Therefore, the combustion rates are influenced by the changes of distribution of oxygen and temperature in the furnaces as well as the quantities of gaseous compounds and char that remain unburned. The oxidizing and reducing zones, as well as the instantaneous temperature distributions, have an important impact in emissions. Due to the boiler's high heat capacity and fluidized solids temperature fluctuations are delayed during rapid changes in load. (Huttunen et al. 2017)

4.6 Measures to minimize fuel-related operational problems

Knowledge of deposit formation and ash behaviour is critical for optimizing boiler operation and ensuring high plant performance and availability. The proper fuel blend control is a key method for reducing or even avoiding the formation of harmful deposits.

4.6.1 Fuel indexes

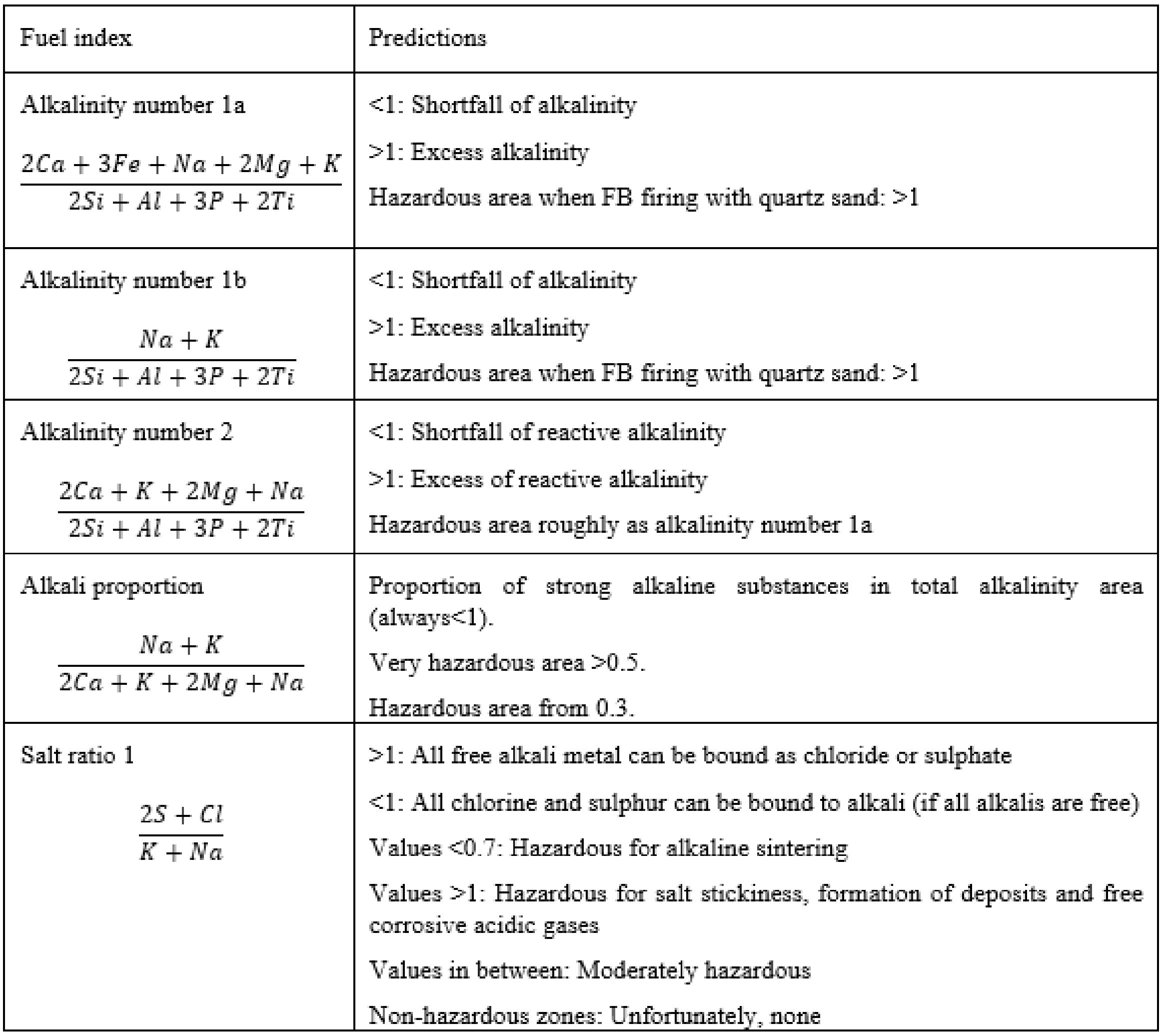
Fuel indexes for biofuels can be used to assess the fuels harmful tendencies. They indicate preliminary information on key combustion features of biomass fuels such as the possibility for gaseous emissions, high temperature risk, the potential for fine particle emissions and deposit formation, and ash melting behaviour. Thus, during combustion, the physical behaviour, chemical reaction processes, and interactions between various components, ideally groups of elements, are all considered. (Sommersacher et al. 2012.) Furthermore, fuel indexes are usually empirical and have been validated using correlations and experiences obtained from pilot-scale and real-scale combustion studies (Obernberger 2014). Fuel indexes based on chemical properties of fuel and ashes allow for the estimation of what can or may have occur (Obernberger 2014; Strömberg 2006, 38).

S and Cl are preferred to form alkaline (K, Na) sulfates and chlorides during combustion. HCl and SO_x. If K and Na are abundant in the gas phase, practically all S and Cl can be bound, with only minor gaseous HCl and SO_x emissions to be predicted. This is the reason (2S+Cl)/(K+Na), known as Salt ratio 1, is so relevant. In the range above 1 increase of the HCl and SO_x emissions has to be expected. In the range below 1 an increase of the alkaline chlorides and sulfates are expected. (Obernberger 2014; Strömberg & Svärd 2012, 403-404)

The fuel index 2S/Cl, known as sulfating number, is probably the key figure that has been most widespread and whose value is often used as income to be able to draw far-reaching conclusions regarding ash chemistry and corrosion. The 2S/Cl gives the ratio between the ability of sulfur and chlorine to bind metals, mainly alkali but also calcium. In order for the sulfating number to give a reasonable interpretation, it is also required that sulfur and chlorine have the same path through the combustion process. In addition, the sulfating numbers assumes that sulfur and chlorine compete for the same alkali metal ions, so Salt ratio 1 needs to be more than 1. If there is an excess of alkali oxides, S and Cl do not compete with each other in the same way for alkali. For clean biofuels, Salt ratio 1 is rarely greater than 1, which is why the value of high sulfation rates when burning clean biofuels is often overestimated. (Strömberg & Svärd 2012, 403-404)

In general, with 2S/Cl ratios greater than 8, no considerable corrosion exists. Corrosion risks increase as the index value decreases, and for values less than 4, risk of significant corrosion must be foreseen (Retschitzegger et al. 2013). However, it is extremely difficult to use only the molar ratio of sulfur to chlorine to make such as assessment. The assumption only applies as long there is no calcium that can absorb the sulfur. Here it is also important to emphasize the role of calcium. If there is an excess of calcium, the sulfur can be adsorbed and relations between sulfur and chlorine based solely on the fuel analysis have no relevance (Strömberg & Svärd 2012, 407). The fuel indices with a brief description of what they predict are shown in Table 4.

Table 4. Fuel indexes with a brief description of what they predict. (Strömberg 2006, 39-40).

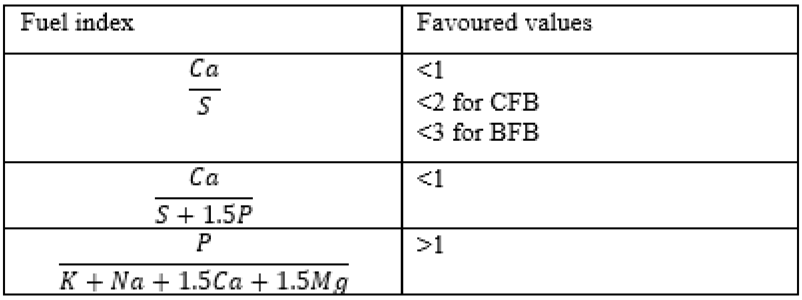


Fuel index	Predictions
Alkalinity number 1a $\frac{2Ca + 3Fe + Na + 2Mg + K}{2Si + Al + 3P + 2Ti}$	<1: Shortfall of alkalinity >1: Excess alkalinity Hazardous area when FB firing with quartz sand: >1
Alkalinity number 1b $\frac{Na + K}{2Si + Al + 3P + 2Ti}$	<1: Shortfall of alkalinity >1: Excess alkalinity Hazardous area when FB firing with quartz sand: >1
Alkalinity number 2 $\frac{2Ca + K + 2Mg + Na}{2Si + Al + 3P + 2Ti}$	<1: Shortfall of reactive alkalinity >1: Excess of reactive alkalinity Hazardous area roughly as alkalinity number 1a
Alkali proportion $\frac{Na + K}{2Ca + K + 2Mg + Na}$	Proportion of strong alkaline substances in total alkalinity area (always<1). Very hazardous area >0.5. Hazardous area from 0.3.
Salt ratio 1 $\frac{2S + Cl}{K + Na}$	>1: All free alkali metal can be bound as chloride or sulphate <1: All chlorine and sulphur can be bound to alkali (if all alkalis are free) Values <0.7: Hazardous for alkaline sintering Values >1: Hazardous for salt stickiness, formation of deposits and free corrosive acidic gases Values in between: Moderately hazardous Non-hazardous zones: Unfortunately, none

Fuel index	Predictions
Salt ratio 2 $$\frac{Cl + 3P + 2S}{K + Na}$$	>1: All free alkali metal can be bound as water-soluble salt. Values <1: hazardous for alkaline sintering Values >1: hazardous for deposit formation or sintering by salt melt
Sulfating number $$\frac{2S}{Cl}$$	<1: All chloride cannot be transformed to sulfate >1: All chloride can be transformed to sulfate Hazardous and non-hazardous areas cannot be easily assigned. Highly process-dependent
Vaporization ratio $$\frac{Cl}{K + Na}$$	>1: All free alkali can be vaporized as chloride (shows the proportion of alkali that can easily be volatile chloride) >0.3: High risk of the formation of chlorine-rich deposits >1: High risk of the formation of other volatile chlorides than with Na and K. Also, high risk of homogeneous chlorine-induced corrosion or low-temperature corrosion with Cl admixture by excess HCl.
Feldspar number 1 $$\frac{2Si}{Al}$$	<6: All silicate can be present as or form aluminosilicate or feldspar >6: Parts of the silicic acid may form alkali silicate with low melting point <6: Generally good >6: Often poor, not always
Feldspar number 2 $$\frac{Al}{K + Na}$$	>1: All alkali is bound or can be bound to the aluminosilicates of feldspar type and with relatively high melting point >1: Often good <1: Often poor
Vitrification number (soda lime glass number) $$\frac{2(K + Na)}{3Si}$$	0.5-1: High risk of the formation of glass phases with low melting points (melting point around 750 °C) 0.2-0.5 and >1: Minor risk <0.2: Small risk (low proportion of melt)
Eutectic number 1 $$\frac{K}{Na + K}$$	Close to 1 or close to 0: Good. 0.2-0.8: Poor.
Eutectic number 2 $$\frac{Ca}{Ca + Mg}$$	Close to 1 or close to 0: Good Close to 0.5: Poor.

The fuel index, Ca/S, indicates whether one can expect a self-absorption of sulfur in the fireplace on a FB boiler. For fuels with low sulfur contents, it is often negative with high Ca/S values because the risk then increases for the formation of alkali chlorides. The calcium reacts with sulfur, which means that the chlorides lose the competition for alkali. The index Ca/(S+1.5P) considers also that calcium reacts with phosphorus. The index P/(K+Na+1.5Ca+1.5Mg) shows whether there is enough phosphorus to be able to replace chlorine with phosphorus in alkali compounds and is important for corrosion. Table 5 summarizes the previously mentioned fuel indices.

Table 5. Fuel index in regards of phosphor and sulfur



Fuel index	Favoured values
$\frac{Ca}{S}$	<1 <2 for CFB <3 for BFB
$\frac{Ca}{S+1.5P}$	<1
$\frac{P}{K+Na+1.5Ca+1.5Mg}$	>1

4.6.2 Additives

In order to avoid alkali-related operational problems, it is important to change the chemical conditions during combustion and thus also the flue gas chemistry. Additives can be utilized to mitigate the potential damages when combusting a problematic fuel that have the potential to cause fouling and corrosion. The additive can prevent the harmful compounds from depositing on boiler surface in variety of ways. The additive can be added to the flue gas or the fuel. (Strömberg&Svärd, 2012, 343-444.)

Binding or adsorbing an alkali can occur by co-combustion with a fuel that contains an ash that can bind alkali e.g., peat, coal, digestate, etc. An additive such as the clay mineral kaolin can also be added. The bed material in a bubbling fluid bed can bind more alkali if the bed temperature is lowered to 750 ° C. Also, sulfur can be added so that alkali chlorides do not form or are converted to alkali sulphates. Sulfur can be supplied by co-combustion with fuels that contain sulfur, such as peat, digestate, rubber tires, coal or adding pure sulfur. Phosphorus has a similar effect as sulfur and can be added e.g., by co-incineration with municipal digestate. When phosphorus is added, alkali chlorides do not form or are converted to alkali phosphates. The enrichment of alkali in the bed of a fluid bed boiler can be reduced by regenerating the bed i.e., addition of a sufficient amount of new sand. Finally, the formation of sticky layers of alkali silicates can be minimized by changing bed material from ordinary quartz-rich sand to an alternative bed material with a less reactive composition. However, there is a risk of increasing the amount of alkali in the flue gas and thus the risk of coatings and corrosion. (Strömberg&Svärd, 2012, 343-444)

It is important to be clear about which problem is wanted to fix and have a good picture of the effect of the measures in the entire plant. Some measures can have positive effects in the furnace, while others may decrease the risk of bed agglomeration but increase the risk of corrosion. For example, you can increase the risk of corrosion and coatings if you bind less alkali in the bed. The various measures taken to change the chemistry thus consists of co-incineration and smart fuel mix, addition of various additives, change of bed material, regeneration of bed material and change the temperature profile in the boiler (Strömberg&Svärd, 2012, 343-444)

5 CASE JÄRVENPÄÄ TESTING DESCRIPTION

5.1 Description of Järvenpää's power plant

Järvenpää's power plant is a high-efficiency multifuel CHP-plant owned by Vantaan Energia (Vantaan Energia). Figure 9 illustrates the primary components of the plant, which include its fuel reception stations and two storage silos, BFB boiler, turbine, generator, heat exchanger, and flue gas condensing unit. Electricity is provided to the national grid by the turbine and generator. The heat exchanger utilizes the heat and recovered heat which is produced from the turbine and the flue gas condenser resulting a rise in the temperature of the water in the local district heat network. (AVI 2020; IRENE 2018, 24)

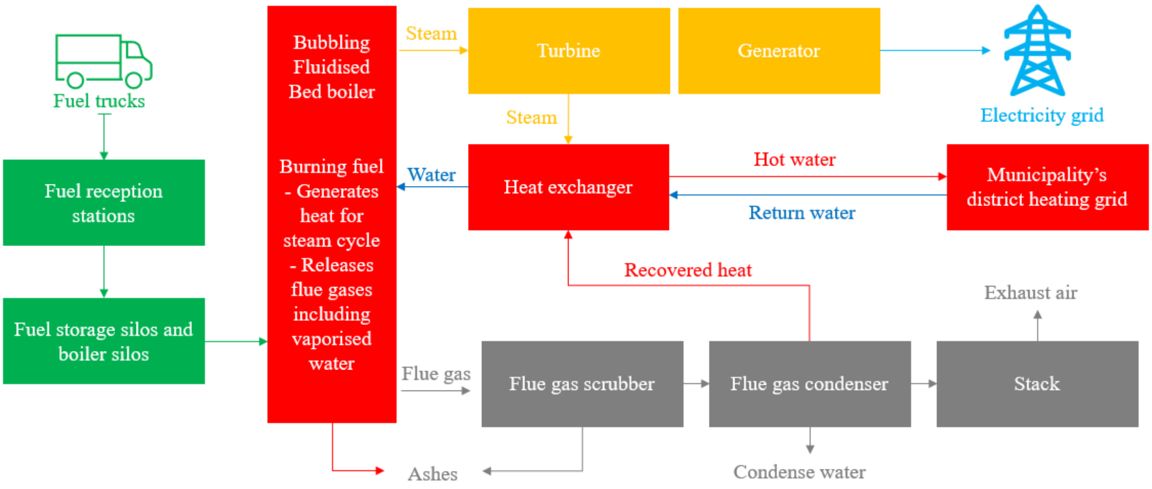


Figure 9. The schematic of the Järvenpää multifuel CHP plant (AVI 2020; IRENE 2018, 25).

Table 6 depicts the maximum capacity of the boiler. The BFB boiler may run with a biomass share ranging from 0 to 100% and a recovered energy waste share ranging from 0 to 30%. The share of different fuels varies according to the operating conditions and the availability of fuels. The share of wood-based biofuels, which are not subject to the waste incineration regulation, varies momentarily between 0-100%. The annual share is 55%. The proportion of waste-derived fuels momentarily varies between 0-60%. The annual share is 45%. The use of waste-derived fuels is not necessarily continuous and only biomass can be used as fuel. (AVI 2020.)

Table 6. The maximum capacities for the boiler (AVI 2020)

Thermal capacity	76 MW_{fuel}
Electricity capacity	23 MW_e
District heat capacity + extra DH by flue gas condenser	45+15 MW_{heat}

5.2 General testing environment description

The testing system consists of two online FUELCONTROL measuring systems, a fuel reception unit, two storage silos, silo feeding and unloading and two boiler silos, as shown in Figure 10. Solid wood fuels and SRF are received and processed separately at their own receiving stations. The system consists of two receiving stations, a scraper conveyor for a screening building, a screen, a crusher, a magnet, a scraper conveyor for storage silos, unloading screws and scrape conveyors to boiler silos. A waste fuel reception system consists of a reception hall, an unloader, a shedder before going to the silo scraper conveyor, a screener/magnet, a crusher, a storage silo, and its silo unloader. The solid wood fuels and waste fuels are mixed on the bucket conveyor right after the storage silos. The screening separates stones, metals, and over-sized particles from the fuel flow. Following the screening, the fuel is kept in an automated storage silo, which serves as a buffer between the boiler silos and the boiler feeding. Screw reclaimers are used to extract the fuel from the silos. X-Ray 1 is installed between the fuel reception unit and the storage silos. X-Ray 2 is installed between a storage silos and boiler silos. The SRF is mixed with the wood fuels after second X-Ray 2.

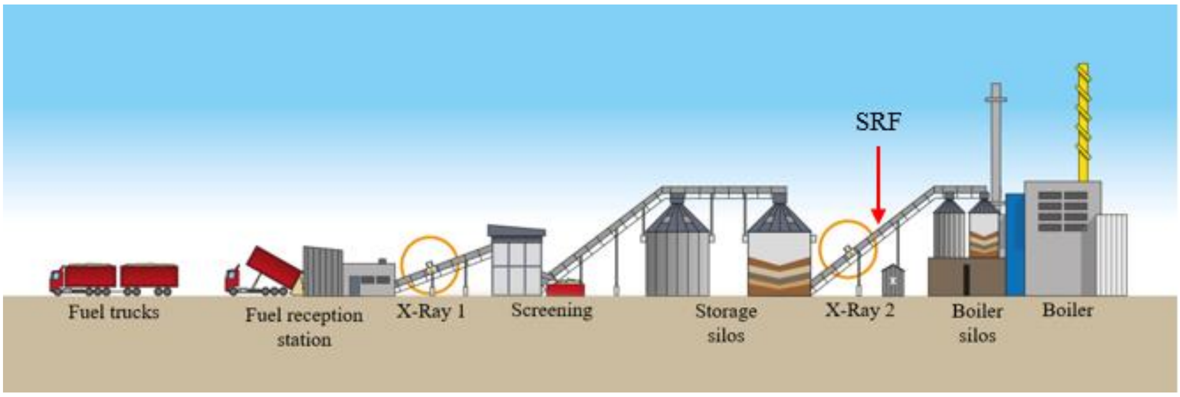


Figure 10. The schematic of components of the testing environment

5.2.1 FUELCONTROL ®

The FUELCONTROL ® system is based on X-ray scanning, with radiation is produced by an electronic radiation source. Radiation is directed through the fuel flow throughout the measurement, and the permeating radiation is measured with a high-resolution sensor. The sensor’s measurement data is utilized to generate X-Ray images, which are then analyzed in real time to evaluate moisture and foreign substances, as well as identify foreign items with a higher density than the fuel (metals, rocks etc.). Laser scanning is used to assess fuel volume flow. (Inray.)

5.2.2 Storage model

Overview of the storage model is shown in Figure 11. The system consists of a FUELCONTROL ® Scanner that measures the moisture, the foreign objects, and the volume of fuel received from the conveyor. A machine vision system can also be added to the fuel reception, which automatically detects different fuel types. The storage model receives online measurement data from the X-Ray 1, as shown in Figure 11, regarding a fuel coming from the fuel reception unit and the control unit is able to continuously calculate from the measurement data at least one of the fuel quality criteria. X-Ray 1 monitor a batch of fuel carried on the conveyor by continuous measuring and supply the storage model with fuel-related measurement data received from the measurement.

The storage model establishes a real-time content model for storage and boiler silos, e.g., two- or three-dimensional model, about its fuel distribution on the basis of at least one of the following fuel parameters: a batch of fuel, a type of fuel, moisture content, foreign matter content, ash content, at least one element concentration, energy content, density, volume, and mass. The model maintains the established content model and updates it real time according to the fuel being supplied and discharged. Furthermore, following data is possible to utilize in the storage model: operating data for the conveyor, identification data for fuel loads, information about supplier, a type and a location, information about a truck scale used for determining the amount of fuel load and other possible information obtained from auxiliary measurements, e.g., operating data for a belt scale or other equipment. The system stores measurement and process data in a database from which it can be monitored using a browser-based interface., as it can be seen from the Figure 12. The plant's distributed control system (DSC) provides information about the surface levels of the storage silos, which informs the silo feeding and a storage model to which part of the silo the measured fuel is delivered and which part of the silo the measured fuel is discharged from.

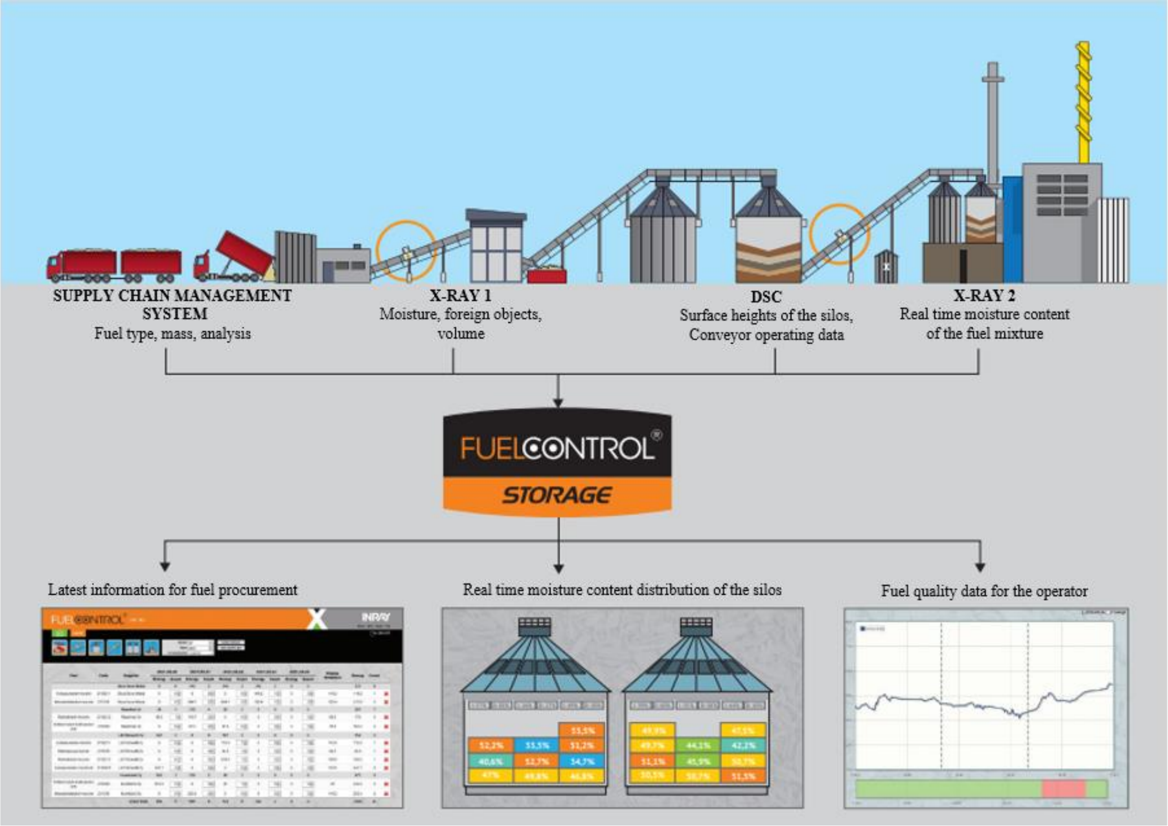
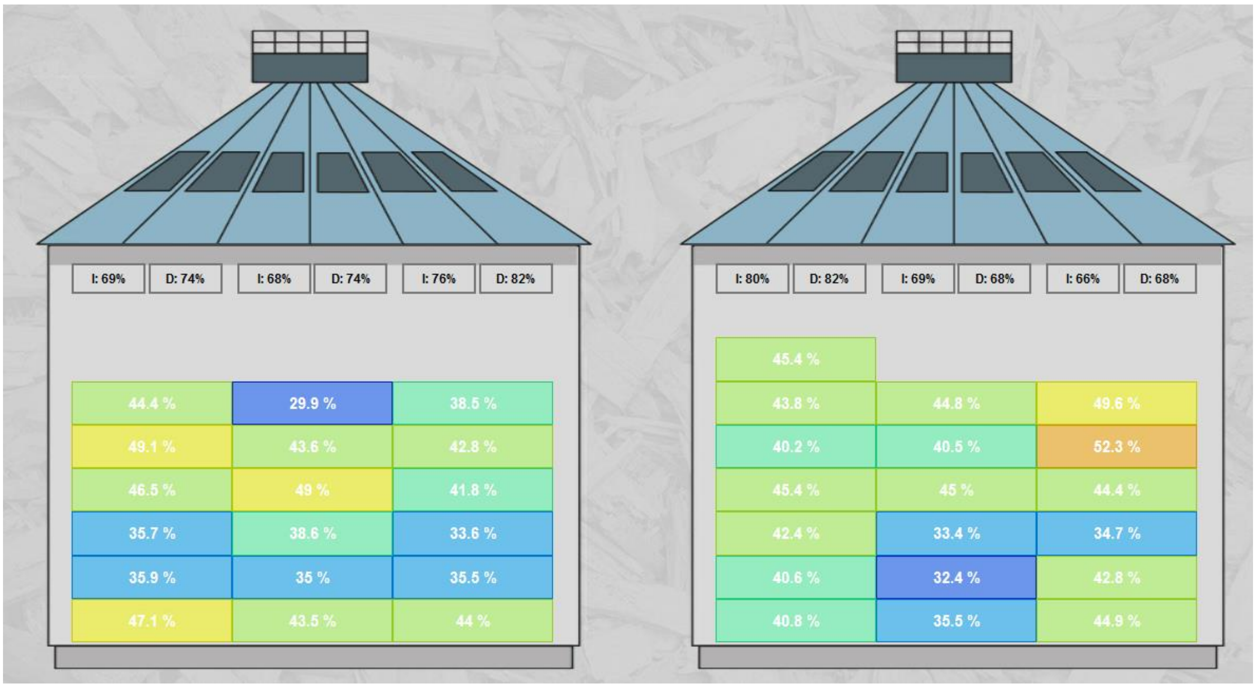


Figure 11. Overview of the storage model

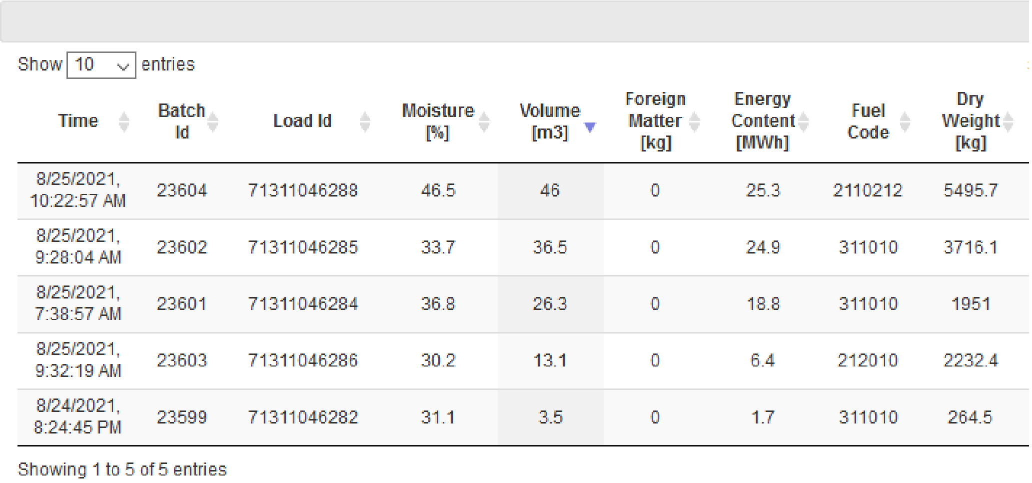


I: 69% D: 74%	I: 68% D: 74%	I: 76% D: 82%
44.4 %	29.9 %	38.5 %
49.1 %	43.6 %	42.8 %
46.5 %	49 %	41.8 %
35.7 %	38.6 %	33.6 %
35.9 %	35 %	35.5 %
47.1 %	43.5 %	44 %

I: 80% D: 82%	I: 69% D: 68%	I: 66% D: 68%
45.4 %		
43.8 %	44.8 %	49.6 %
40.2 %	40.5 %	52.3 %
45.4 %	45 %	44.4 %
42.4 %	33.4 %	34.7 %
40.6 %	32.4 %	42.8 %
40.8 %	35.5 %	44.9 %

Figure 12. The storage model in graphical user interface

The storage model is able to transmit fuel demand information based on the content model of the storage silos. The demand information makes it possible to report which fuel fractions are needed in the boiler for maintaining an optimal fuel distribution. The fuel cubes in the graphical user interface contains all data about the scanned fuel: time stamp, fuel type, energy content, load ID and the moisture, volume and foreign matter measured by X-Ray 1. The example of this is given in Figure 13.



Show 10 entries

Time	Batch Id	Load Id	Moisture [%]	Volume [m3]	Foreign Matter [kg]	Energy Content [MWh]	Fuel Code	Dry Weight [kg]
8/25/2021, 10:22:57 AM	23604	71311046288	46.5	46	0	25.3	2110212	5495.7
8/25/2021, 9:28:04 AM	23602	71311046285	33.7	36.5	0	24.9	311010	3716.1
8/25/2021, 7:38:57 AM	23601	71311046284	36.8	26.3	0	18.8	311010	1951
8/25/2021, 9:32:19 AM	23603	71311046286	30.2	13.1	0	6.4	212010	2232.4
8/24/2021, 8:24:45 PM	23599	71311046282	31.1	3.5	0	1.7	311010	264.5

Showing 1 to 5 of 5 entries

Figure 13. Information that one fuel cube contains

5.3 Baseline situation

Normally, after the X-Ray 1 is measured the fuel load at the reception station, the fuel is fed to the storage silos based on the surface height of the silos. The surface heights of both storage silos are kept close to each other. Both storage silos are usually discharged at the same time unless the heat demand is low. No arrangement regarding of the moisture or fuel composition are done to the storage silos. The feeding rate of SRF is kept constant in relation to wood fuels. As no arrangement is done to silos, the fuel mixture consists of a heterogeneous mixture of different fuel types.

6 METHODOLOGY

Three test drives are organized at Järvenpää power plant to be able to analyse functioning of the storage model and its different factors during May and June of 2021. The methodology used to perform this research, as well as the experimental setup, are outlined and presented in this chapter. The standard sampling and analytical procedures are also covered.

6.1 Test schemes

Generally, the main methodology of verifying a storage silo is that the fuel stream discharged from the storage silos is sampled and analysed and compared to the storage model. A characterization of the output stream of the storage silo in terms of its physical characteristics and moisture content is done and compared to the storage model. The following factors are verified of the upcoming fuel stream: moisture content, volume flow, fuel composition is the same compared to the fuel distribution of the storage model. Moreover, the correctness of the real time according to the fuel being supplied and unloaded is discussed and analysed.

The output of the storage silo is analysed for fuel composition and moisture content and the results are compared with the data produced by the storage model. The composition of the fuel mixture is also compared to the storage model with respect to time, whether the storage model is in real time with respect to the fuel flow, or whether it is ahead or behind. The fuel mixture in the samples is compared to the storage model in terms of whether the sample contains the same fuel fractions as the storage silo shows.

As discussed in the chapter 5.3, the baseline situation is that the storage silos are not arranged according to the moisture or to achieve a certain fuel mixture. This makes it difficult to verify the performance of the storage model, as changes in the quality of the fuel mixture in terms of composition and moisture are minimal and difficult to detect based on visual inspection. The test drives are further explained below. The arrangement was based on the average moisture data provided by the X-Ray 1 for the different fuel fractions from the past month in April 2021. Moisture was not analysed for a longer period of time, because during the winter season the average moistures were higher than usual. As it can be seen from the Figure

14 the driest fuel types were stem wood, recycled wood, and wood chips. Therefore, it was decided that the stem wood, recycled wood, and wood chips are fed to the dryer silos and other fuel types are arranged to the wetter silo. However, the final arrangement depends on the fuel loads ordered by the plant before the planned test drives, which could not be influenced. The fuel names and their corresponding fuel classification number of Statistics Finland is given in Table 7.

Table 7. Fuel codes and the corresponding fuel type

Fuel code	Fuel name
2110212	Stem wood
215010	Recycled wood
2110201	Wood chips B
211030	Forest residues
2110211	Wood chips
2110202	Stem wood
212080	Unspecified industrial wood residue
212010	Bark
212020	Sawdust
212030	Wood residue chips
211040	Crushed stumps

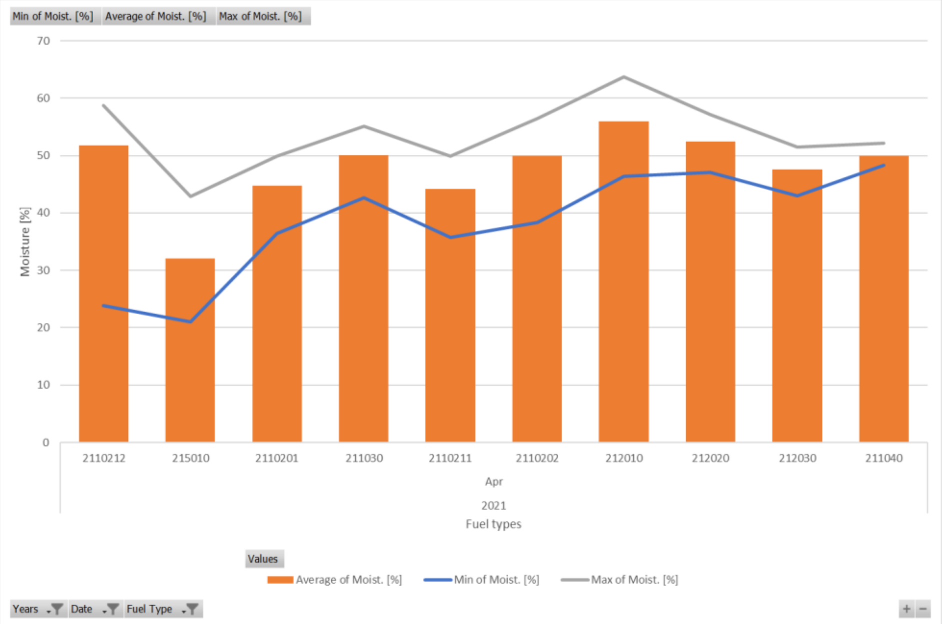


Figure 14. Average moisture values of different fuel types for one month before the test drives

The aim of the first test drive is to detect the shift from the wet layer to dry layer in order to analyse if the storage model updates the model in real time. The aim is to notice the shift in moisture from wetter moisture to dryer and in fuel composition. Two days before the first test drive, the operator is instructed to arrange the storage silos as follows: all loads containing stem wood, recycled wood and wood chips are unloaded in storage silo 1 and all other fuel fractions in the other storage silo 2. Storage silo 1, which is arranged to dry silo, consist of forest residue, bark, and sawdust before the arrangement is started. Only storage silo 1 is being unloaded during the test drive.

Second test drive is performed, when the storage silos are sorted to dry and wet silos. The plant’s operators are instructed to arrange the storage silos following way: recycled wood, wood chips and stem wood are unloaded to other silo and all the other fuels are unloaded to other silo to arrange the so-called wet and dry silo. The aim is to get dryer fuel composition compared to the baseline situation to detect a dryer fuel on X-Ray 2 moisture data and reference samples. Only storage silo 1 is being unloaded during the test drive, since the aim is to measure a dryer fuel mixture compared to the baseline.

Third test drive is performed in baseline situation, where no arrangement to storage silos is performed. The aim is to further analyse the baseline situation of the storage silos, as the first and second test drive is done at special arrangements. In addition, particle size distribution is done for the third test drive’s reference samples to further analyse the fuel composition of the reference samples.

6.2 Sampling methodology

In the test drives the sampling is done after the fuel is unloaded from the storage silos and the X-Ray 2 has measured the fuel stream. Before the sampling location, the SRF is mixed with the wood fuels on the conveyor. The samples are a mixture of wood fuels and SRF and the SRF is sorted manually from the samples before they are analysed since the X-ray 2 measures the fuel before the mixing of SRF. The sampling location is placed to be as close to the X-Ray 2 as possible, as shown in Figure 15.

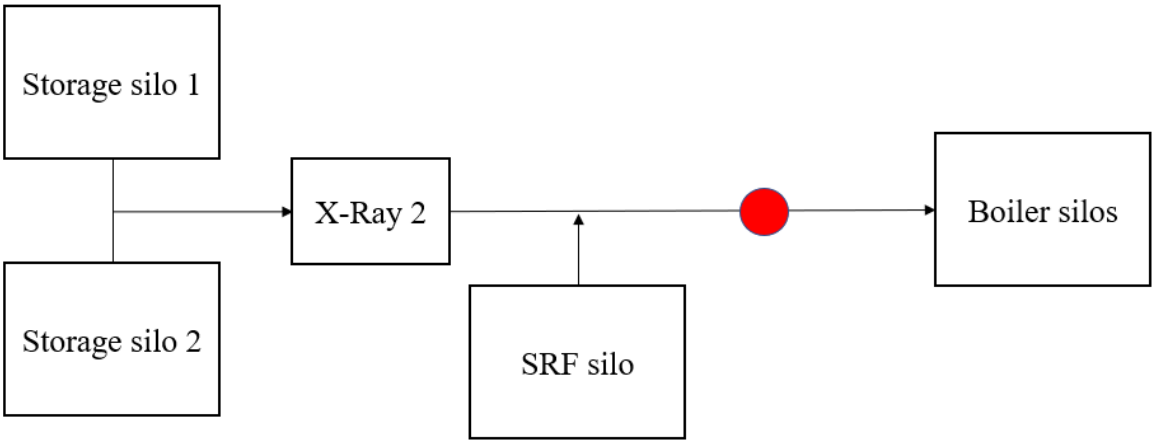


Figure 15. Sampling location of the test drives is marked on a red dot.

All the samples are further treated for their preparation for laboratory analysis according to ISO 18135:2017 standard methods for solid biofuels. The sampling methods used was based on the operating conditions and practical situations of the Järvenpää plant.

The representativeness of samples was ensured by following the standard SFS ISO 18135:2017. The fundamental concept of proper sampling is to get a representative sample of the whole fuel lot under examination. The method applied for the sampling of fuel stream were:

- the sampling was done directly from the fuel stream falling from the load
- the sampling interval is determined so that enough incremental samples are obtained evenly from different parts of the fuel stream
- several smaller increments are taken from the fuel stream
- the entire fuel stream or the majority of it is being subjected to sampling
- the samples are evenly representative of the whole load and no sorting or selection are taking place during sampling. (SFS ISO 18135:2017)

The incremental samples are taken every two or three minutes. Five to six samples are taken at one interval. This is done due to the heterogeneous nature of the fuels, since it is often difficult to take incremental samples in a way that meets the principle of good sampling and that each individual part has an equal probability of being included in the final sample. The samples are taken into closable sample bags. When sample is taken, the sample location

(JAR2) and the time of the sampling (day and time of the day) is written down. This way the sample results can be compared afterwards to the data produced by FUELCONTROL ® online measurement system (X-Ray 1 and 2) and storage model. The long-handled sampling bucket was used to take the samples. The confidence in sampling and analysis of different parameters was founded on the fact that sampling of fuel streams and sample preparation for laboratory analysis were carried out in accordance with standard SFS ISO 18135:2017. The sampling quantities of different test drives are given in Table 8.

Table 8. The sampling quantities taken from the Järvenpää CHP-plant during the test drives

	First test drive	Second test drive	Third test drive
Moisture samples	24	34	33
Fuel composition	30	72	51
Particle size distribution	0	0	33

6.3 Fuel analysis

For the samples taken from the sampling location standard SFS-EN ISO 18134-1:2015 is applied when determining the moisture content of the samples. The particle size distribution for reference samples is done with accordance with the standard SFS-EN ISO 17287-1.

Composition of fuel samples means their breakdown by type of fuel fractions contained (such as bark, sawdust, stem wood, branches etc.). The composition of the fuel samples is determined by means of manual sorting of each sample and visual inspection. Photographs are taken during visual inspection of the samples to assist with the documentation.

7 RESULTS AND ANALYSIS

In this chapter the data from the test drives are reviewed and analysed. Sources of uncertainty, analysis techniques, and their potential influence on the results are also discussed.

7.1 First test drive results

Figure 16 showed the GUI of the storage model at the beginning and at the end of the test drive. The fuels that were at the storage model's first and second layer during the test drive are given in Table 9. The storage silo consisted of five fuel loads of stem wood, one fuel load of bark, two fuel loads of forest residue, one fuel load of sawdust, and one fuel load of recycled wood. The moisture of the Fuel ID 4 was 53,86%, which was higher compared to other stem wood loads. Furthermore, as the Fuel ID 4's fuel composition is analysed based on the pictures of the fuels provided by the X-Ray 1 camera, it is a mixture of stem wood, bark and sawdust. Appendix 1 showed the pictures taken from the reference samples during the first test drive.

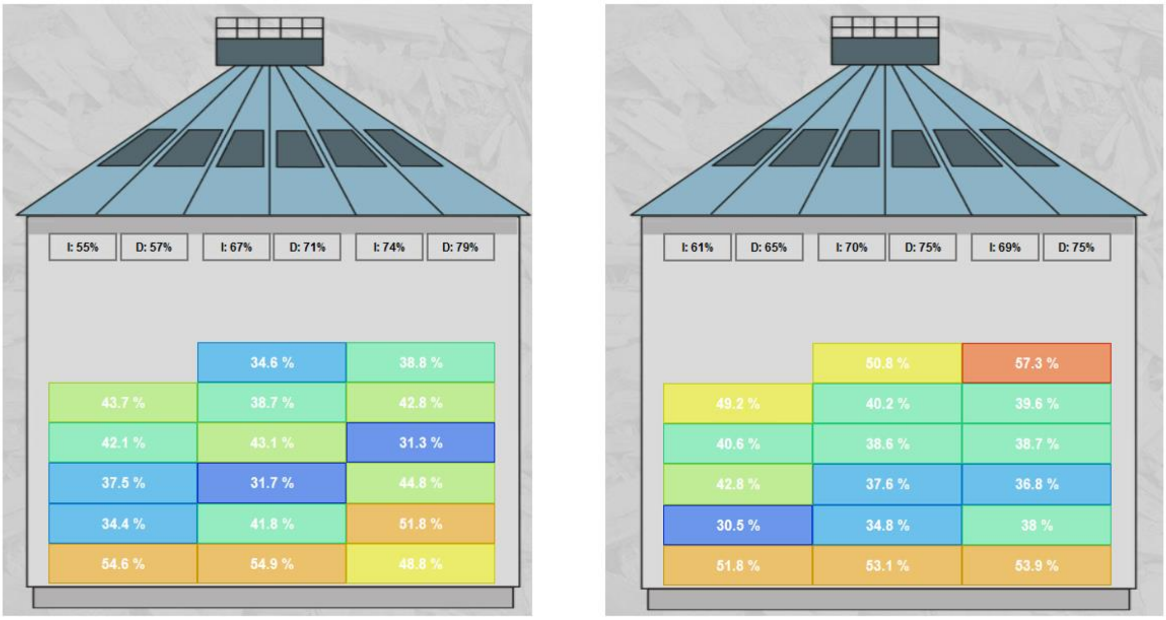


Figure 16. The storage model in graphical user interface at the beginning of the test drive and the end of the test drive

Table 9. Fuel loads that were in the first and second layer of storage model during first test drive.

X-Ray 1 moisture [%]	Fuel ID	Fuel type	Fuel name
43.72	1	2110212	Stem wood
57.25	2	212010	Bark
43.75	3	2110212	Stem wood
53.86	4	2110212	Stem wood
46.31	5	211030	Forest residue
45.46	6	211030	Forest residue
57.1	7	212020	Sawdust
46.01	8	2110212	Stem wood
30.81	9	215010	Recycled wood
29.62	10	2110212	Stem wood

The X-Ray 2 moisture measurement data is given in Figure 17. The average moisture content of the fuel mixture during the first test drive was 42%. No major variation was achieved in moisture content measured by X-Ray 2 during the first test drive.

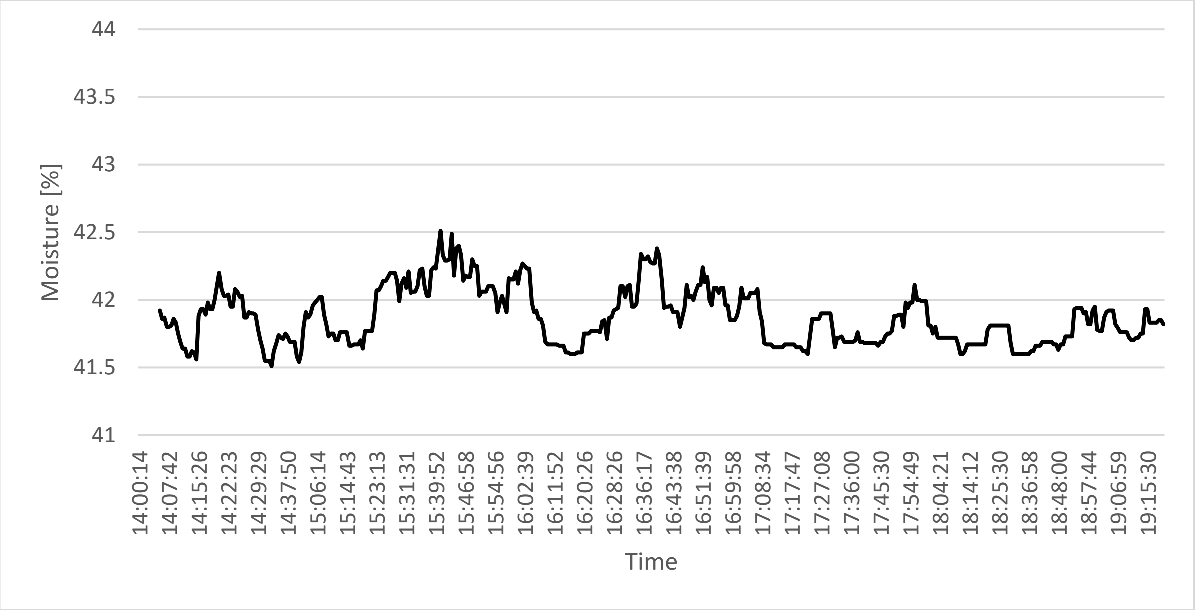


Figure 17. X-Ray 2 measured moisture data

The first test drive consisted of 28 reference samples which were collected within five hours. The moisture of the reference sample, X-ray 2 measured moisture and the average moisture of first and second layer of the storage model and the average of both layers are shown in the Figure 18.

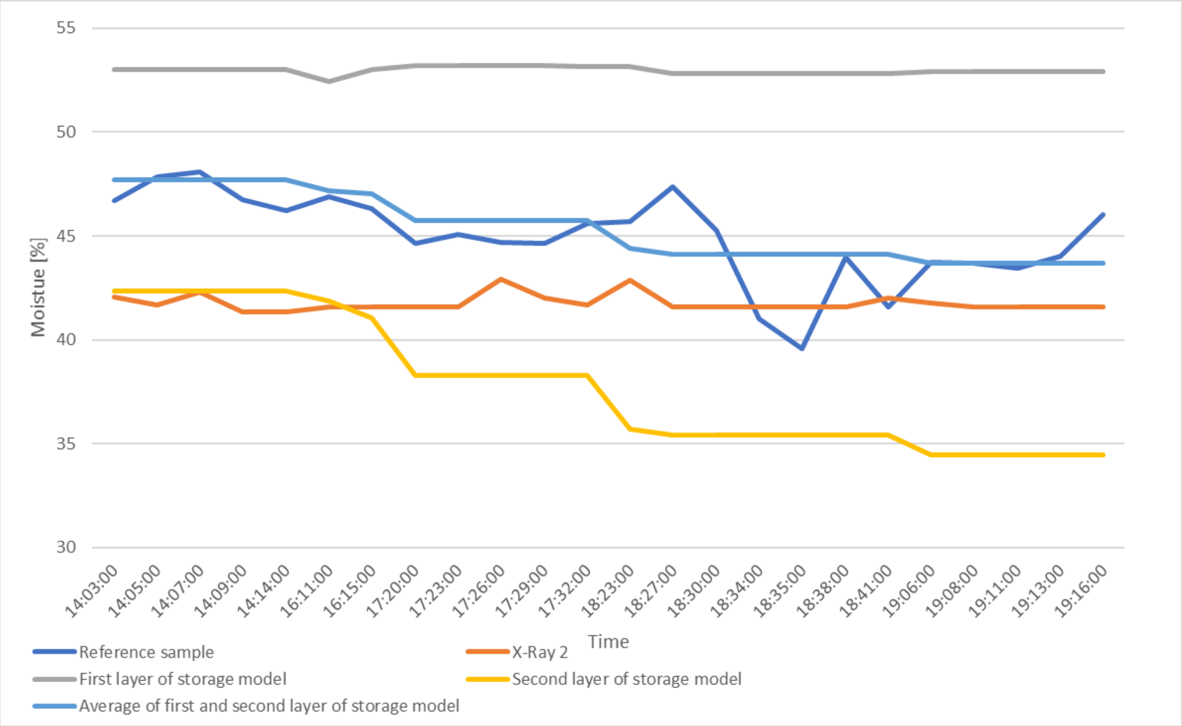


Figure 18. Moisture values during first test drive

As it can be seen from the Figure 18, the moisture remained relatively constant in the reference samples, X-ray 2, and the storage model's first and second layers. The moisture value of first layer of the storage model was within 4-13 % higher compared to reference samples. The moisture value of second layer of storage model was 4% lower at the beginning, but the difference increased to 10% as the second layer of storage model was shifting drier. The average moisture of first and second layer of storage model was within 2% compared to the reference samples and is therefore the most accurate, when the storage model's moisture values are compared to the moisture values of reference samples. The moisture data measured by X-Ray 2 remains the steadiest during the test drive. Furthermore, it measures the moisture on average 5% dryer compared to the reference samples. The moisture of the reference samples lowers under 45% approximately at 18:30 and stayed there for a while but increased back to 45% at the end of the test drive. It seems that a storage silo discharged momentarily drier fuel mix. As the Figure 18 is compared to Figure 19, from the moment of 18:27 to 19:13 there was a recycled wood in the fuel mix, increased share of stem wood and decreased share of bark, which can explain the dryer moisture values. The fuel composition of reference samples is presented in Figure 19.

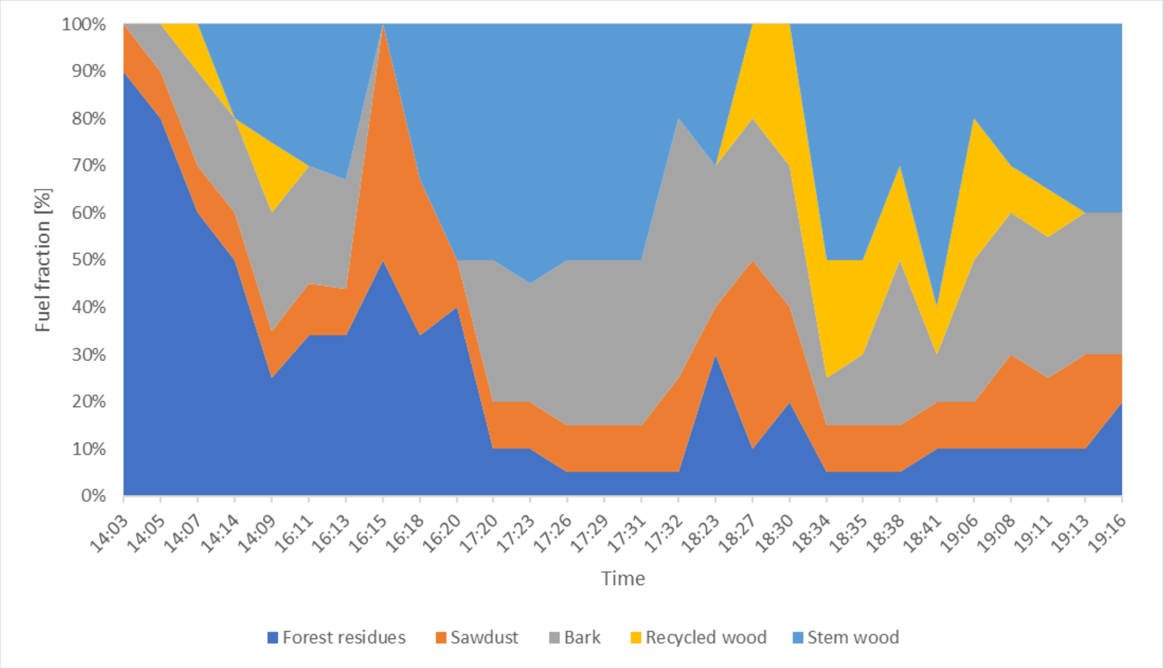


Figure 19. Fuel composition of reference samples during first test drive

As it can be seen from the Figure 19, the reference samples consisted of forest residues, sawdust, bark, recycled wood, and stem wood. The share of sawdust remained constant, being on average 15%. The share of forest residue was at the beginning of the test drive 90% but it decreased throughout the test drive, but the most notable decrease seems to happen after 17:20. At the end of the test drive, the share of forest residue varied from 10-20%. The share of bark varied throughout the test drive from 10% to 55% being on average 23%. The share of stem wood varied from 20% to 60% being on average 30%. Recycled wood wasn’t found in each reference sample, but at 18:23 the share of recycled wood started to be consistent in the reference samples from 20% to 30%. In addition, the share of recycled wood and stem wood began to increase momentarily at 18:23. The fuel composition of the first layer of the storage model is presented in Figure 20.

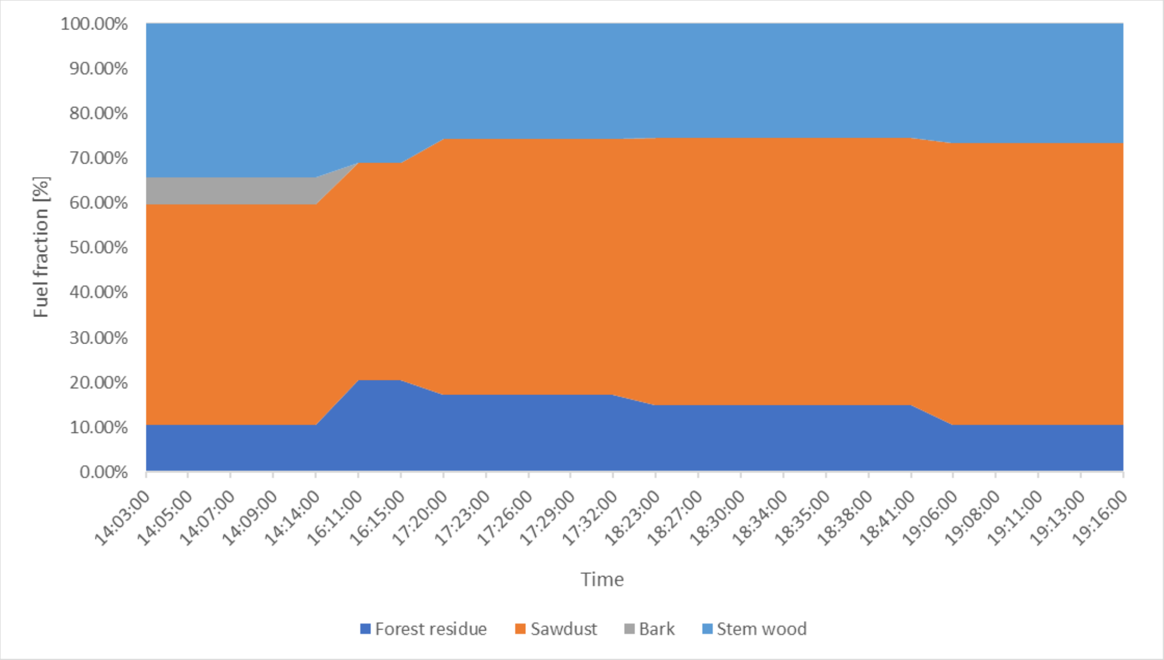


Figure 20. Fuel composition of first storage layer in storage model during first test drive

The first layer of the storage model consisted of forest residue, sawdust, bark, and stem wood. The share of forest residue varied from 10% to 21%. The share of the sawdust varied from 49% to 63% and had the largest share in the first layer of the storage model. The share of bark was almost non-existent, the share was 6% from 14:03 to 14:14, before it was completely unloaded from the storage model. The share of stem wood was at the beginning 34% and it decreased little throughout the test drive and at the end of the test drive, the share of stem wood was 27%. The fuel composition of the second layer of the storage model is presented in Figure 21.

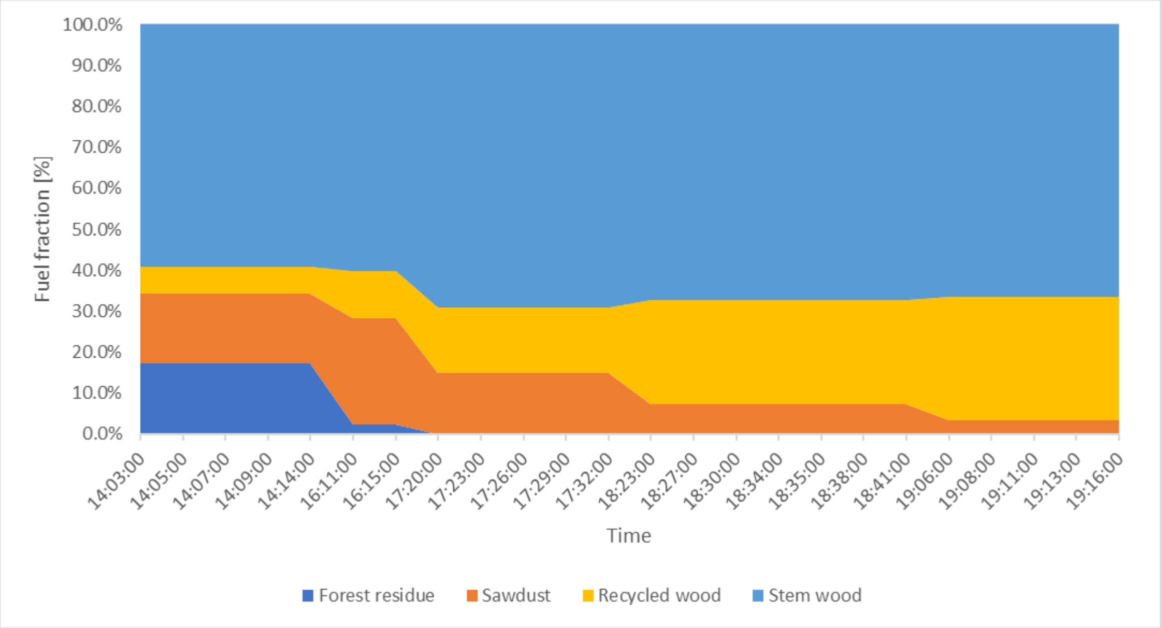


Figure 21. Fuel composition of second storage layer in storage model during first test drive

The second layer of storage model consisted of forest residue, sawdust, recycled wood, and stem wood. The second layer consisted of the share of 17% of forest residue at the beginning of the test drive, but at the 16:15 the share of forest residue dropped to 2%. The share of sawdust was at the beginning 17% and it decreased throughout the test drive to 3%. The share of recycled wood was at the beginning of the test 7% and the share increased throughout the test drive to 30%. The share of stem wood stayed relatively constant throughout the test drive varying from 59% to 69%. The average fuel composition of first and second layer of the storage silo are shown in Figure 22.

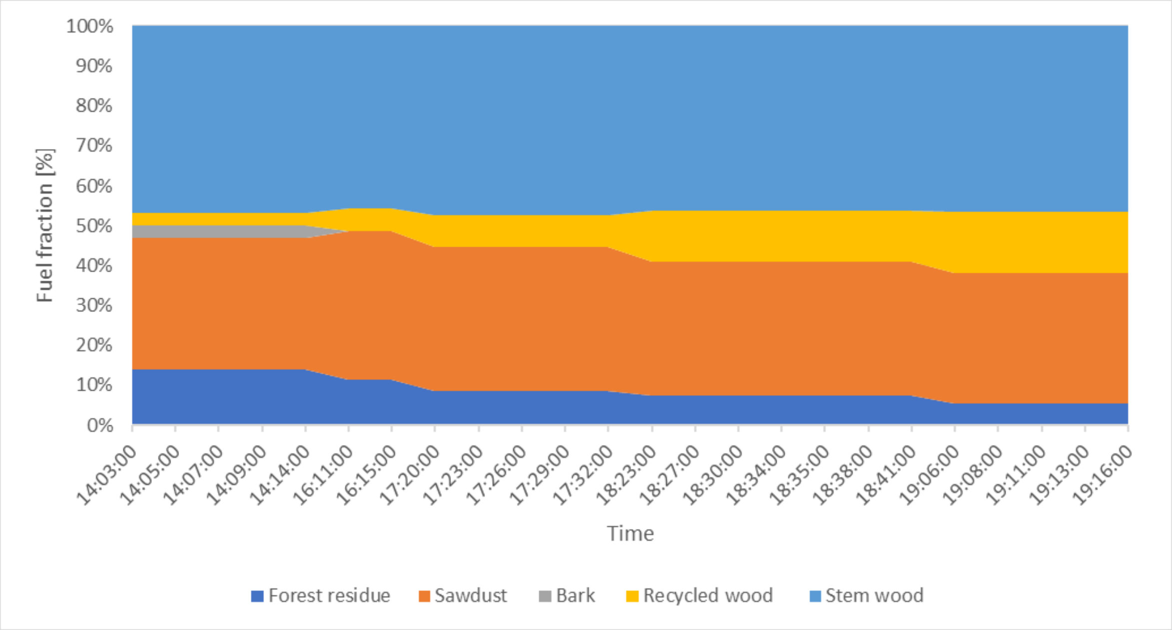
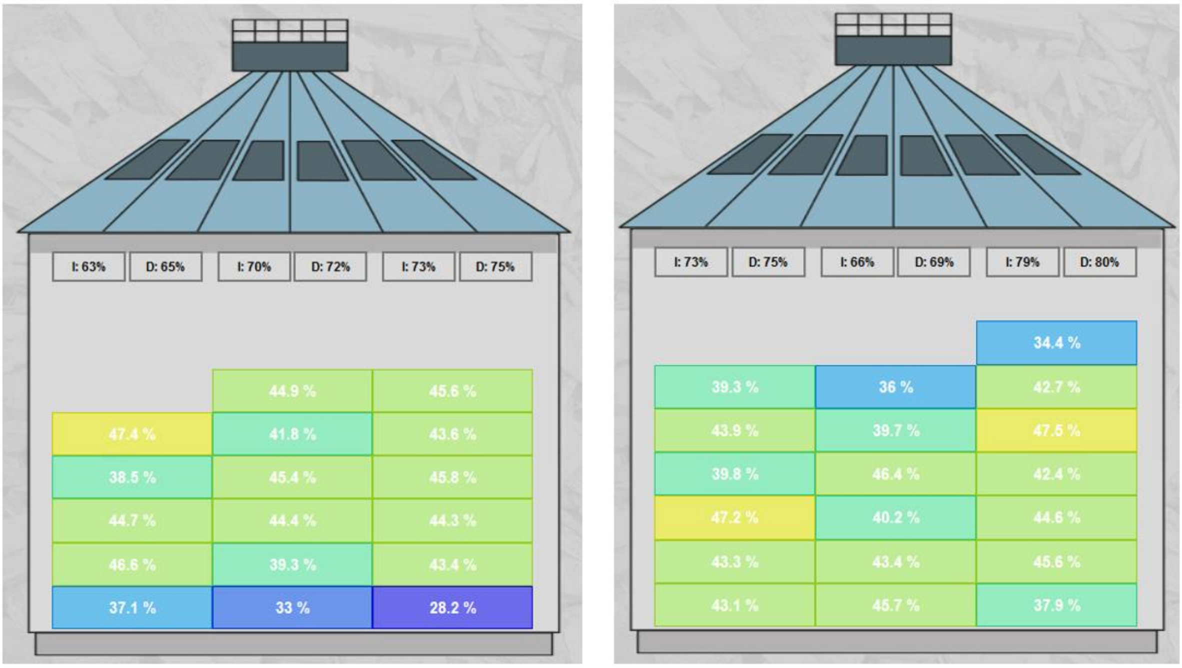


Figure 22. Average fuel composition of first and second storage layer during first test drive

As it can be seen from the results, during the first test drive the shift from wetter fuels to dryer fuels couldn’t be detected in the reference samples. Due to the production process of the plant, it wasn’t possible to speed up the unloading speed of the screw reclaimer. Also, the sampling time at the plant couldn’t be prolonged so that the dryer layer in the storage model would have shifted to the lowest level (first layer) in the storage model. However, it was still possible to generally analyse the operation of the storage model on the results. The fuel composition of reference samples had larger variation compared to storage model, as the fuel composition at the storage model stayed relatively constant during the testing period. The share of bark was considerably larger in the reference samples compared to the storage model, since the storage model doesn’t contain bark at all after 14:14. Also, the recycled wood was inspected in the reference samples. However, at the first layer of storage model the fuel cubes didn’t contain any recycled wood. The recycled wood was only present at the second layer of storage model. Therefore, the results indicated a possibility of mixing of different fuel fractions between the first and second layer of storage model or the storage model was slightly behind. Since the storage model’s fuel cubes and layers are only directive and not absolute prediction, this can be expected.

7.2 Second test drive results

After the first test drive, modifications to the volume flow of the unloaded fuel in the storage model was made as it was found out to be too small. Figure 23 showed the GUI of the storage model at the beginning and at the end of the test drive. As it can be seen from the Figure 23, at the beginning of the test drive, according to the storage model, there was a dryer layer of fuel mixture, which was unloaded completely during the test drive and the first layer shifter to wetter. The fuels that were at the storage model's first and second layer during the test drive are given in Table 10. The storage silo consisted of five fuel loads of stem wood, one fuel load of wood chips, one fuel load of sawdust, and four fuel loads of recycled wood. The aim was to reach dryer fuel composition to the storage silo; however, fuel loads' Fuel ID 5 and Fuel ID 9 were wetter than average compared to other fuel loads. Appendix 2 showed the pictures taken from the reference samples during the second test drive.



I: 63% D: 65%	I: 70% D: 72%	I: 73% D: 75%
	44.9 %	45.6 %
47.4 %	41.8 %	43.6 %
38.5 %	45.4 %	45.8 %
44.7 %	44.4 %	44.3 %
46.6 %	39.3 %	43.4 %
37.1 %	33 %	28.2 %

I: 73% D: 75%	I: 66% D: 69%	I: 79% D: 80%
		34.4 %
39.3 %	36 %	42.7 %
43.9 %	39.7 %	47.5 %
39.8 %	46.4 %	42.4 %
47.2 %	40.2 %	44.6 %
43.3 %	43.4 %	45.6 %
43.1 %	45.7 %	37.9 %

Figure 23. The storage model in graphical user interface at the beginning of the test drive and the end of the test drive

Table 10. Fuel loads that were in the first and second layer of storage model during second test drive.

X-Ray 1 moisture [%]	Fuel ID	Fuel type	Fuel name
35.5	1	2110211	Wood chips
47.45	2	212020	Saw dust
22.22	3	215010	Recycled wood
37.55	4	215010	Recycled wood
50.05	5	2110212	Stem wood
22.17	6	215010	Recycled wood
44.96	7	2110202	Stem wood
45.3	8	2110212	Stem wood
50.05	9	2110212	Stem wood
37.55	10	215010	Recycled wood
33.68	11	2110212	Stem wood

The X-Ray 2's moisture measurement data is given in Figure 24. The average moisture content of the fuel mixture during the first test drive was 43%. The measured moisture varies between 43,0-46,3%, so the moisture stays relatively constant and no major variations in moisture could be achieved in X-Ray 2.

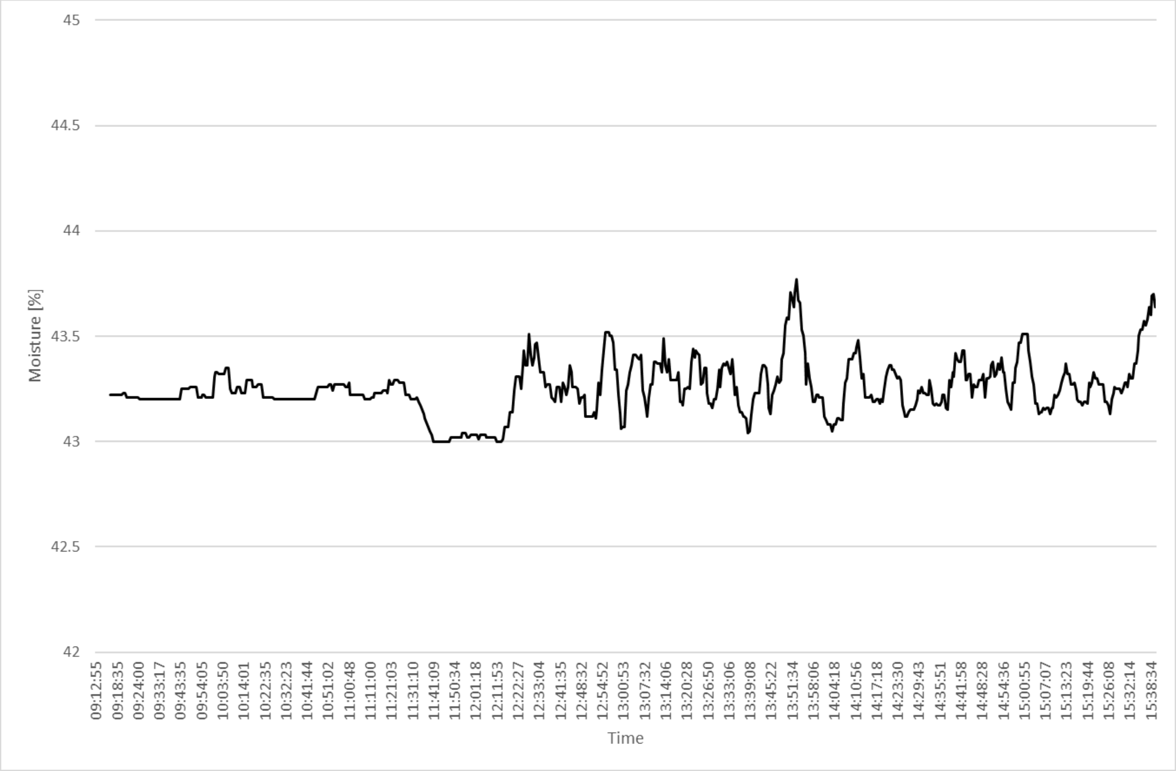


Figure 24. X-ray 2 moisture measurement data

The moisture of the reference sample, X-ray 2's measured moisture and the average moisture of first and second layer of the storage model and the average of both layers are shown in the Figure 25.

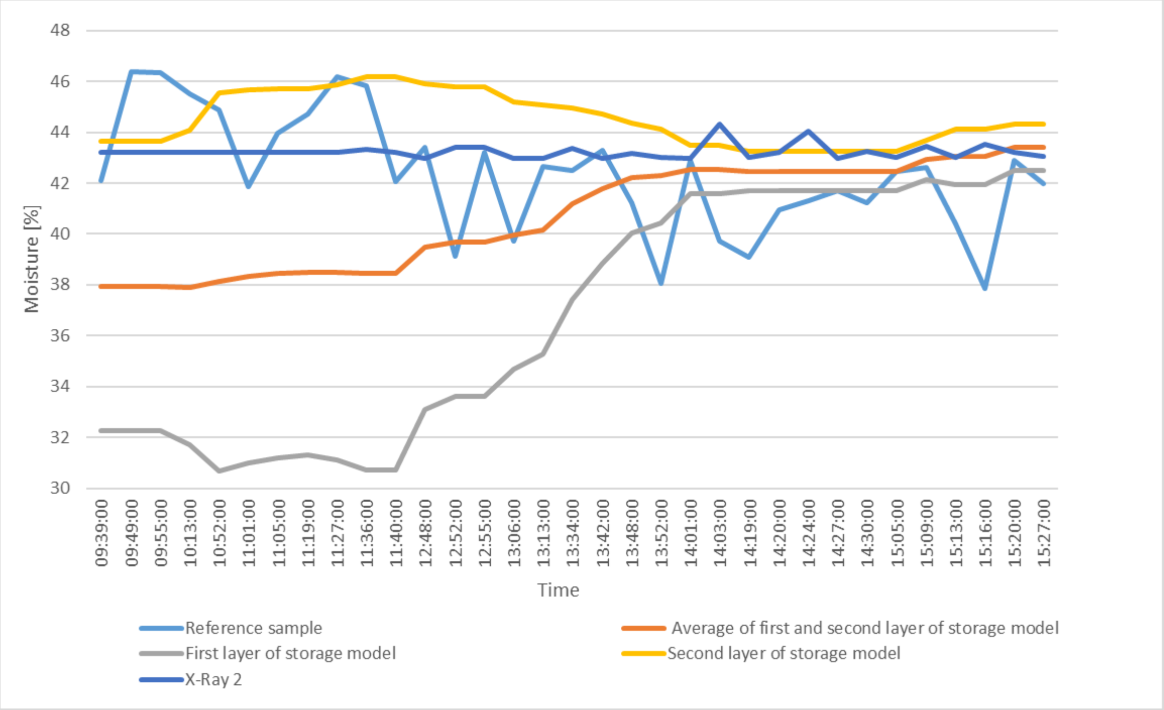


Figure 25. Moisture values during second test drive

As it can be seen from the Figure 25, the moisture values fluctuated more compared to the first test drive. The moisture of reference samples varied from 38% to 46%. However, when the moisture of reference samples was compared to the moisture results of one interval sampling period, the moisture content remained more constant. Largest difference occurred between the first layer of storage model and the reference samples at the beginning of the test drive. The moisture of first layer in storage model was over 10% dryer compared to reference samples. However, the difference begins to decrease approximately at 11:40 and at 14:01 the difference is only 1,3%. The fuel composition of reference samples is presented in Figure 26.

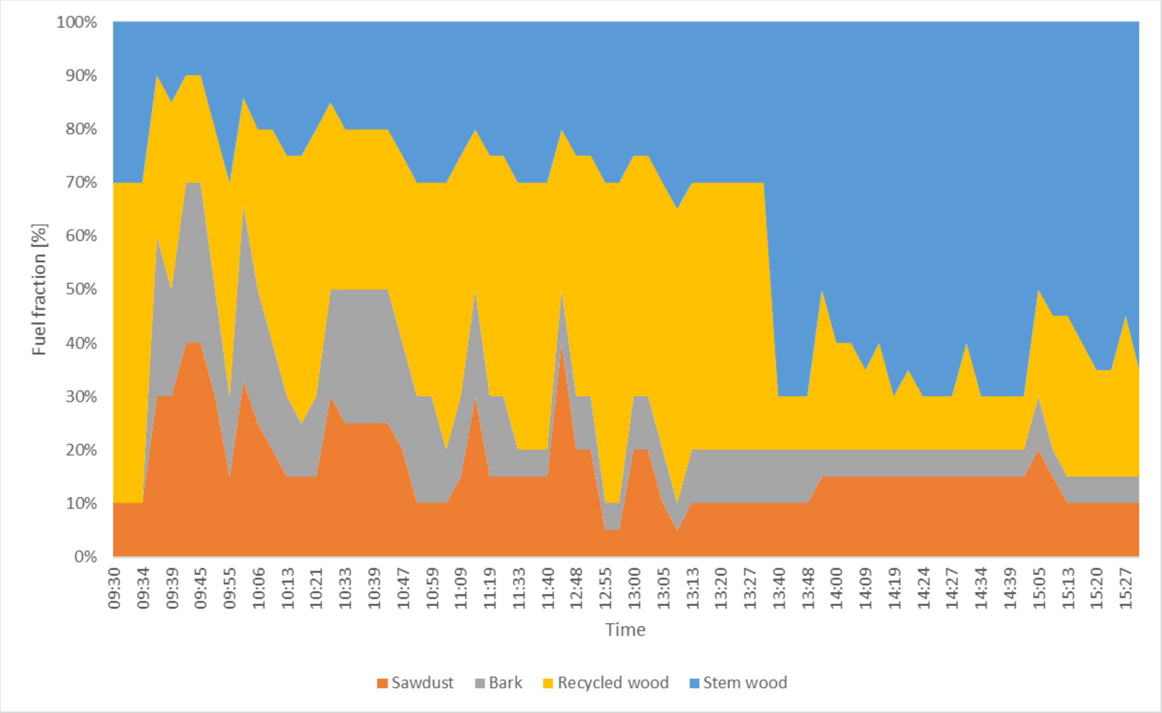


Figure 26. Fuel composition of reference samples during second test drive

As it can be seen from the Figure 26, the reference samples consisted of sawdust, bark, recycled wood, and stem wood. The share of sawdust varied from 5% to 40% being on average 17%. The share of bark varied from 0% to 33% being on average 11%. The share of recycled wood varied from 10% to 60% being on average 33%. The share of stem wood varied from 10% to 70% being on average 39%. The share of stem wood increased during the test drive, while the share of recycled wood decreased. The share of bark slightly decreased while the share of sawdust remained quite constant in the samples. The fuel composition of first layer of storage model is presented in Figure 27.

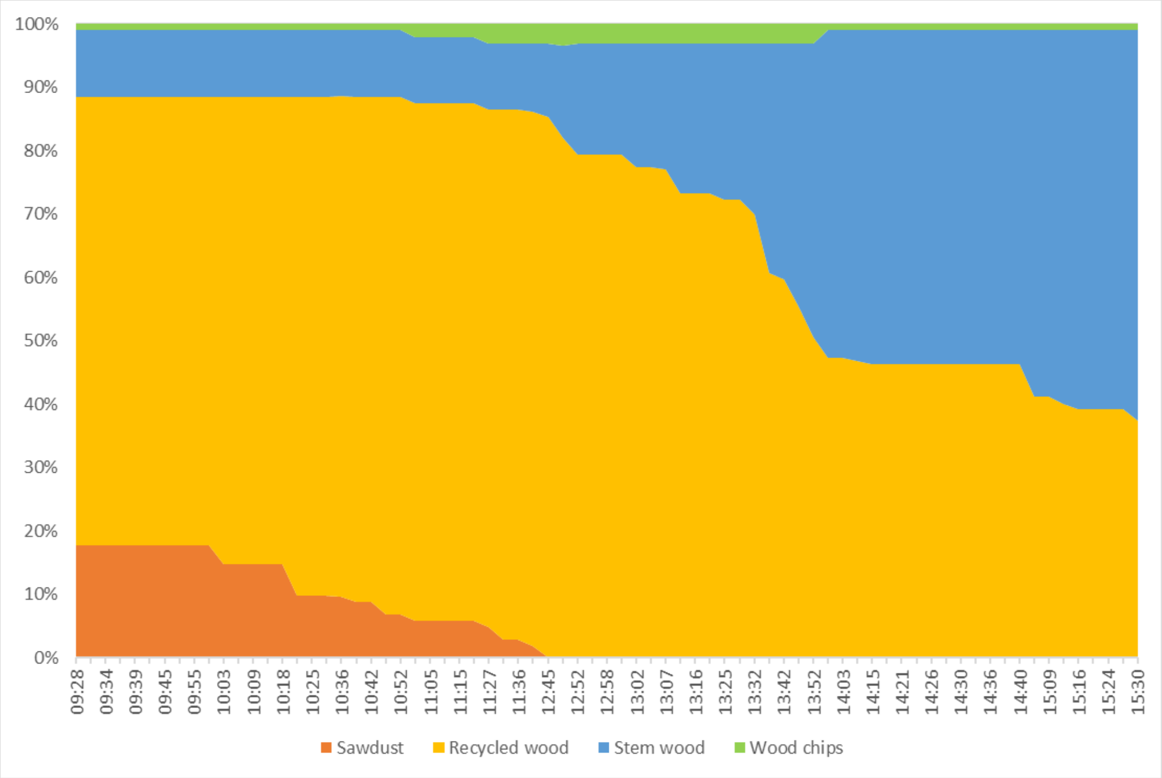


Figure 27. Fuel composition of first layer of storage model during second test drive

The first layer of storage model consisted of sawdust, recycled wood, stem wood and wood chips. The share of sawdust was at the beginning of the test drive 18%, but it was completely unloaded from the storage model at 11:40. The share of recycled wood was at the beginning of the test drive 71% and increased to over 80% from 10:39 to 12:48, followed by the steady decrease of the share of recycled wood. At the end of the test drive the share of recycled wood has dropped to 37%. The share of stem wood was at the beginning of the test drive 11%. The share of stem wood started to increase at 12:45 and at 13:40 the share of stem wood increased instantly over 10%. At the end of the test drive the share of stem wood was 62%. The share of wood chips was minimal throughout the test drive from 1% to 3%. The fuel composition of the second layer of the storage model is presented in Figure 28.

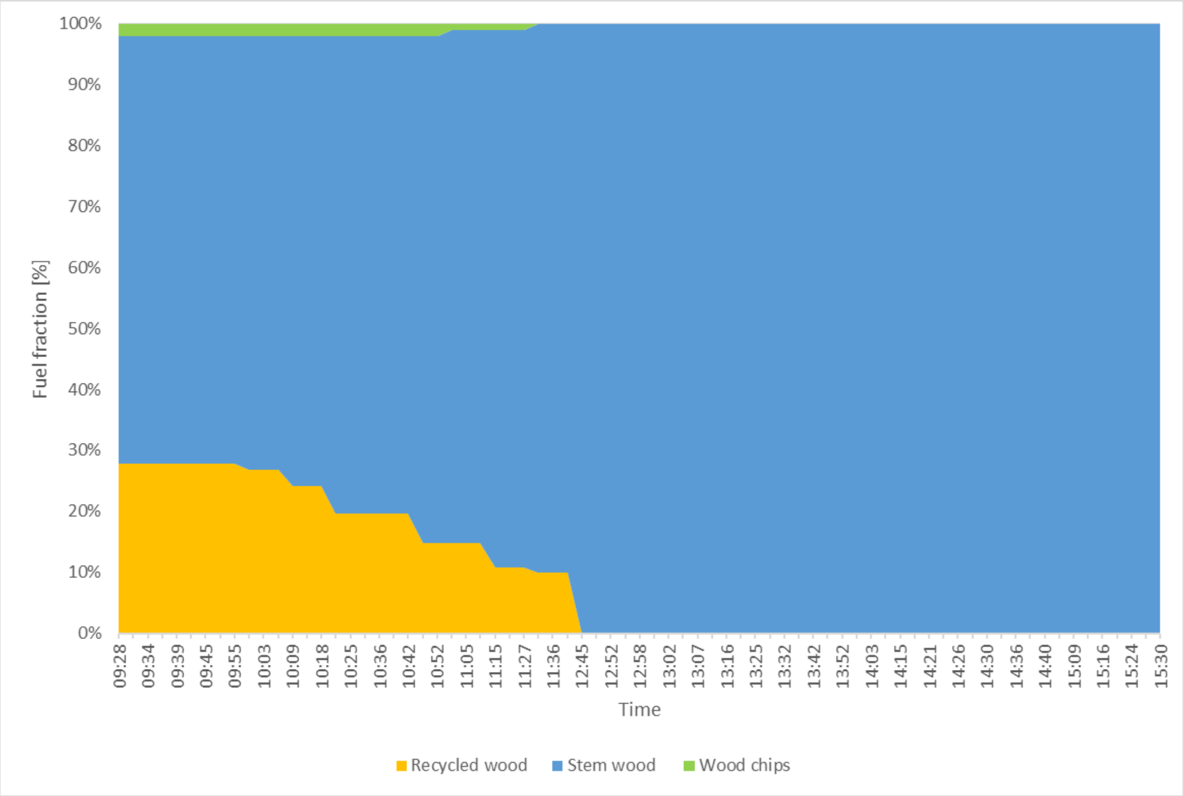


Figure 28. Fuel composition of second layer of storage model during second test drive

The second layer of storage model consisted of recycled wood, stem wood and wood chips. The share of wood chips was 1% at the beginning of the test drive and at 11:27 the wood chips was unloaded completely from the second layer of the test drive. The share of recycled wood was at the beginning of the test drive 28% after which the share of recycled wood started to decrease. The recycled wood was completely unloaded from the second layer of the storage model at 11:40. The share of stem wood was 70% at the beginning of the test drive and increased to 100% at 12:45. The average fuel composition of the first and second layer of the storage model is presented in the Figure 29.

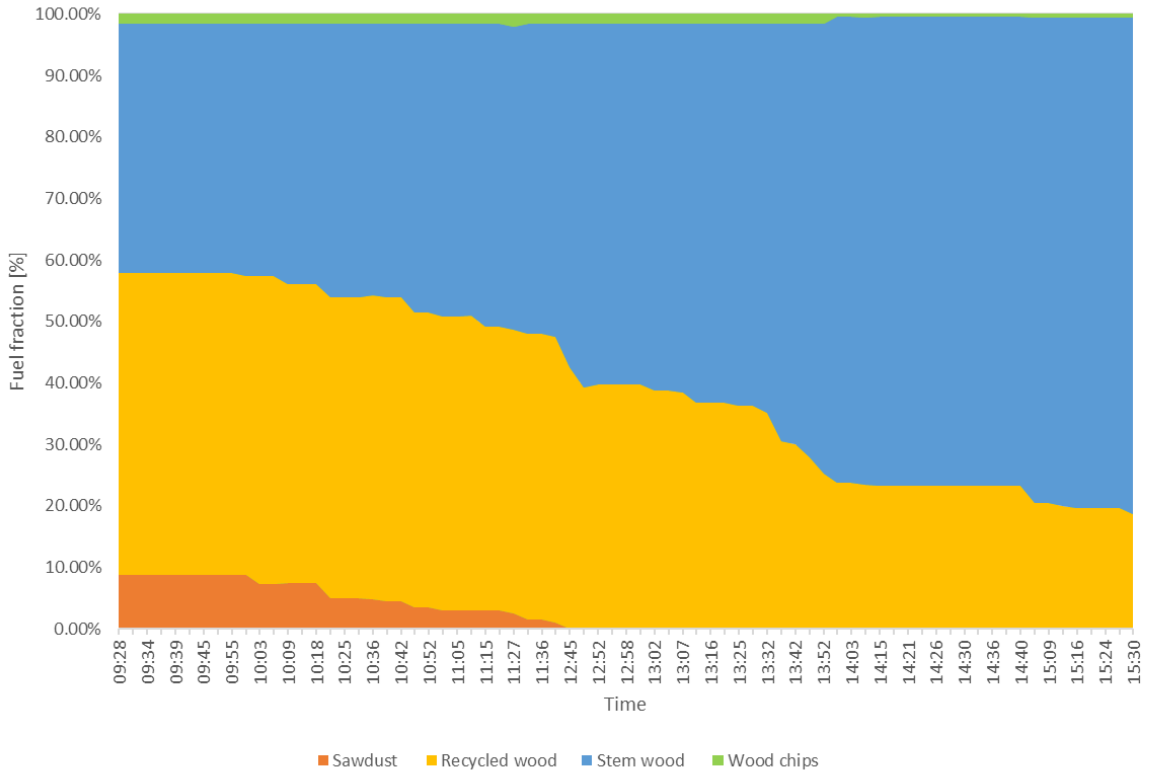


Figure 29. Average fuel composition of first and second layer of storage model during second test drive

The storage model consisted of mainly recycled wood and stem wood and minimal share of sawdust and wood chips. As it can be seen from the Figure 26 and Figure 29 the reference samples contained bark, but in the storage model, there was no bark in present either at the first or second layer of the storage model. The reference samples also consisted of sawdust throughout the test drive, but the sawdust in the first layer was completely unloaded at 11:27. The same decrease of recycled wood and increase of stem wood happened both in the storage model and the reference samples. Overall, during the test drive, the share of recycled wood decreased both layers in the storage model and in the reference samples. Therefore, the results indicated that the storage model's output volume flow is more correct after modification and the storage model was unloading the fuel in realtime and was no longer lagging behind.

7.3 Third test drive

Since the third test drive was arranged as a normal situation, the storage silos weren't arranged based on the fuel types. As a result, the reference samples and the storage model consisted of many different fuel fractions. This further complicated the analysis of the fuel fractions in the samples. The fuels that were at the storage model's first and second layer during the test drive are given in Table 11. The storage silo 1 consists of one fuel load of saw dust, three fuel loads of stem wood, one fuel load of recycled wood, one fuel load of wood chips, two fuel loads of unspecified industry waste and three fuel loads of bark. The storage silo 2 consists of four fuel loads of stem wood, one fuel load of saw dust, one fuel load of forest residue, and four fuel loads of bark. Appendix 3 showed the pictures taken from the reference samples during the third test drive.

Table 11. Fuel loads that were in the first and second layer of storage model in both storage silos during third test drive

X-Ray 1 moisture [%]	Storage silo	Fuel ID	Fuel code	Fuel name
50.8	1	1	212020	Saw dust
41.85	1	2	2110212	Stem wood
32.68	1	3	215010	Recycled wood
25.62	1	4	2110211	Wood chips
39.38	1	5	2110212	Stem wood
53.77	1	6	212080	Unspecified industry waste
52.62	1	7	212010	Bark
30.72	1	8	2110202	Stem wood
52.97	1	9	212010	Bark
39.22	1	10	212080	Unspecified industry waste
50.9	1	11	212010	Bark
34.44	2	12	2110212	Stem wood
53.04	2	13	212020	Saw dust
49.71	2	14	211030	Forest residue
51.91	2	15	2110212	Stem wood
52.62	2	16	212010	Bark
56.57	2	17	212010	Bark
41.16	2	18	2110202	Stem wood
53.55	2	19	212010	Bark
54.46	2	20	212010	Bark
51.01	2	21	2110212	Stem wood

The X-Ray 2 moisture measurement data is given in Figure 30. The average moisture content of the fuel mixture during the third test drive was 41%. The measured moisture varies between 40,1-45,9%.

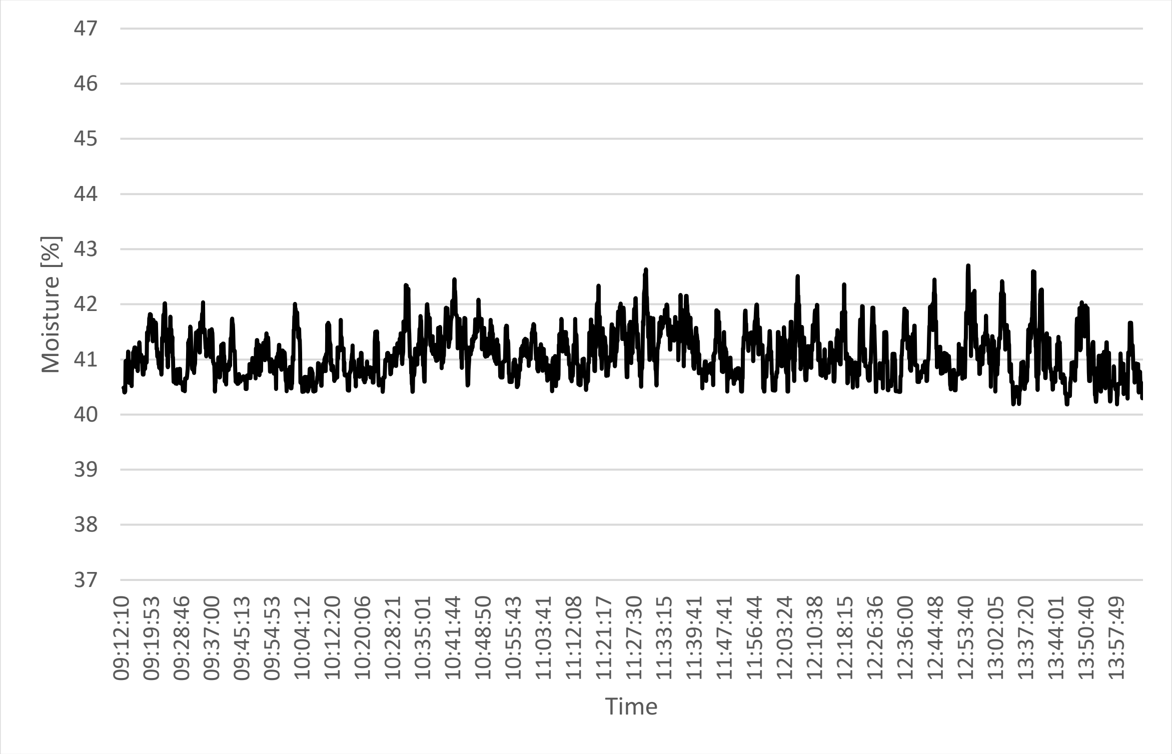


Figure 30. X-ray 2 moisture measurement data

7.3.1 Storage silo 1

Figure 31 showed the GUI of the storage model at the beginning and at the end of the test drive. As it can be seen from the Figure 31, due to short testing period, no major variation happened at the GUI of the storage model. The moisture of the reference sample, X-ray 2 measured moisture and the average moisture of first and second layer of the storage model and the average of both layers are shown in the Figure 32 for storage silo 1.

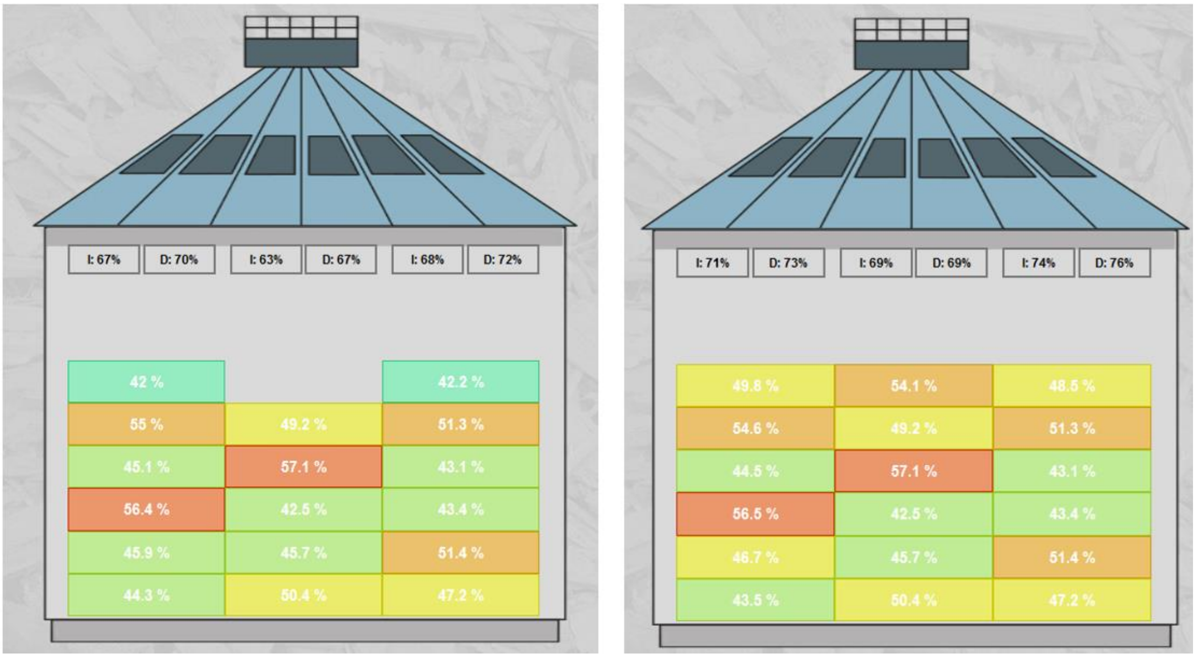


Figure 31. The storage model in graphical user interface at the beginning of the test drive and the end of the test drive for silo 1.

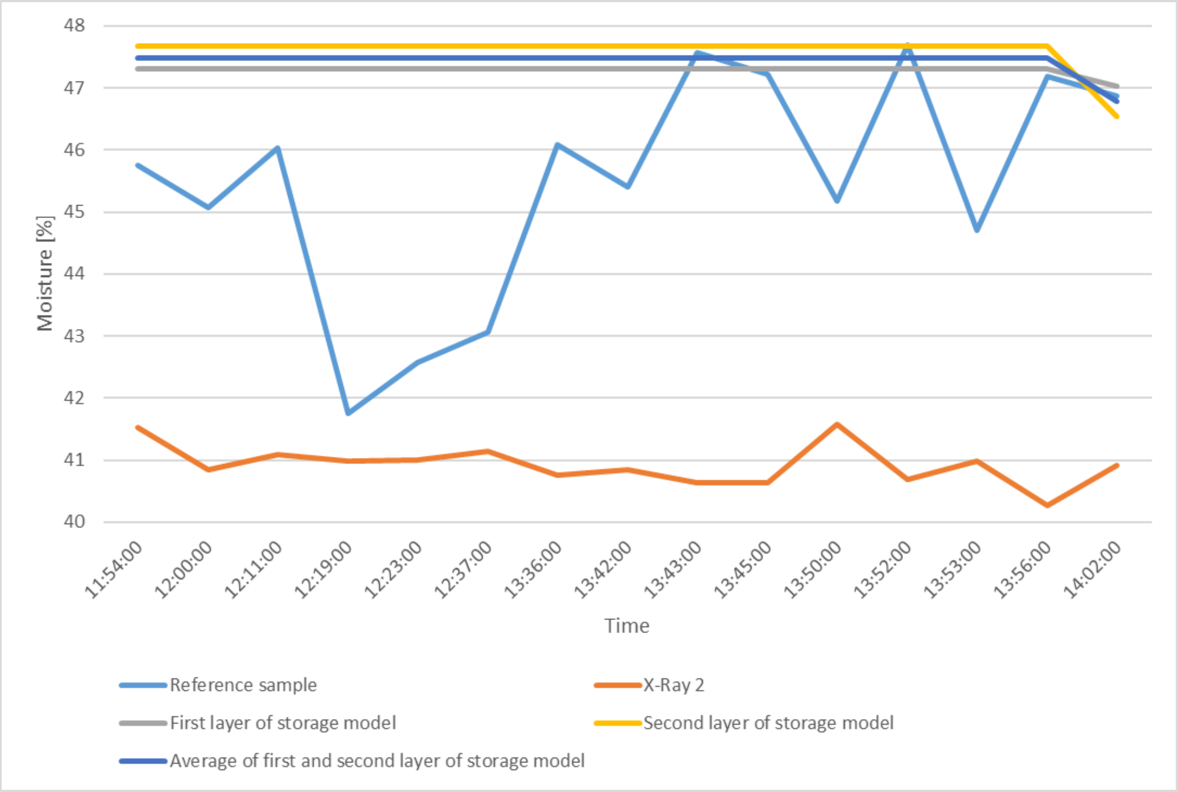


Figure 32. Moisture values in storage silo 1 during third test drive

As it can be seen from the Figure 32, the moisture values of the first and second layer of the storage silos remained exceedingly constant. The moisture of the reference samples varied from 41,8% to 47,7% being on average 45,5%. Therefore, the moisture values of the storage silos were only approximately 2% wetter compared to the average moisture value of the reference samples. The fuel composition of the reference samples for storage silo 1 is given in Figure 33.

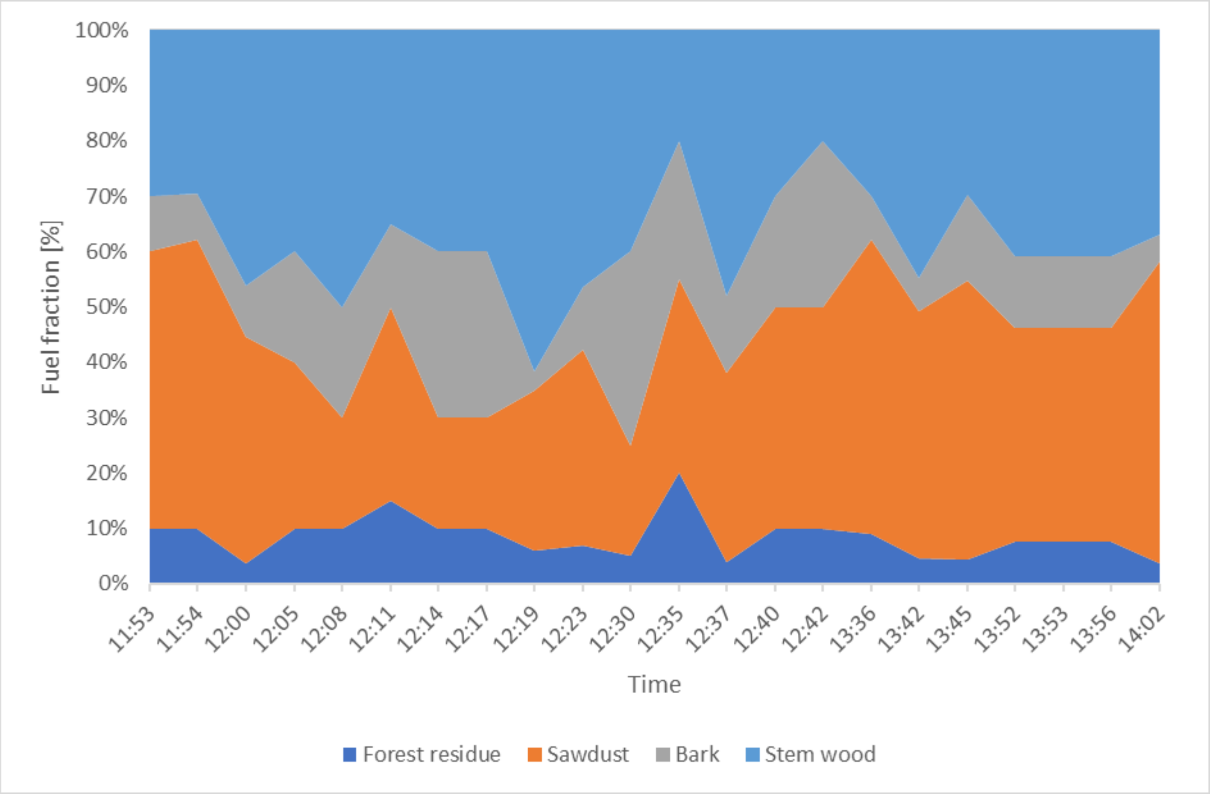


Figure 33. Fuel composition of reference samples during third test drive. Silo 1.

The reference samples consisted of forest residue, sawdust, bark, and stem wood. The share of forest residue varied from 4% to 20% being on average 8%. The share of sawdust varied from 20% to 50% being on average 37%. The share of stem wood varied from 20% to 62% being on average 38%. The share of bark varied from 5% to 30% being on average 16%. The fuel composition of the first layer in storage model is given in Figure 34.

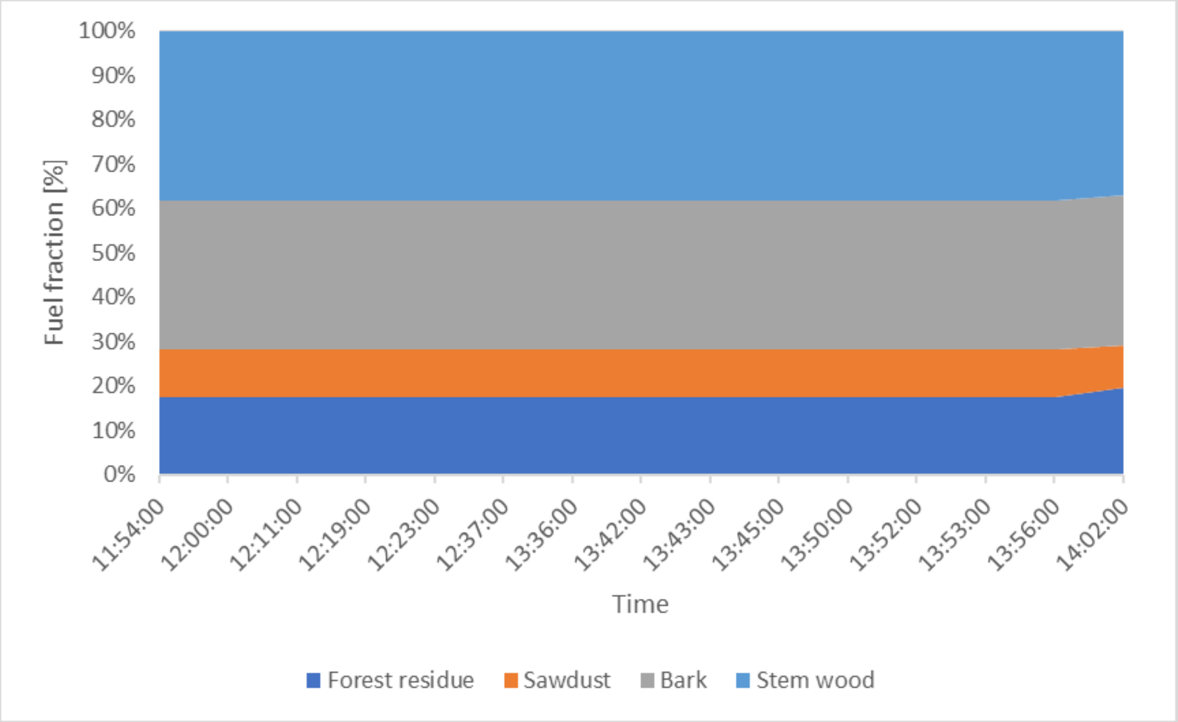


Figure 34. Fuel composition of first layer in storage model during third test drive. Silo 1.

The first layer of storage model consisted of forest residue, sawdust, bark, and stem wood. The share of sawdust was 11%, the share of stem wood was 38%, the share of bark was 34% and the share of forest residue was 17%. The fuel composition of the second layer of the storage model is presented in Figure 35.

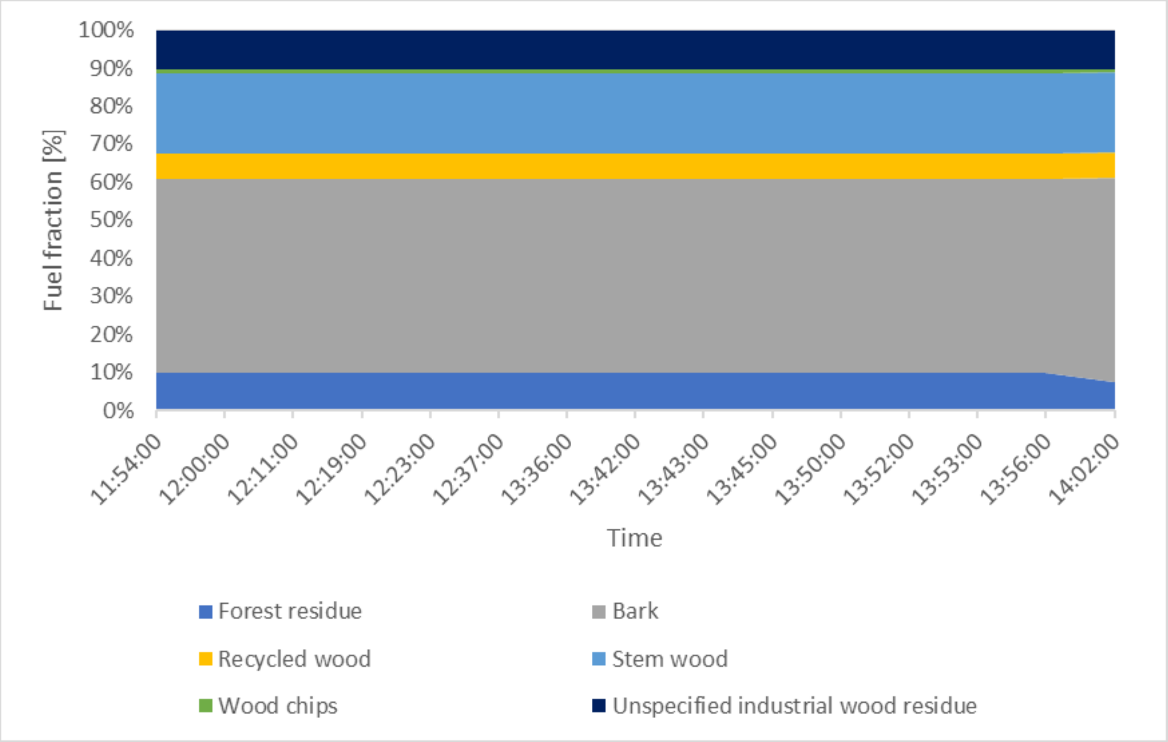


Figure 35. Fuel composition of second layer in storage model during third test drive. Silo 1.

The second layer of storage model consisted of forest residue, recycled wood, stem wood, wood chips and unspecified industrial wood residue. The share of forest residue was 10%, the share of recycled wood was 7%, the share of wood chips was 1%, the share of stem wood was 21%, the share bark was 51% and the share of unspecified industrial wood residue was 10%. The average fuel composition of the first and second layer of the storage model is presented in the Figure 36.

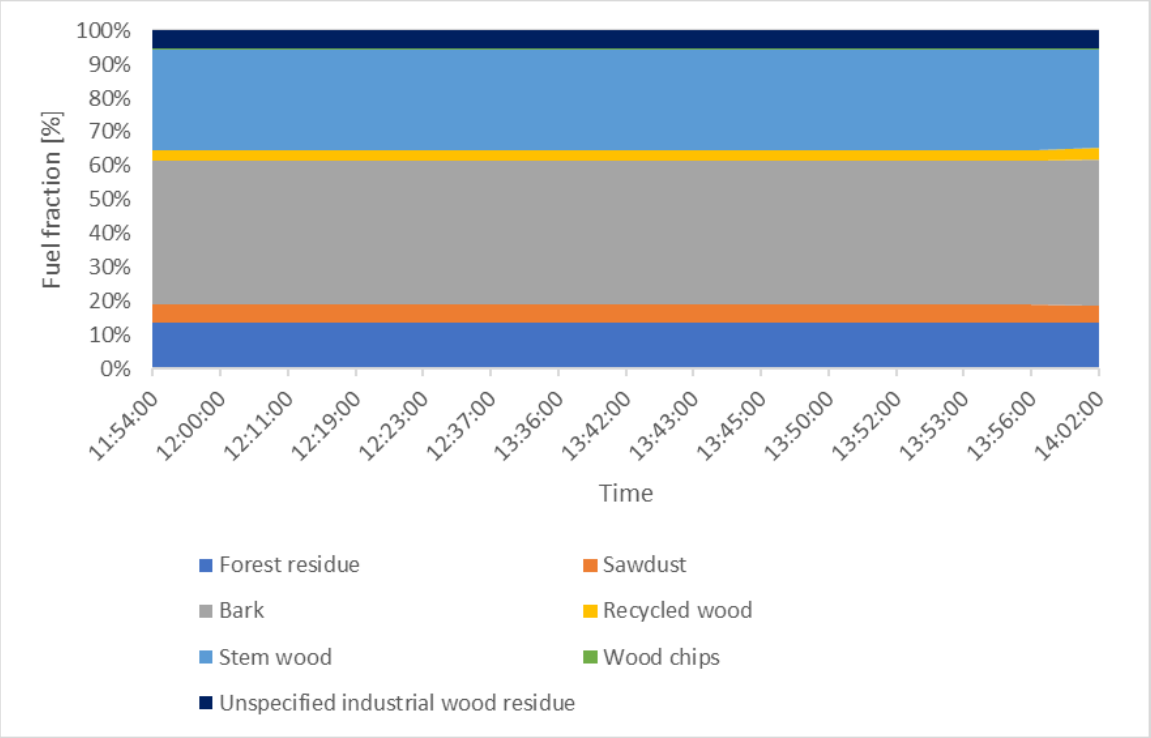
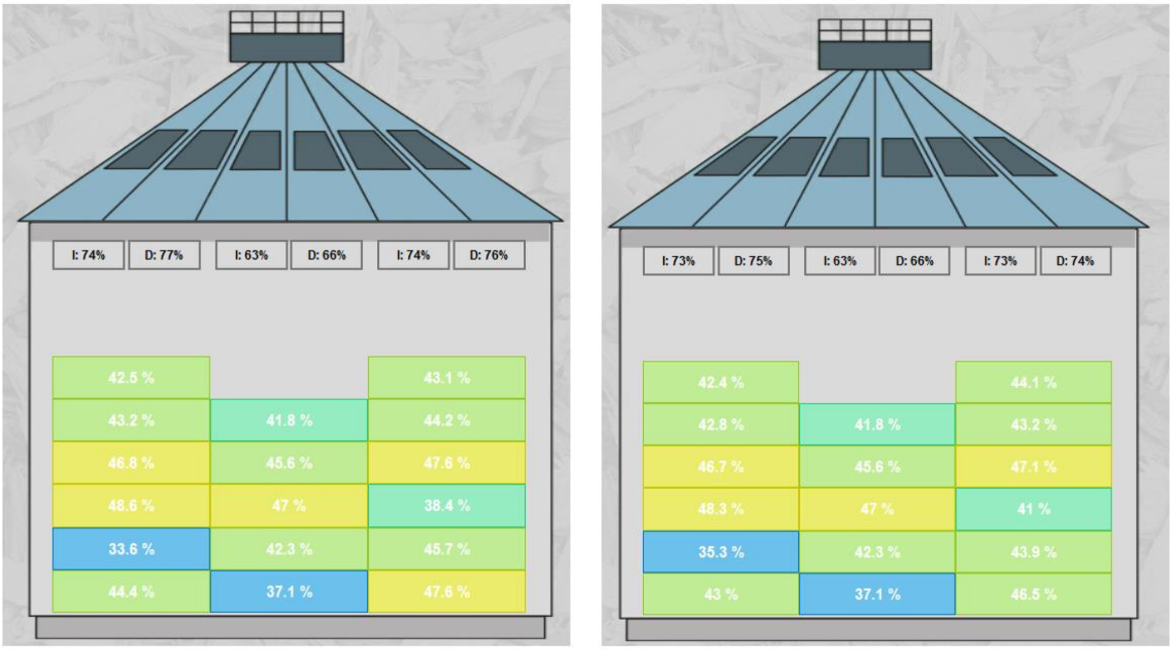


Figure 36. Average fuel composition of first and second layer in storage model during third test drive. Silo 1.

As the Figure 33 and Figure 34 is compared to each other, it can be seen that the share of forest residue and stem wood remained quite constant with a maximum difference of 10%. The share of sawdust and bark has a larger variation in reference samples compared to the storage silo. The share of sawdust and bark is hard to determine, since the reference samples always consisted solid biofuels with particles typically 1 to 5 mm in size. Both the reference samples and the first layer of storage model contained the same fuel types. As it can be seen from the Figure 35, the second layer contained recycled wood, wood chips and unspecified industry waste, that weren’t present in the first layer of storage model. Since recycled wood, wood chips or unspecified industry waste weren’t found in the reference samples, it can be concluded that no major mixing has occurred between the first and the second layer. Overall, the share of different fuel fractions in reference samples varies much larger than in the storage model, where the changes remained at the minimum.

7.3.2 Storage silo 2

Figure 37 showed the GUI of the storage model at the beginning and at the end of the test drive. As it can be seen from the Figure 37, due to short testing period, no major variation happened at the GUI of the storage model.



I: 74% D: 77%	I: 63% D: 66%	I: 74% D: 76%
42.5 %		43.1 %
43.2 %	41.8 %	44.2 %
46.8 %	45.6 %	47.6 %
48.6 %	47 %	38.4 %
33.6 %	42.3 %	45.7 %
44.4 %	37.1 %	47.6 %

I: 73% D: 75%	I: 63% D: 66%	I: 73% D: 74%
42.4 %		44.1 %
42.8 %	41.8 %	43.2 %
46.7 %	45.6 %	47.1 %
48.3 %	47 %	41 %
35.3 %	42.3 %	43.9 %
43 %	37.1 %	46.5 %

Figure 37. The storage model in graphical user interface at the beginning of the test drive and the end of the test drive for silo 2.

The moisture of the reference sample, X-ray 2 measured moisture and the average moisture of first and second layer of the storage model and the average of both layers are shown in the Figure 38 for storage silo 2.

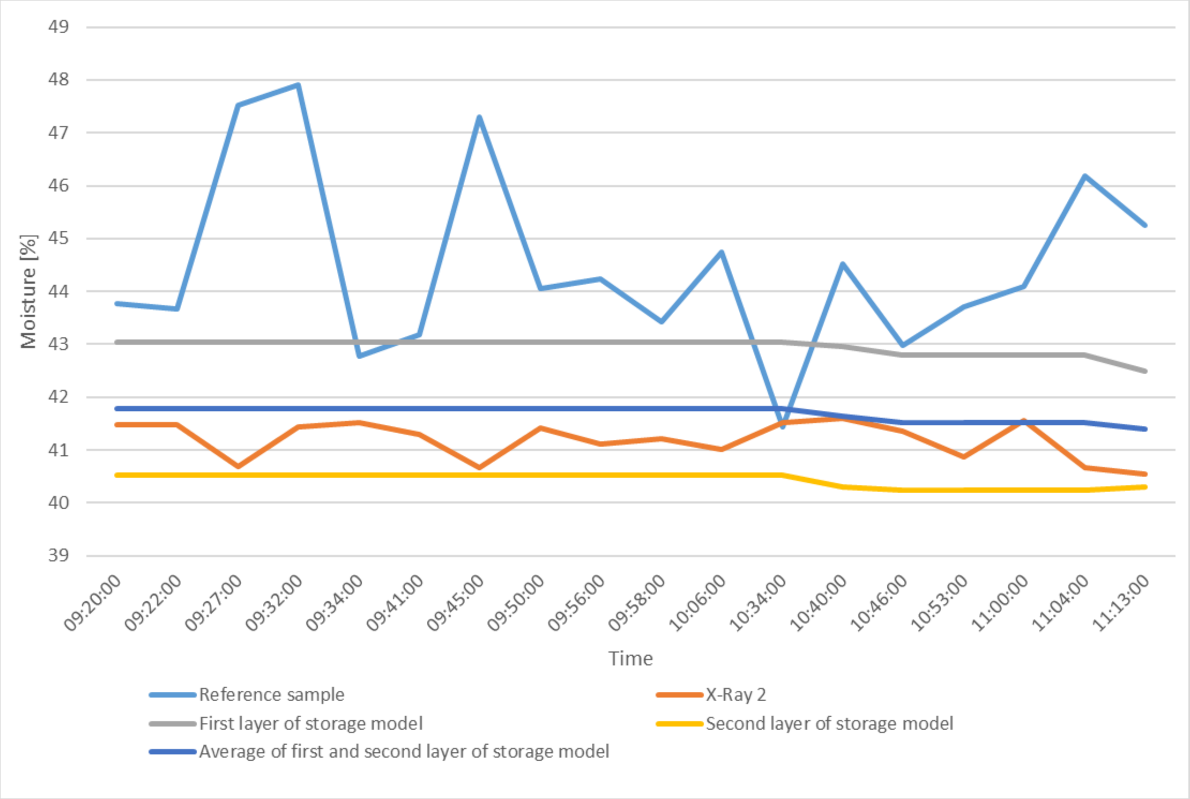


Figure 38. Moisture values during third test drive. Silo 2.

The moisture of the reference samples varied from 41% to 47% being on average 45%. The moisture of the reference samples was on average 2% higher compared to the first layer of the storage model. The average of first and second layer of storage model was closest to the moisture values measured by X-Ray 2. The fuel composition of the reference samples for storage silo 2 is given in Figure 39.

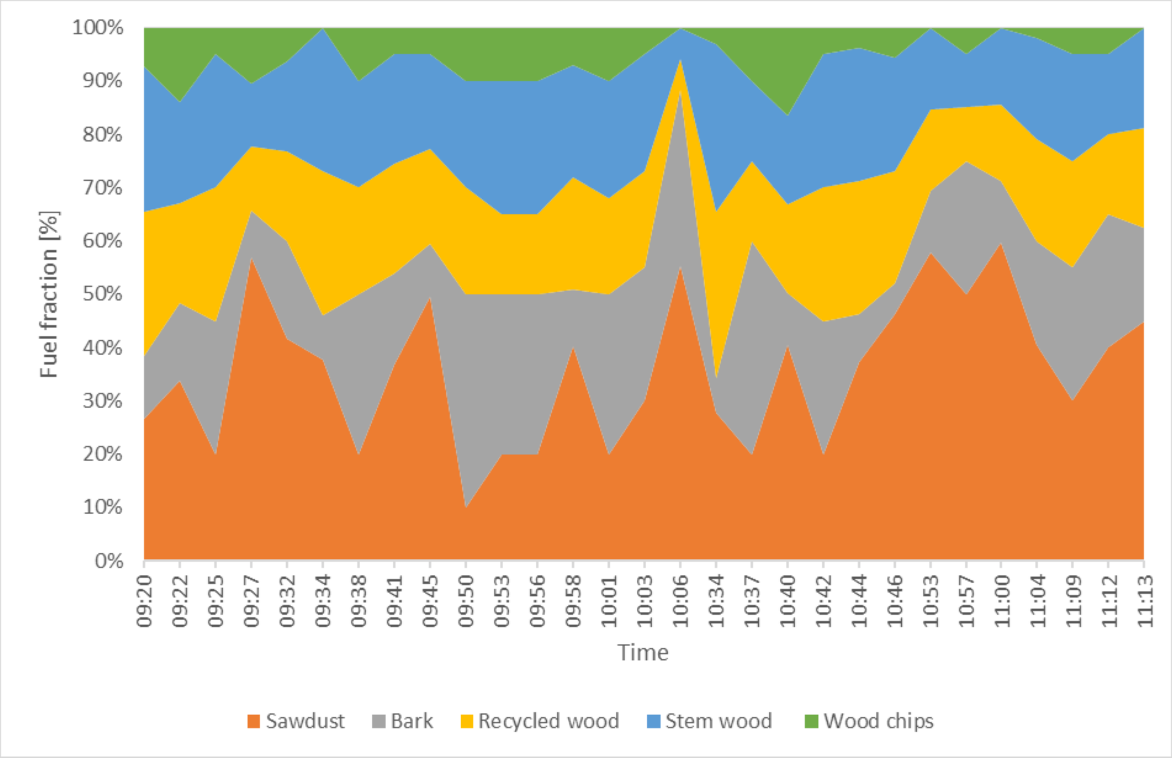


Figure 39. Fuel composition of reference samples during third test drive. Silo 2.

The reference samples consisted of sawdust, bark, stem wood, recycled wood, and wood chips. The share of sawdust varied from 10% to 60% being on average 36%. The share of bark varied from 6% to 50% being on average 22%. The share of recycled wood varied from 6% to 27% being on average 19%. The share of stem wood varied from 6% to 31% being on average 19%. The share of wood chips varied from 0% to 17% being on average 4%. The fuel composition of the first layer in storage model is given in Figure 40.

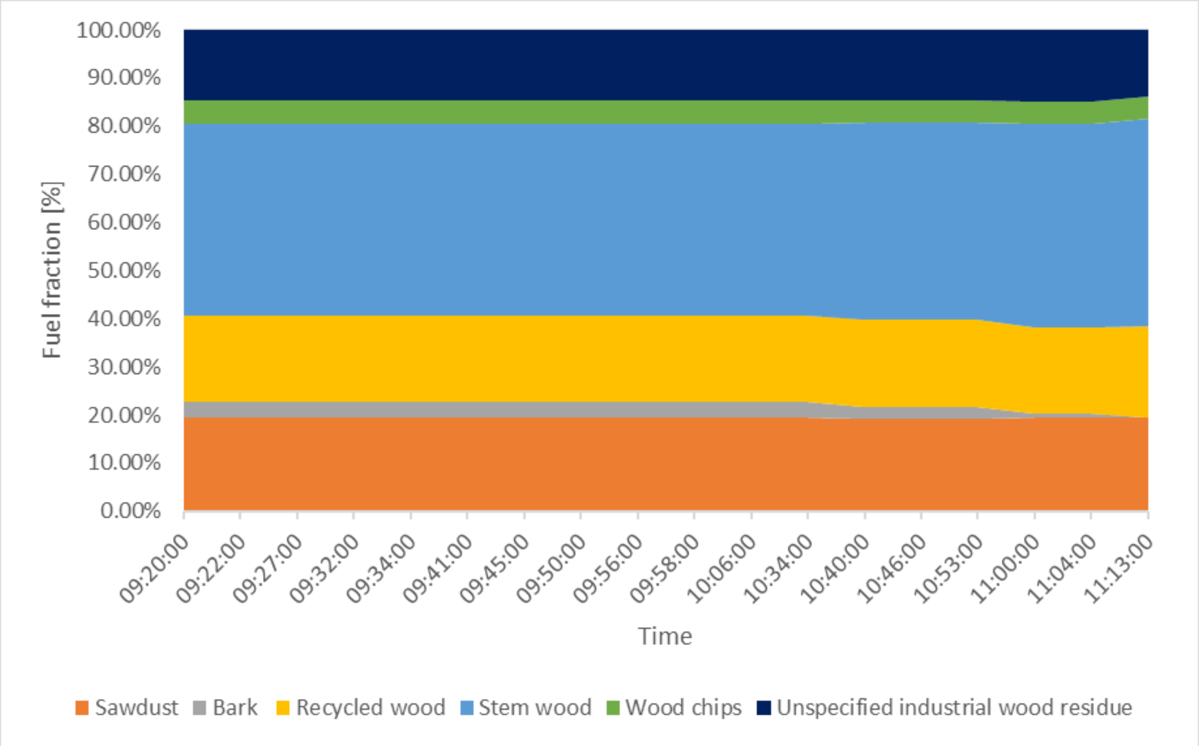


Figure 40. Fuel composition of first layer in storage model during third test drive. Silo 2.

The first layer of storage model consisted of sawdust, bark, stem wood, recycled wood, wood chips and unspecified industrial wood residue. The share of sawdust was 19%, the share of stem wood was 40%, the share of recycled wood was 18%, the share of wood chips was 5%, the share of unspecified industrial wood residue was 15% and the share of bark was at the beginning of the test drive 3%, but the share decreased throughout the test drive and was completely unloaded from the model at the end of the test drive. The fuel composition of the second layer of the storage model is presented in Figure 41.

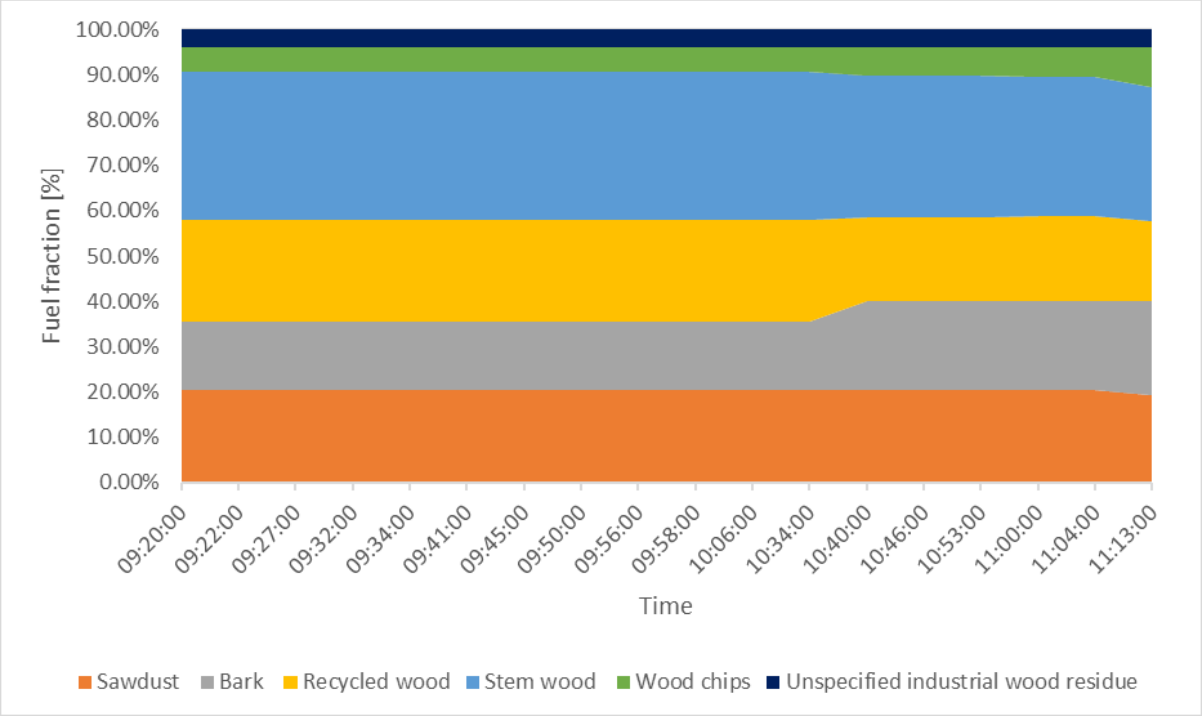


Figure 41. Fuel composition of second layer in storage model during third test drive. Silo 2.

The second layer of storage model consisted of sawdust, bark, recycled wood, stem wood, wood chips and unspecified industrial wood residue. The share of sawdust was 20%, the share of stem wood was 32%, the share of recycled wood was 21%, the share of wood chips was 6%, the share of unspecified industrial wood residue was 4% and the share of bark was 17%. The average fuel composition of the first and second layer in the storage model is shown in Figure 42.

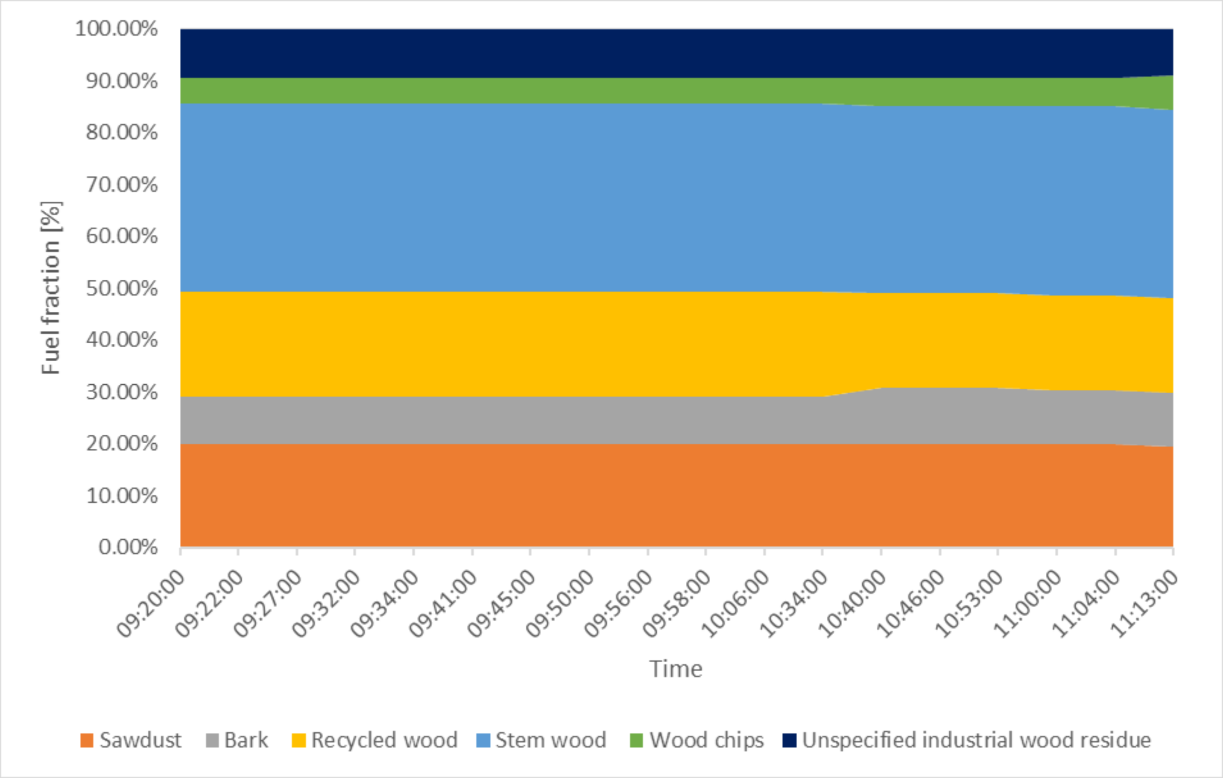


Figure 42. Average fuel composition of first and second layer in storage model during third test drive. Silo 2.

The share of sawdust and bark appeared to be higher in the reference samples compared to the first layer storage model, while the share of stem wood seemed to be lower. The share of bark and sawdust varied from 30% to 80% in the reference samples, while the share of bark and sawdust stayed on average of 23% in the first layer of storage model. On average the share of recycled wood was 19% in both reference samples and storage model and stayed constant throughout the test drive. The first layer of storage model consisted of unspecified industry waste, but it wasn’t included in the reference samples. The fuel composition in the reference samples had much larger variation than in the storage model where the fuel composition remained exceedingly constant. The second layer of storage model consisted of same fuel types as the first layer and the share of different fuels was also same, so no conclusions can be drawn about the mixing of the first and second layers.

7.3.3 Particle size distribution

The particle size distribution analysis was done for both storage silos’ fuel samples and they are shown in Figure 43 and Figure 44. The particle size distribution refers to an index that indicates what particle sizes are present in what proportions in the sample particle group to be measured.

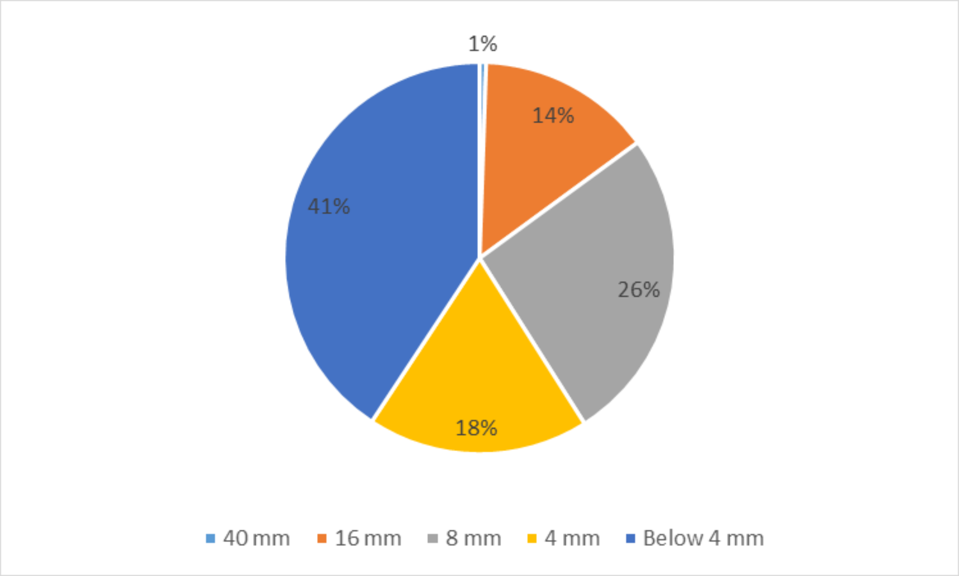


Figure 43. Particle size distribution. Storage silo 1.

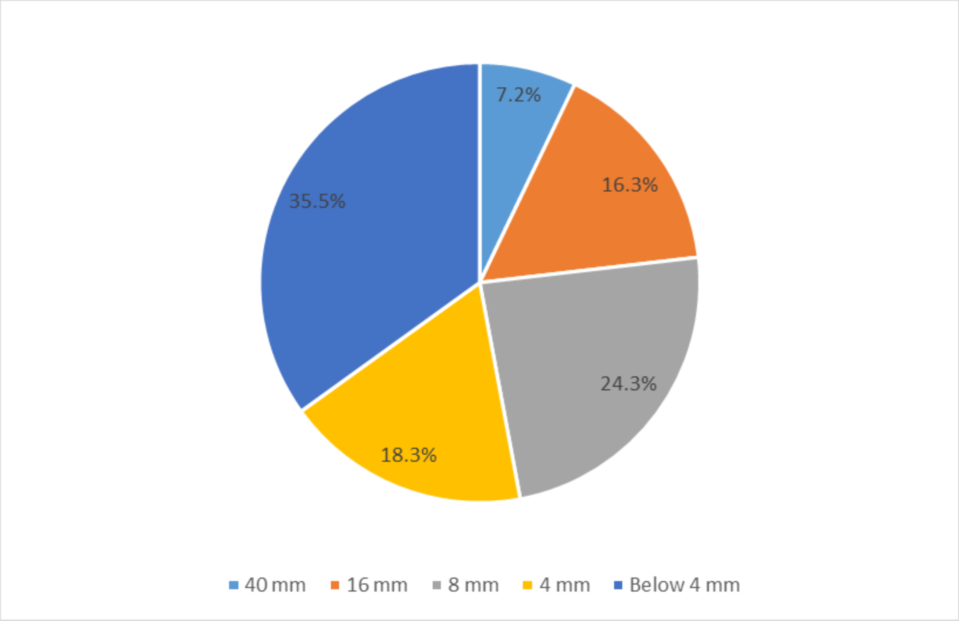


Figure 44. Particle size distribution. Storage silo 2.

As it can be seen from the Figure 43 and 44, the main fraction size of the composition is below 4 mm both storage silo 1 and storage silo 2. On average, 41% of the fuel’s dry mass was distributed in particles of below 4 mm in storage silo 1 and 35,5% of the fuel’s dry mass was distributed in particles of below 4 mm in storage silo 2. The picture samples of the different particle sizes are given in Appendix 4. As it can be seen, the particles below 4mm contained a mixture of sawdust and small particles of bark. It can be concluded that due to the small particle size, the particles can run from the surface to the bottom of the storage silo, even if the storage silo does not appear to contain, for example sawdust, in the fuel mixture.

7.4 Sources of uncertainty

During the test drives the largest sources of uncertainty are the evaluation methods on the fuel composition in the reference samples. The evaluation was done by traditional human visual inspection. Therefore, there is potentially high possibility of inspection errors. After the sample was taken, the sample was analysed using the naked eye to look the share of different fuel fractions. Comprehensive manual sorting wasn’t applied to reference samples to determine the composition of the samples. Therefore, the percentages of different fuel fractions are indicative and not completely accurate. Fuel composition of the reference samples are challenging to verify since the more heterogeneous the fuel mixture, the less reliable and representative are the samples received. Physical characteristics and appearance of solid biofuels varies in wide range. Therefore, it is difficult to evaluate, which fuel type the fuel particle belongs. For example, the particle of bark in the reference samples can be identified as a bark, wood chips and forest residue. Wood chips have a more homogeneous particle size than recycled wood. The sorting of reference samples’ components into the relevant fuel types is done by their physical properties or appearance (e.g., particle size, shape). The storage model could provide guidelines since it showed the fuel mixture in real time. However, the aim of this master thesis was to prove the functionality of the storage model and so identifying the fuel composition of the reference samples was purely based on the visual inspection.

Another source of uncertainty is the method used to collect the sample. It was frequently difficult to take samples in a way that adheres to the principle of proper sampling, which states that each individual particle should have an equal chance of being picked for the final sample. Although the samples were collected from a falling fuel stream, larger fuel pieces flew apart from the main fuel stream, and the fuel sample easily consisted only smaller fuel particles. Therefore, there was a source of uncertainty of collecting the fuel samples in such a way that the entire cross section of the fuel stream is represented in the sample.

8 EVALUATION TOOL FOR FUEL MIXTURES

As discussed in the chapter 2, the special features of solid biofuels are low calorific value, moisture variations and high volatile matter content. In addition, the fuel ash is rich in alkalis. These characteristics give rise to problems that need to be considered in the design and operation of a power plant that combust solid biofuels. Chapter 4 discussed these problems caused by the combustion of biofuels and what are the causes behind them. In this chapter, the aim is to develop a tool that can be used to predict the boiler problems by evaluating the elemental analysis of the fuel mixture. For each fuel type or blend, the estimation can be created. It can utilize the private data from the power plant or boiler manufacturer, historical fuel analyses or the values of the fuels from the literature and databases. Based on the fuel data, the tool calculates the chosen fuel indexes for different fuel blends and the model compares the results to the given limiting values and provides as estimate of whether any problems occur. The goal is to achieve real-time estimation model of the characteristics of the provided fuel and fuel blend and apply it to existing storage model.

8.1 Method

Elemental analysis of the different fuels is collected from the literature and the databases. There are several databases that contains assessments of fuels and ashes. Detailed assessments of the fuels are provided, including references to the published papers. In other cases, simply a few specific parameters may be provided. The fuel indexes are calculated from the literature values of the fuels, that are used at Järvenpää plant. Since the data in the studies is provided in mass base (mg/kg ds), by using the molar mass for each component, recalculations are done to modify the concentrations to molar basis (mole/kg ds). Appendix 5 demonstrates the calculation formulas to recalculations. The fuel indexes are calculated using the equations in Table 4 and 5 and molar fractions in each deliver. Since each fuel load contains a various weight, for each evaluated parameter weighted value for the molar components are calculated. The weighted value takes into consideration the fuel load's weight as a percentage of the entire weight in the fuel mixture. The different fuel types of elemental analysis and the risk limits are given to the model. The effect of the boiler conditions during combustion on the problems that arise will not be considered in this work. Once the properties of the fuel mixture and its ash have been calculated from the initial data and are relevant to the problems, they are compared to the limit values compiled in the work. If the calculated value is greater than the limit value, the boiler is most likely experiencing issues.

8.2 Model testing for Järvenpää plant

Two fuel indexes were selected and applied to the study the combustion related problems of fuels used at the Järvenpää power plant, including sulfating ratio 2S/Cl and salt ratio 1. These fuel indexes were elected because they are most relevant to the FB technology and they are heavily related to each other, as discussed in chapter 4.6.1. The fuel indexes are calculated from the literature values of the fuels used at Järvenpää and compared to the limit values provided by the literature. The elemental analysis used for fuels are shown in Appendix 6. For the industry waste and for the mix of bark and sawdust, literature values weren’t found, so they were established based on the values used for stem wood and bark. The data provided by the storage model of the discharged fuel mixture was used for the model testing. SRF was not considered in the fuel mixture, as it was being mixed with the solid wood fuels after the storage silos. The fuel cube in the GUI of storage model showed the weighted average of the different loads that the fuel cube contains, as shown in Figure 45. Fuel indexes were showed per one load inside the fuel cube, as shown in Figure 46.

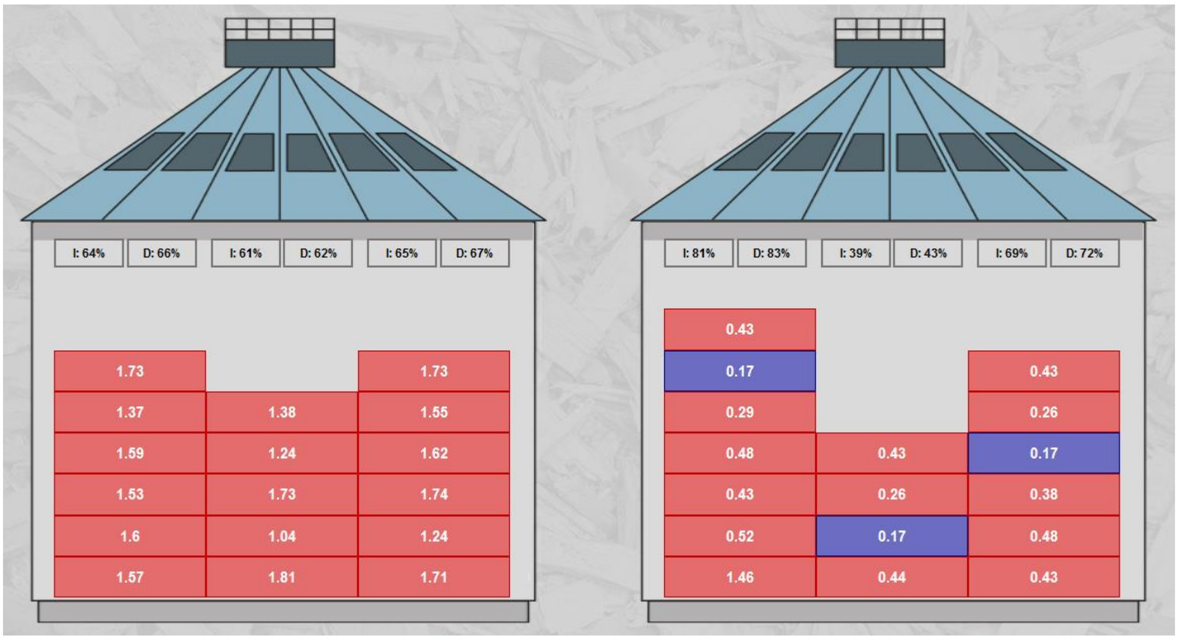
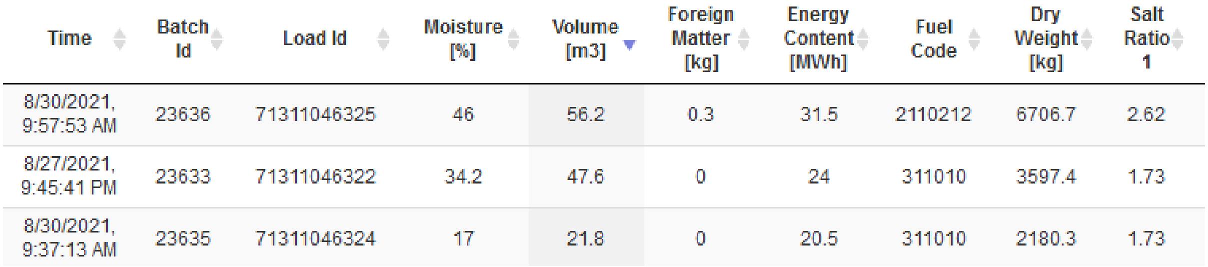


Figure 45. GUI of storage model showing the Salt ratio 1, where the fuel cube contained the weighted average of salt ratio 1.



Time	Batch Id	Load Id	Moisture [%]	Volume [m3]	Foreign Matter [kg]	Energy Content [MWh]	Fuel Code	Dry Weight [kg]	Salt Ratio 1
8/30/2021, 9:57:53 AM	23636	71311046325	46	56.2	0.3	31.5	2110212	6706.7	2.62
8/27/2021, 9:45:41 PM	23633	71311046322	34.2	47.6	0	24	311010	3597.4	1.73
8/30/2021, 9:37:13 AM	23635	71311046324	17	21.8	0	20.5	311010	2180.3	1.73

Figure 46. Fuel indexes showed per one load inside the fuel cube

The fuel mixture discharged from the storage silos for one month is analysed by using the fuel indexes applied to the storage model. The salt ratio 1 for a period of one month is shown in Figure 47. The risk area was based on the literature values, which are 0.2-4. As can be seen, most of the values fall into the risk zone. Since the fuel indexes varied drastically, no major conclusion can be done whether there are more Cl and S atoms present compared to Na and K. The variation in salt ratio 1 for one day is shown in Figure 48.

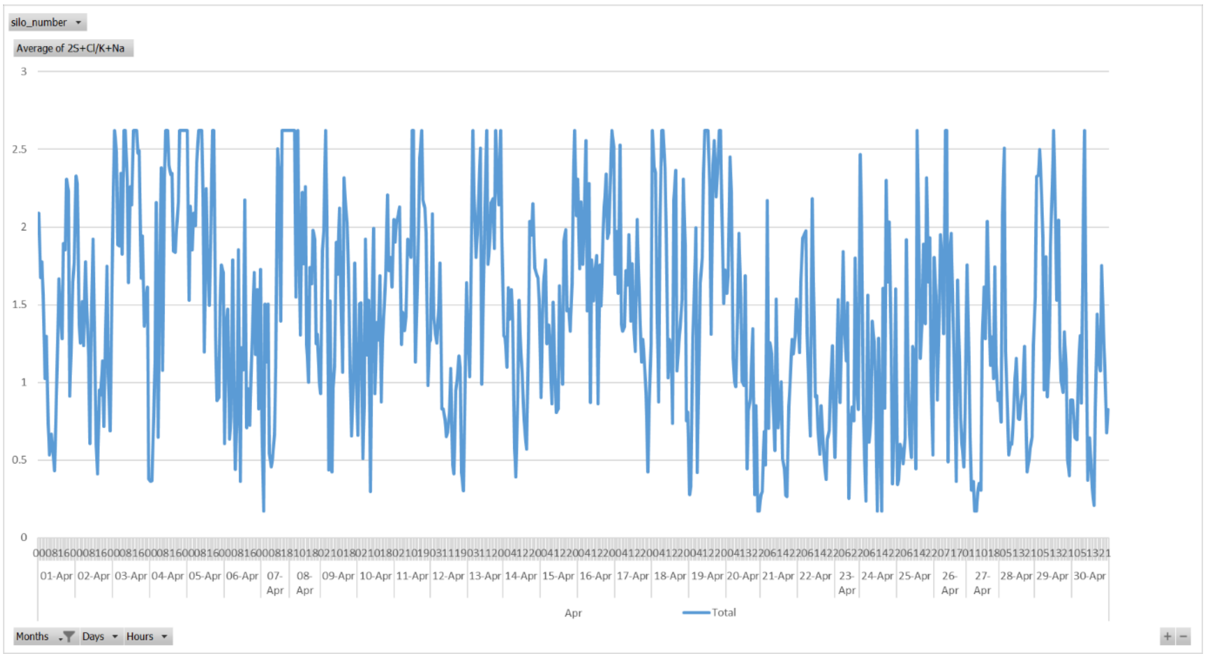


Figure 47. Salt ratio 1 for fuel mixture discharged from the storage silos at Järvenpää for a period of one month

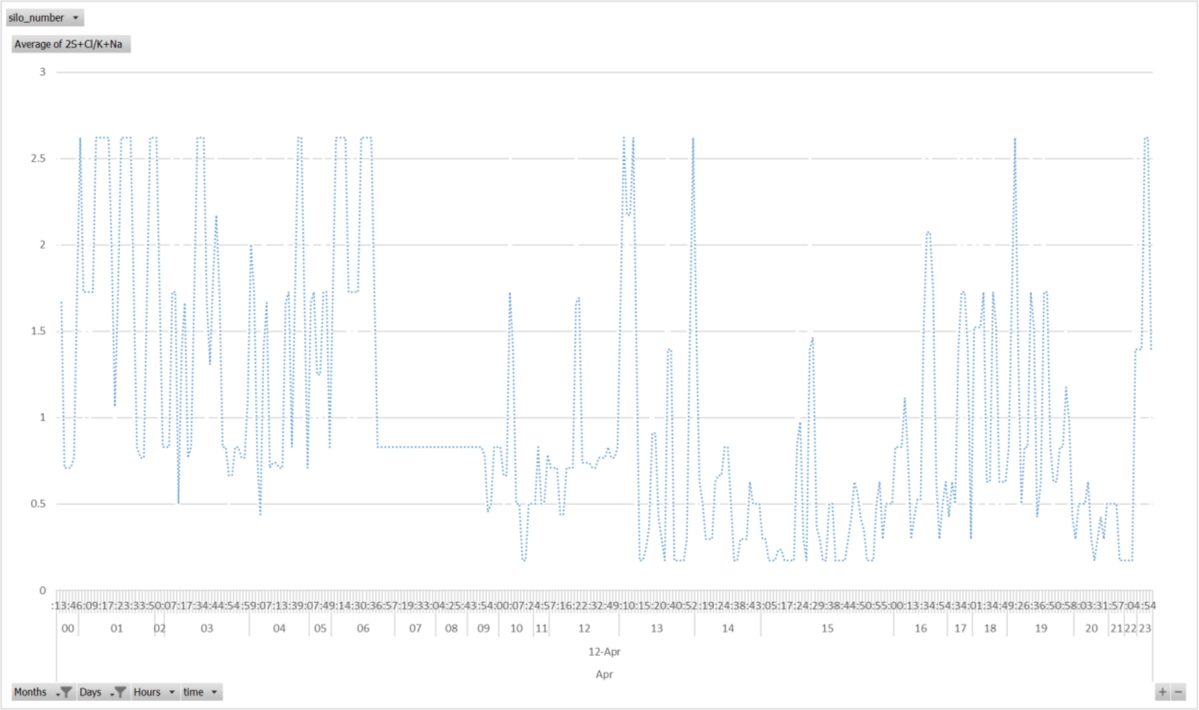


Figure 48. Salt ratio 1 for fuel mixture discharged from the storage silos at Järvenpää for one day

The calculated sulfating number for a period of one month are shown in Figure 49. As it can be seen in the figure, the fuel index had a high variation. As previously stated in section 4.6.1, the molar ratio of 2S/Cl can be used to predict high temperature corrosion risks. The majority of the values was under 4 which indicated a risk of corrosion. Furthermore, as seen from the Figure 50, the sulfating number also varied greatly, when the fuel indexes were analysed for a one day.

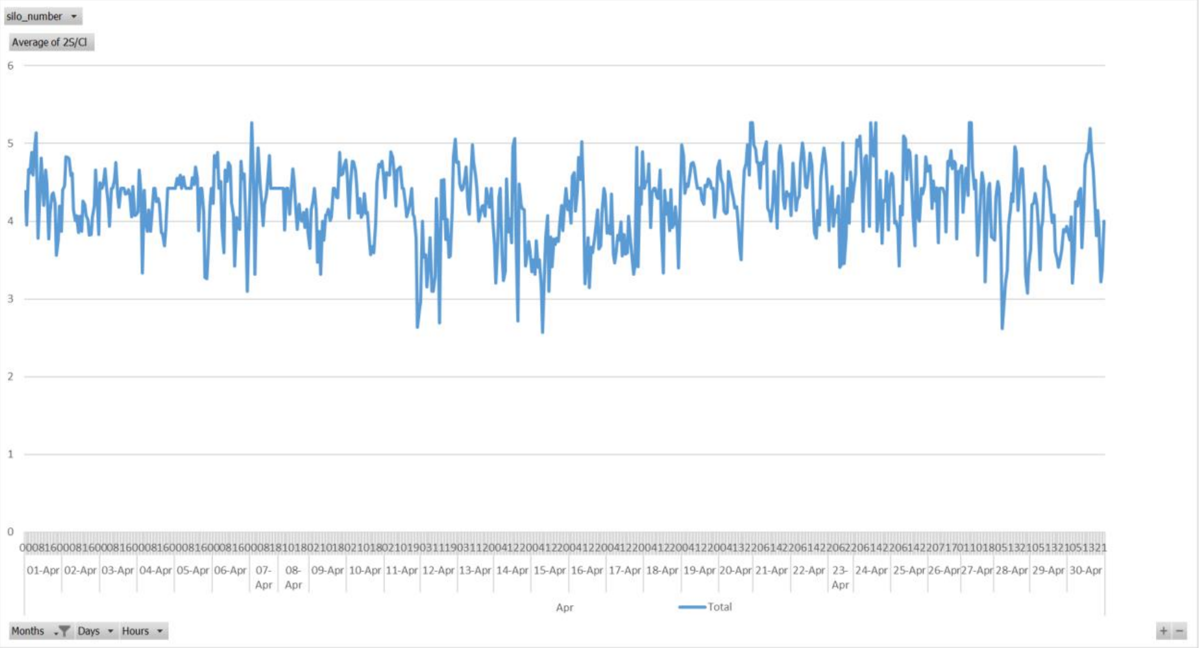


Figure 49. Sulfating number for fuel mixture discharged from the storage silos at Järvenpää in one month.

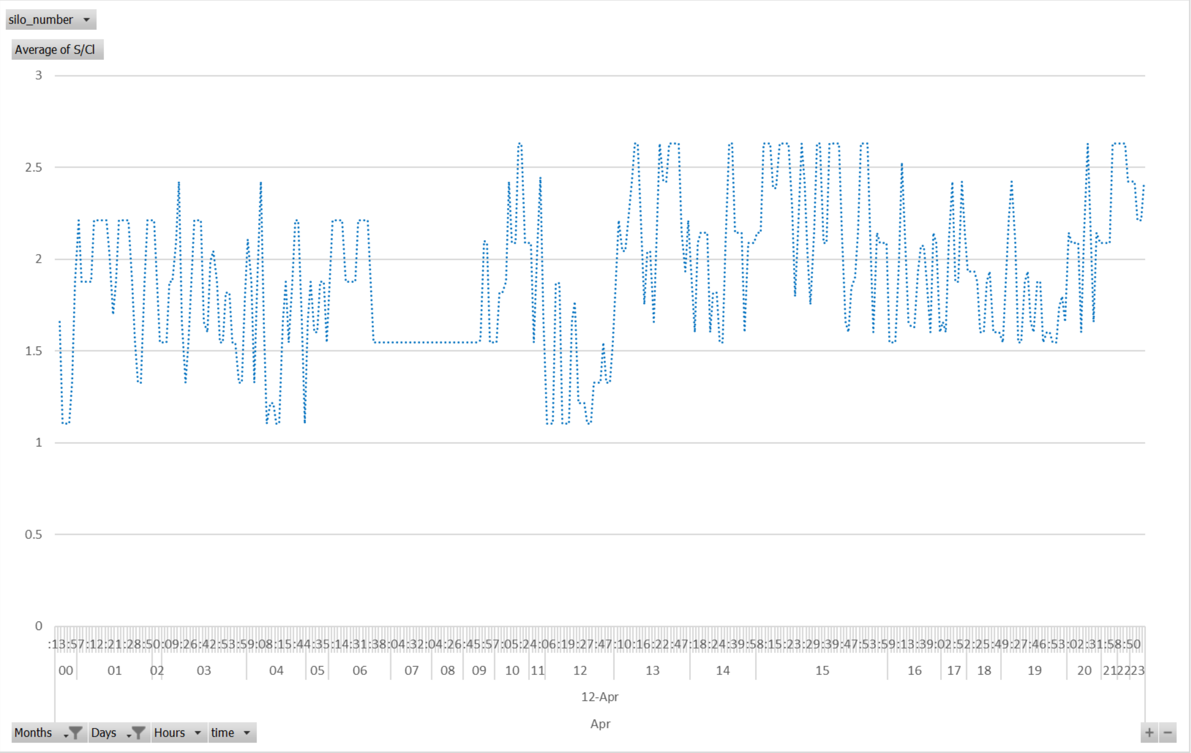


Figure 50. Sulfating number for fuel mixture discharged from the storage silos at Järvenpää in one day

The results convincingly shows that the values vary significantly as a function of time. As the problems in the boiler can happen extremely rapid and the quality of the fuel mixture can decrease quickly, it is clear that fuel indexes may be applied as a foundation for evaluating the effects of fuel mixture on the fuel characteristics, particularly ash-related problems. Controlling the feeding and discharging of the silos with fuel indexes in the storage model can improve the chemical properties of the fuel supplies into the boiler and achieve more homogeneous fuel, thus optimizing the combustion process. However, as the data for the investigation are based on the literature, the indexes derived in this work are not completely accurate and applicable for Järvenpää power plant.

9 CONCLUSIONS

In this research work, the aim was to verify the performance of the FUELCONTROL ® Storage model. The fuel factors to be analysed were the composition, moisture content and the real time of the storage model. Finally, the evaluation tool based of the elemental analysis of the fuel was implemented to the storage model.

The research results lead to the following conclusions:

- As the fuel composition of the reference samples is compared to the storage model, it is found that the fuel composition corresponds to each other. Generally, the reference samples contained the same fuel fractions as the first layer of the storage model and same changes in the fuel composition happened at the same time both in the reference samples and in the storage model. Especially the share of stem wood and recycled wood in the reference samples corresponded really well with the share shown by the storage model. Due to heterogeneous nature of the fuel mixtures and analytical inaccuracies as the fuel samples were analysed, the share of different fuel fractions in the reference samples varied greatly compared to the storage model at times. The share of recycled wood and stem wood was easiest to define in the reference samples due to the larger particle size compared to other fuel fractions. Therefore, that result seems to be the most accurate.
- The biggest difference in fuel composition between the reference samples and the storage model was in the share of sawdust and bark. During all of the three test drives, the reference samples consisted of invariably a share of small fine particles less than 4 mm in length. The type of fuel particles seemed sawdust, bark, and other fuel types, for example recycled wood, that have been broken down into smaller pieces. This share of small fuel particles caused the largest variation in fuel mixture between the reference samples and the fuel composition of the storage model, as the storage model didn’t always contain sawdust or bark at all or relatively small share of them.
- The moisture data measured by X-Ray 2 stayed constant throughout all three test drives. The largest variation in moisture content occurred in the reference samples due to the relatively small sampling volume. Since the moisture values in the storage model is provided by the X-Ray 1, the moisture values don’t take into consideration

the moisture changes occurring due to storage conditions. Significantly drier or wetter moisture values could not be achieved during the test runs. Although, especially during the second test drive, the first layer of the storage model showed drier moisture content, the moisture of the reference samples stayed over 40%. Based on the results provided by all three test drives, the storage conditions compensate the moisture differences really strongly and the average moisture of the fuel mixture stays almost always between 40-50%.

- The implementation of elemental analysis of the fuels as fuel indexes to the storage model can offer a relevant information and evaluation for the effects of fuel mixture on the fuel properties and crucial combustion-related issues that may occur. As the storage model shows the fuel indexes in real-time, they can provide guidance for the operator. However, further research needs to be done in order to improve prediction preciseness.

Based on the result of this study the storage model performs accurately and can be utilized to optimize the performance of the plant. Controlling the feeding and discharging of the storage silos enables an improvement in the quality of a fuel supplied into the boiler as the fuel can be provided with quality as consistent as possible, whereby it is optimal from the standpoint of a combustion process. Furthermore, the control makes is possible to optimize the fuel mixtures and to maximise the use of low-quality fuels. The optimization of mixture ratios is a way of decreasing and even avoiding the feeding of expensive additives, for example sulfur and sulfates, into the boiler in case there is a risk of chlorine-induced corrosion. The model enables a protection of the boiler by avoiding undesired fuel blends which increase the corrosion risk. The model further provides an ability to maintain the boiler and a turbine in optimal operation, to reduce emissions and to improve the efficiency of a combustion process. Since the operator has an accurate initial data about the quality of fuel, the boiler can be operated more safely within its design limits. The quality fluctuations of the fuel, regarding moisture, complicate the adjustments of the boiler, whereby the bed temperatures fluctuate with resulting emission spikes, the efficiency suffers, and the corrosion risk increases. In addition, the storage model can be utilized in the procurement of fuel, because when placing orders, the person responsible for the procurement of fuel has accurate information about the plant's storage situation. In the storage model, it is possible to reverse back in time and look at the fuel ratios of the silos or the fuel mixture fed to the boiler and its contribution to the problem. When a possible cause is found, situations can be learned by, for example, taking corrective measures to fuel procurement. Systematic collection and review of fuel data plays a key role in solving power plant problem situations more broadly. Statistical studies and the links between fuels and, for example, corrosion damage can be examined, and further efforts made to avoid these unfavorable conditions. Table 12 sums up the benefits of the storage model briefly.

Table 12. Overall, of the benefits of the storage model

Benefit	Description
The procurement of fuel	There is an accurate information about the storage situation, when fuel orders are placed.
Arrangement of the storage silos	For example, it makes it possible to keep the second storage silo drier, where moisture variations can be reduced by changing the unloading ratios of the storage silos
Prevention of problems	Operators have more accurate advance knowledge of the fuel supplied into combustion, allowing them to react to potential problem situations.
Optimization of production	Optimization of fuel blend in regards of physical characteristics and chemical composition. For example, data can be transferred to complement the boiler’s operational data.
Safe operation of the boiler	The information provided by the storage model can be used to avoid adverse conditions in the boiler.
Learning	The software can be used to go back in time and look at situations after problems occurred and learn from them.

Recommendations for further research are provided below:

- In order to decrease the uncertainty elements in reference samples very large sampling volumes are needed and was not possible for this size of study and manual sorting may be applied to further determine the more accurate fuel composition of the samples.
- The feeding and unloading of the storage silos may be analysed further. During this testing period, it wasn't possible to further research the feeding and unloading of the storage silos. Further research needs to be done regarding of the unloading screws to know how the fuel is precisely unloaded from the silo.
- Some type of mixing formula for storage model could be created that considers the share of small particles that are constantly in the fuel mixture, even if the storage model doesn't consist of those fuel types when the fuel stream is being discharged.
- The storage model's moisture values are based on the data provided from the X-Ray 1. At the moment, the storage model doesn't take into consideration the temporal changes in the quality characteristics of storage silos. Corresponding calculation functions for fuels during storing may be considered. The function could indicate the change in moisture of the fuel during storing, if its initial moisture, the technical characteristics of the storage and environmental conditions of the storage are known. This may be especially considered if the storage model is implemented in the power plant without the second X-Ray that measures the fuel mixture being discharged from the storage silos.
- The arrangement of the storage silos to wet and dry silo was based on the moistures of different fuels and historical data provided by the X-Ray 1. However, due to heterogeneous nature of the wood fuels there occurs a high variation on the quality of the fuel, especially on the moisture content. For further research, the arrangement of the storage silos based on the moisture content needs to be done in real-time based on the data provided by X-Ray 1 and not based on the historical data. This wasn't possible to carry out during this master thesis.
- The duration of test drives needs to be increased, so major changes regarding the fuel composition and moisture can be detected in the long run and the real-time of the storage model can be further analysed.

- Since the fuel indexes are guiding parameters rather than absolute predictions, the risk limits for needs to further be assessed for each boiler individually. Each boiler is different, and the rates of damage being acceptable vary for each boiler.
- Furthermore, for optimizing and recommending fuel mixtures may be established in the storage model in which the risk limits can defined for fuel indexes and heavy metals resulting a range of potential fuel mixtures that meet those specific recommendations. The evaluation tool may be further tested to investigate the maximum safe share of SRF in the fuel mixture without the risk of serious boiler problems. This results as maximising the share of inexpensive fuel in the combustion.
- An optimization of the chemical additives, such as sulfur, to the boiler may also be researched. Moreover, performing fuel analyses may be useful in order to improve the representativity and accuracy of them.

10 SUMMARY

This master's thesis was assigned by Inray Oy Ltd, which has developed FUELCONTROL ® Storage. It is a real-time storage model for solid fuel management in biomass-fired power plants. The aim of the storage model is to provide for the operators and the automation system real-time fuel quality information by collecting process and fuel data from the X-Ray and plant's other system. It can, for example, show real-time energy content, moisture content or fuel distribution in the storage silos. The purpose of this thesis was to verify the functionality of the storage model. In addition, one goal is to create a tool to implement the elemental analysis of the fuels to the model.

The thesis was divided into two parts: theory and empirical. In the theory part, the physical and chemical characteristics of solid biofuels and SRF were gone through, and a more detailed overview of the various fuels was provided in order to comprehend and clarify the features and issues connected with each fuel. Furthermore, multifuel operation in CHP plants regarding the boiler technologies, combustion principles, supply chain and fuel quality measurement were reviewed. Common challenges and problems in the biomass-fed boilers were discussed and finally fuel indexes were reviewed since they offer the opportunities for a pre-assessment of combustion-related problems. The empirical part was made up of test drive plans, their execution, and analysis of the findings. Lastly, the evaluation tool for elemental analysis of the fuels was implemented to the model by utilizing fuel indexes.

The methods used during the experimental section of the thesis were test drives, laboratory analyses and statistical analyses. Three test drives were arranged at the Järvenpää power plant, one for to detect the change from wetter fuel mixture to dryer one, one to get dryer fuel mixture compared to the average moisture content of the discharged fuel stream and one to analyse the baseline situation of the storage silos. The functionality of silos was verified according to the composition and moisture of the fuel mixture. The discharged fuel stream from the storage silos was sampled and the reference samples were analysed and compared to the data provided by the storage model.

As the result of the test drives it was found out that composition of the reference samples corresponds well with the storage model. As the volume flow was fixed after the first test drive, the results indicated that the storage model performed itself realtime when was being compared to the reference samples. The largest difference occurred between the reference samples and storage model in the share of bark and sawdust. Every reference sample consisted of various share of bark, sawdust and other small particles crushed from other fuels during all three test drives, even though these weren’t present in the storage model. As the particle size distribution was done during the third test drive, the results indicated that the fuel mixture discharged from the storage silos constantly consisted of small particles less than 4mm in length. As the operation of storage silos and the storing conditions couldn’t be further researched during this thesis, it can only be assumed that these played a role in the formation of small particles.

The moisture measured by X-Ray 2 stayed relatively constant during all three test drives. The largest variation in moisture occurred in reference samples due to small sampling volume. As the moisture values showed in the first and second layer of storage model are provided by the X-Ray 1 moisture measurements, the storage model doesn’t consider how the storing conditions affects the moisture values. As the evaluation tool for fuel mixtures is implemented to the storage model and demonstrated, it was shown that the fuel indexes had a large variation. Since the boiler problems can happen very rapidly, it is increasingly important to detect fuel mixtures, that can cause serious harm in the combustion process. As the risk limits are better set to match each boiler individually and fuel analyses are done to verify the elemental analyses of the fuel, the tool can perform better to evaluate the fuel mixtures.

For further research it is recommend that the feeding and discharging of the storage silos is investigated in order to further develop the unloading of the storage silos in the model. Also, some mixing formulation for the small fuel particles less than 4mm long may be developed. Moisture function for fuels during storing may be further researched, especially if the second X-Ray aren’t being installed to the power plant to measure the real-time moisture content. It can be concluded that the storage model can be used to optimize the performance of the plant.

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Pictures from the fuel samples from the first drive

 At 13:31	 At 14:04
 At 14:05	 At 14:07
 At 14:09	 At 16:13

 At 16:18	 At 16:20
 At 17:27	 At 17:31
 At 17:34	 At 18:26

 At 18:39	 At 18:40

Pictures of the fuel samples from the second test drive

 At 09:30	 At 09:32
 At 09:34	 At 09:37
 At 09:49	 At 09:55

 At 09:59	 At 10:15
 At 10:21	 At 10:39
 At 10:42	 At 10:46

 At 10:59	 At 11:09
 At 11:22	 At 11:27
 At 11:32	 At 11:40

 At 12:46	 At 12:48
 At 12:56	 At 12:58
 At 13:20	 At 13:25

 At 13:43	 At 14:02
 At 14:21	 At 14:34
 At 15:08	 At 15:30

Pictures of the fuel samples from the third test drive

 At 09:24	 At 09:34
 At 09:38	 At 09:40

 At 09:53	 At 10:01
 At 10:03	 At 10:37

 At 10:42	 At 10:46
 At 10:51	 At 11:09

 At 12:08	 At 12:14
 At 12:30	 At 12:42

Pictures of the different particle sizes taken during the particle size distribution

 Below 4mm	 Below 4mm
 4mm	 4mm

 8mm	 16mm
 40mm	 40mm

Molar calculations

Here is an example how to calculate the chlorine content in fuel from % of dry substance to kmole S/kg ds. Variable X represents the value of chlorine content and the molar mass of chlorine, M_{Cl} is

$$X\%Cl = 0{,}01 * X\frac{kg\ Cl}{kg\ ds}$$

$$0{,}01 * X\ \frac{kg\ Cl}{kg\ ds} * \ \frac{1}{M_{Cl}}\frac{kmole\ Cl}{kg\ Cl} = 0{,}01 * \ \frac{X}{M_S}\frac{kmole\ S}{kg\ ds}$$

A calculation example of the mass ratio to molar fraction sulfur, S, is also provided. Variable Z represents the sulfur content value and the mass fraction, M_S is 22,99 kg/kmole.

$$Z\frac{S\ mg}{kg\ db} * \ 10^{-6}\frac{kg}{mg} * \ \frac{1}{M_S}\frac{kmole\ S}{kg\ S} = \frac{Z * \ 10^{-6}}{M_S}\frac{kmole\ S}{kg\ ds}$$

A calculation formula of the weighted value in the fuel mixture:

$$X = \frac{w_1x_1 + \ w_2x_2 + \cdots + \ w_nx_n}{w_1 + \ w_2 + \cdots + \ w_n} = \frac{\sum_{i=1}^{n} w_ix_i}{\sum_{i=1}^{n} w_i}$$

A formula for calculating the elemental composition of the fuel mixture.

$$X = \ w_1x_1 + \ w_2x_2 + \cdots + \ w_nx_n = \sum_{i=1}^{n} w_ix_i$$

Literature values for Elemental Analysis of Fuel

Specie	**Stump wood** [mg/kg ds]	**Sawdust** [mg/kg ds]	**Forest residue** [mg/kg ds]	**Recycled wood** [mg/kg ds]	**Stem wood** [mg/kg ds]	**Bark, conifer** [mg/kg ds]	**Bark, birch** [mg/kg ds]	**Wood chips** [mg/kg ds]
References	Strömberg &Svärd 2012, 57	Strömberg &Svärd 2012, 41	Strömberg &Svärd 2012, 54	Strömberg &Svärd 2012, 68	Alakangas et al. 2016, 56	Strömberg &Svärd 2012, 96	Strömberg &Svärd 2012, 99	Koppejan & Van Loo 2012
Al	688	156	540	1778	4	500	339	79-580
As	0.2		0.08	30		0.7	0.64	0-1.5
Ba	14	8.9	73.1			100	83	
Ca	2258	1158	5186	4039	787.67	8500	7296	2900-7000
Cd	0.1	0.2	0.22	0.6		0.4	0.32	0.06-0.4
Co	0.1		0.16	1.6		0.5	0.35	0.1-0.7
Cr	2.8	0.5	2.7	56		1.6	0.48	1.6-17
Cu	1	1	2.7	56		5.3	3.8	0.3-4.1
Fe	539	149	225	1855	5.67	200	166	64-340
Hg			0.03	0.1		0.02		0.01-0.17
K	828	498	2059	1110	664	1900	1718	910-1500
Mg	270	183	566	748	193	700	666	310-800
Mn	92	67	430	103	76	400	298	63-900
Mo	0.4		0.1			0.4		
Na	101	27	231	946	12	200	218	20-110
Ni	0.6	0.1	0.7	3		1.4	0.45	1.7-11
P	102	61	463	381	78.67	400	374	97-340
Pb	0.3	0.4	1.5	54		1.6	1.2	0.3-2.7
Sb								
Si	2417	693	3053	7577	81.67	2400	2278	440-2900
Ti	38	6.8	29.4	1039		<100	19	
Tl				0				
V	1.3	0.2	0.5	3		0.5	0.38	0.6-1.4
Zn	17	11	54.3	515		120	115	7.0-90

Specie	**Stump wood** % daf	**Saw dust** % daf	**Forest residue** % daf	**Recycled wood** % daf	**Stem wood** % daf	**Bark, conifer** % daf	**Bark, birch** % daf	**Wood chips** % daf
References	Strömberg &Svärd 2012, 57	Alakangas et al. 2016, 54	Strömberg &Svärd 2012, 54	Strömberg &Svärd 2012, 68	Alakangas et al. 2016, 196	Strömberg &Svärd 2012, 96	Strömberg &Svärd 2012, 99	Alakangas et al. 2016, 54
C	51.8	51	53.1	51.7	52	55	55.5	51.8
H	6.1	6	6	6.3	6	6.2	6.4	6.1
O	41.8	42.8	40.6	41.1	54.2	38.3	37.4	41.2
S	0.18	0.1	0.31	0.84	0.06	0.03	0.04	0.3
N	0.02	0.08	0.04	0.07	0.5	0.4	0.64	0.01
Cl	0.02	<0.00050	0.02	0.05	0.03	0.02	0.02	0.0042