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Master's Thesis

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Utilization of an online quality measurement system in a biomass power plant

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ABSTRACT

Author: Jesse Jäävalli **Title:** Utilization of an online quality measurement system in a biomass power plant	
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Master's Thesis, LUT University, Industrial Engineering and Management, Innovation and Technology Management, 77 pages, 5 appendix pages **Supervisors:** Prof. Olli-Pekka Hilmola	
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Biomass power plants take samples from solid biofuel loads to determine delivered biofuel's average quality. When moisture is known, a biomass power plant can estimate total energy of solid biofuel and use energy-based payment. Manual sampling is the most common way to take samples from loads. It is slow, requires labour and accuracy of results is suspicious because of biofuel's heterogeneity and sampling mistakes. Because of limits of manual sampling other solution have been studied and commercialised. Online measurement measures all biofuel of delivered load and provides information of biofuel's moisture immediately. An X-ray based online measurement system can also recognise impurities, like stones and metals.

Potential benefits of an online measurement for biomass power plants are inspected in this research work. Comparison is mostly done to manual sampling. The research work is made for Inray Oy. The company provides X-ray based online measurement systems and supporting service. The study is made using literature review and semi-structured interview. It includes nine interviewees including two representing biomass supply chain, five representing biomass power plants and two representing biomass combustion suppliers. The focus of study is on solid biofuels from forests.

The research ultimately inspects six different benefits of online measurement. These are feedback for a supply chain, increased accuracy of moisture determining, increased safety, less failures, ash handling saves and no need for sampling labour. An online measurement system can be used to develop supply chain of biomass by providing information to downstream suppliers. However, upstream suppliers have more potential to affect moisture of solid biofuel. More accurate way to determine biofuel's moisture would provide significant amount of saves at least if the power plant is combusting Finnish logging residue. Using an online measurement system would decrease risks of dust exposure physical accidents for drivers of solid biofuel load. An X-ray measurement system recognise impurities like stones and metals. If this information can be exploit, it would decrease amount of failures in the biomass power plant. It would also reduce occurrent of bottom ash from biofuel's combustion. Number of needed increments per solid biofuel load, for moisture analysing, is reasonable if a plant only needs average moisture of a defined time period. Number of required increments is unreasonable if load-based information is needed.

TIIVISTELMÄ

Tekijä: Jesse Jäävalli **Työn nimi:** Online laadunmittausjärjestelmän hyödyntäminen biomassavoimalaitoksessa	
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Diplomityö, Lappeenrannan–Lahden teknillinen yliopisto LUT, tuotantotalous, innovaatio ja teknologiajohtaminen, 77 sivua, 5 liitesivua **Tarkastajat:** Prof. Olli-Pekka Hilmola	
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Biomassavoimalat ottavat niihin toimitetuista kiinteistä biopolttoainelasteista näytteitä selvittääkseen toimitetun biopolttoaineen keskimääräisen laadun. Kun kosteus tiedetään, biomassavoimala voi määrittää kiinteän biopolttoaineen kokonaisenergian ja maksaa biopolttoaineesta energiaperusteisesti. Manuaalinen näytteenotto on yleisin tapa ottaa lasteista näytteitä. Se on hidas, vaatii työvoimaa ja tulosten tarkkuus epäilyttää biopolttoaineen heterogeenisyyden ja näytteenotossa tapahtuvien virheiden takia. Näytteenoton rajoitusten vuoksi muita ratkaisuja on tutkittu ja kaupallistettu. Online mittaus mittaa koko toimitetun lastin biopolttoaineen ja antaa kosteus tulokset välittömästi. Röntgen teknologiaan perustuva online mittaus tunnistaa myös epäpuhtaudet kuten kivet ja metallin.

Tässä työssä tarkastellaan online mittauksen potentiaalisia hyötyjä biomassavoimaloille. Vertaus tehtiin enimmäkseen manuaaliseen näytteenottoon. Tutkimus on tehty Inray Oy:lle. Yritys tarjoaa röntgen tekniikkaan perustuvia online mittausjärjestelmiä ja niiden ylläpitopalvelua. Tutkimus on toteutettu kirjallisen arvion ja puolirakenteellisen haastattelun avulla. Siihen osallistui yhdeksän henkilöä, joista kaksi edustaa biopolttoaineen toimitusketjuja, viisi edustaa voimalaitoksia ja kaksi edustaa biopolttokaluston toimittajia. Työ keskittyy metsästä haettuihin kiinteisiin biopolttoaineisiin.

Tutkimus tarkasteli lopulta kuutta eri online mittauksen käyttöönoton hyötyä. Nämä ovat palautteenanto toimitusketjuun, kosteuden määrittämisen tarkkuuden parantuminen, työturvallisuuden kasvattaminen, laitteiston käyttövarmuuden paraneminen, tuhkan käsittelykustannussäästöt ja näytteenottoon tarvittavan työnteon poisjättäminen. Online mittausjärjestelmää voi käyttää kiinteän biopolttoaineen toimitusketjun kehittämiseen luomalla informaatioita toimitusketjun loppupään toimittajille. Alkupään toimittajilla on kuitenkin suurempi potentiaali vaikuttaa kiinteän biopolttoaineen kosteuteen. Tarkempi kosteuden määrittämismenetelmä toisi merkittävästi säästöjä, ainakin jos voimalaitos polttaisi suomalaista metsähaketta. Online mittausjärjestelmän käyttö vähentäisi kuljettajien riskiä fyysisille onnettomuuksille ja pölylle altistumiselle. Röntgen-mittaus tunnistaa epäpuhtauksia, kuten kivet ja metallit. Jos tämä informaatio voidaan hyödyntää, vähenisi biovoimalan vikojen määrä. Tällöin myös pohjatuhkaa syntyisi vähemmän biopolttoaineen polttamisesta. Tarvittavien lastikohtaisten yksittäisnäytteiden määrä kosteuden analysointia varten on kohtuullinen, jos voimala haluaa vain tiedon keskimääräisestä kosteudesta määritellylle aikavälillä. Tarvittavien näytteiden määrä on kohtuuton, jos kosteus halutaan tietää kuormakohtaisesti.

FOREWORDS

I wish to thank Inray's Mr. Janne Kovanen and Mr. Mika Muinonen for the opportunity to make this research work and letting me be part of the company. I express my gratitude to my supervisor professor Olli Pekka-Hilmola for his valuable support. I thank all the interviewees for giving me a little bit of their time.

I thank my father for caring. I thank brother for caring. I thank my mother for caring more than enough.

Mikkeli, 11st of March

Sincerely,

Jesse Jäävalli

NOMENCLATURE

BFB	bubbling fluidized bed
CFB	circulating fluidized bed
CHP	combined heat and power
FBC	fluidized bed combustion
FSE	Fundamental Sampling Errors
GSE	Grouping & Segregation Errors
IDE	Increment Delineation Error
IEE	Increment Extraction Error
IPE	Increment Preparation Error
NIRS	near infrared spectroscopy
TOS	Theory of Sampling

$\mathbf{A_i}$	inherent availability
$\mathbf{A_a}$	achieved availability
$\mathbf{A_o}$	operational availability
$\mathbf{C_{tot}}$	maintenance cost
M	moisture (p-%)
MTBF	mean time between failures
$\mathbf{q_{gr}}$	gross calorific value at constant volume (J/g)
$\mathbf{q_{net}}$	net caloric value at constant pressure (J/g) for a dry sample
$\boldsymbol{q_{net.M}}$	net calorific value as delivered at constant pressure (J/g)
$\mathbf{R(t)}$	reliability
$\boldsymbol{\lambda}$	failure rate

1 INTRODUCTION

This research work was made for a Finnish company Inray Oy. It provides an online measurement solution for solid biofuel industry. The study started 2018 at late May and ended 2019 in February. The reason for the study was to understand better the challenges and possibilities of quality measurement of solid biofuels.

This chapter introduces the content of the research. First the background and reasons for this study are explained. Next the objective and research questions are presented. Last part includes the structure of rest of the research work.

1.1 Background of the research

Producing electricity and heat in thermal power plants requires lots of solid fuels, like coal, peat and solid biofuels. In many standpoints coal and peat are superior compared to (unpressed) solid biofuels. Their calorific value is better, storing is easier and quality is more regular. However, coal and peat also provide more environmental issues and governments aims to reduce or completely remove their use. In Finland, coal is prohibited to be in use in 2029 (Helsinki Times, 2018.). With taxation of peat, Finnish government makes it financially less attractive energy source than logging residue (Huttunen, 2017). Solid biofuel is renewable, and it has good availability in many countries. It is also in large use. In Europe it's currently the most important renewable energy source. According to Eurostat (2018) Around 49.4 % of primary production of renewable energy was from wood or other solid biofuels in 2016. Most of this is heating energy, but importance of solid biofuels uses to produce electricity is increasing.

In energy trade market the value of solid biofuel is connected to amount of energy it contains. Because of solid biofuels' large heterogeneity (Lestander, 2013), kilograms or volume aren't reliable sources to calculate the total heat energy. For solid biofuel, heterogeneity means a lot of variances in quality, calorific value and physical and chemical properties. Common way to determine solid biofuel's thermal energy is to calculate it from the calorific value and weight. To determine calorific value, the biofuel is needed to be analysed or measured. Moisture is important factor to calculate calorific value of delivered solid biofuel load (SFS-EN ISO 18125:2017, 2017, p.29-30). Payment purpose sampling is also in use for coal trade market (Rowland, 2014). Biofuels sampling accuracy calculations are based on formulas used in coal industry (Järvinen, 2012, p. 4).

Combination of manual sampling and using drying oven is the current norm to measure moisture of biofuel loads. However, the results come late. Drying of manually taken samples can take 24 h (SFS-EN ISO 18134-2:2017:en, 2017, p. 7). Handling of samples require labour. Representativity of sampling is also criticized because of solid biofuels large heterogeneity (Fernandes-Lacruz & Bergström, 2016; Wagner, 2012). Manual sampling can be done properly, but it's limited. Mechanical sampling systems and online measurement systems are optional solutions for manual sampling to determine biofuel loads' moisture. In mechanical sampling, samples are taken by machines. An online measurement systems solid biofuel in a real time. Different technologies for biofuel's online measurement solutions have been studied in researches. Usually these studies have been about accuracy of the studied technology. In Nyström's and Dahlquist's (2004) review, X-ray, near infrared spectroscopy, radio frequent microwave and indirect methods were inspected. Fernandes-Lacruz and Bergström (2016) researched accuracy of a commercial high-frequency-based online measurement system. Torgrip and Fernandez-Cano (2017) demonstrated X-ray based method to determine solid biofuels moisture and ash. An online measurement system's potential benefits are presented in some researches. The benefits are connected to the limitations of sampling as it doesn't include sampling labour and it measures all delivered biofuel. Because an online measurement system gives immediate information, process control and performance optimization are possible (Skvaril et al., 2017). It might also be used to create feedback for suppliers. Measuring solid biofuel/biomass at many different stages would increase efficiency of biomass supply chain from forest to power plant (Sikanen et al., 2017). Although there are many studies about accuracy of online measurement systems, its benefits in solid fuel field aren't as much discussed. Researches of benefits of online measures are needed.

Commercial online measurement systems already exist, and these solutions can provide potentially many advantages comparer to manual sampling. Inray Oy is a Finnish company from Mikkeli, that was founded in 2009. The company provides X-ray based measurement service solutions to biomass power plants and sawmills. This includes measurement system, software and support service. (Inray 2018) The online measurement system is called FuelControl. When solid biofuel is moving at a conveyor, FuelControl measures its moisture and identifies impurities, like stones and metals. To measure delivered loads moisture Fuel Controller is installed close to beginning of the conveyer before the solid biofuel load is mixed with any other loads. If the FuelControl is used to create more steady combustion of solid biofuel, it's installed closer to plant's end use.

1.2 Objectives and scope

The objective for this thesis is to study benefits of using an online method to measure solid biofuels in a biomass power plant. Some benefits are already believed to known, but the thesis inspects these claims thoroughly and where these benefits are based on. The comparison is done mostly to a manual sampling and oven drying. In manual sampling, samples are (usually) taken by solid biofuel load drivers. Oven drying is a basic way to analyse solid biofuel samples' moisture. The researcher question is: *What are the potential benefits of X-ray based online measurement comparer to manual sampling in a biomass power plant?*

An online measurement system can be potentially used to improve solid biofuel's combustion process if it's installed close to solid biofuel's feeding system to the boiler. This possibility is also studied although it isn't related to manual sampling.

Effects of an X-ray measurement system may depend on many factors, like where the biomass power plant is, solid biofuels type and it's supply chain. The thesis is focused on solid biofuels from forests. There are other technologies to measure solid biofuels moisture in online and some of these solutions are mentioned during the literature review. Large amount of information (literature and interview) is related to Finland/North Europe and this scales the viewpoint. Fluidized bed combustion is an effective way to convert solid biofuels to heat energy and the technology is usually used in middle - large size biomass power plants. By European directives large combustion plant's output is over 50 MWth (European Commission, 2019). The thesis also focuses on fluidized bed combustion.

1.3 The research methods

Sources of the research are acquired by literature review and by interviews. The interviews were in semi-structured form and provide mostly qualitative data. Based on the literature review and the interview, results were inspected partly with calculations.

Large parts of the studied literature were documents of Finnish Standards Association (SFS). These standards are European standards that are also positioned as Finnish national standards. They are provided by the International Organization for Standardization (ISO). Other remarkable source were materials created by VTT Technical Research Centre of Finland. Some of the sources were acquired by recommendations. LUT-University’s library database was used to find sources. The search was done by using combination of key words like; biomass, supply chain, combustion, conveyor, fluidized bed, online measurement, solid biofuel, sampling, transport and forest residue. Part of the sources are acquired through or from websites.

A Semi-structured interview includes list of themes and possible key questions to be covered. The questions can between interviews. Order of the questions can change based on how the interview proceeds. The information acquired from semi-structured interviews can be recorded with audio recorder or possibly by taking notes. (Saunders, Lewis, Thornhill, 2016, p. 391)

For the interviews, ten different persons were approached by e-mail and nine of them agreed. Nine persons were thought to provide enough information for conclusions. The interviewees were chosen, based on their location (for practical reasons), plant’s size, used fuel and to get different kind of approaches. Five of the interviewees were power plant presentative, two of them were biomass supply chain presentative and two of them were boiler supplier presentative. The interviews were done by using an interview form. It was tested during the first interview and some questions were changed. Chapter 6 provides more information about the interviews. Original English version of the interview form is presented in Appendix 1. The interview form helps to connect each interviews result. It increases designed researches repeatability (Ellram, 1996). After the first interview necessary time was taken before the next interview. It’s important to have some space after an interview, to adapt the new information, before proceeding to the next one (Saunders et al. 2016, p. 571).

Literature review and interviews were done simultaneously and the acquired results from both sources affect each other. Acquired information from interviews provide better understanding of the subject. This helped to wide and narrow subjects for literature review. Findings from the literature review create possibility to ask more specific questions of certain areas. In Eisenhardt's (1989) review, altering data collecting methods during the research is reasoned because in case studies the goal is to understand each case situation individually, not produce summary statics.

Based on the literature review and the interviews, results were inspected partly with calculations. The numbers used in calculations are acquired mostly from interviews and from secondary data. Secondary data is information that was collected originally for other purpose (Saunders et al. 2016, p. 316). The secondary data was used to reason calculations and increase believability of them. The results of calculations are presented. Used formulas are based on the literature review. The formulas were also used to create three different Excel sheets.

1.4 Execution of the research work

In addition of the introduction chapter, this thesis includes chapters forming the literature review, results of the semi-structured interview, examination of the results and the conclusion. Figure 1 presents input and output model of the thesis.

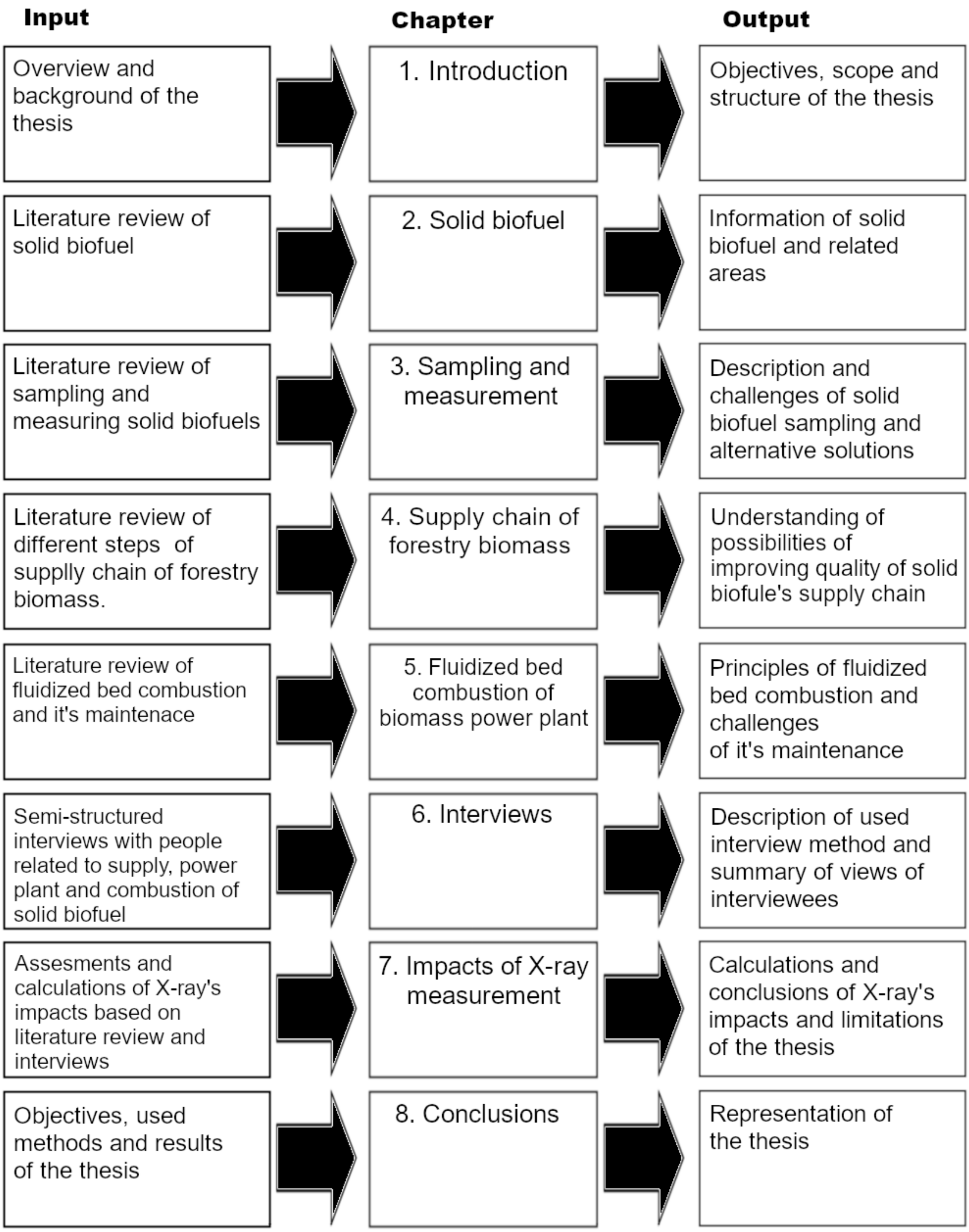

Figure 1 Structure of the thesis

Chapters 2 to 5 focus on literature. Order of these chapters is designed to be natural for reader to go through. Information acquired from the “Solid biofuel” -chapter is connected to all following chapters. “Sampling and measurement” -chapter explains different options to determine biofuel’s moisture. The “Supply chain of forestry biomass” -chapter and the “Fluidized bed combustion of biomass power plant” -chapter are in chronological order in point of view of biopower produce. Results of the “Interviews” -chapter are easier to survey after literature review. “Impacts of X-ray” is the second last chapter because it’s based on previous chapters. It inspects founded benefits of online measurement with calculations. The thesis is summarized in its final chapter “Conclusions”.

2 SOLID BIOFUEL

Based on International Organization for Standardization's (ISO) standard, solid biofuel is defined as solid fuel that is produced directly or indirectly from biomass (SFS-EN ISO 16559, 2014, p. 25). It's combusted in a biomass power plan to produce electricity and heat. Solid biofuel can be divided to different categories based on its origin. The categorising can differ depending on the source. In ISO standard the main categories are woody biomass, herbaceous biomass, fruit biomass, aquatic biomass and blends and mixtures. (SFS-EN ISO 17225-1:en, 2014, p. 4). Rentizelas (2013) categorizes origin of biomass to virgin wood, energy crop, agricultural residue, municipal solid waste and industrial waste. In this thesis, studied solid biofuels' origin is mostly the same than the ISO's woody biomass category incudes.

2.1 Woody and forestry biomass

Woody biomass is a solid biomass type and one of the suitable biomasses for heat and energy production. In Finland, calorific value of woody biomass is usually close to around 19-20 MJ/kg depending on the material (Alakangas et al., 2016, p. 62). It's usually strongly heterogenous, which creates challenges to combust it efficiently.

Origin of woody biomass is mostly from forest. In 2015, 30.8 % of earth's land area was covered by forests which is about 39 991 336 km^2 (World Bank, 2018). Biomasses that are contained from these forests are called forestry biomass and divided to three types. Primary includes trunks from full grown trees. Because producing bioenergy from woody biomass is secondary to other wood products, primary forestry biomasses aren't usually used to produce energy. Secondary includes branches and crowns from fully grown trees and smaller trees' trunks. There isn't usually any other use for secondary forest biomass than combustion to energy. Tertiary is the third forestry biomass type and it includes residues after processing primary forestry biomass. (Wolf, 2013) Some of the basic woody biofuels from forest are explained below.

Wood chips are chipped woody biomass with defined particle size. There are more than one types of wood chips like, cutter chips, forest chips, green chips, stem wood chips and whole tree chips. (SFS-EN ISO 16559:en, 2014, p. 30)

Forest chips is used as a generic term for delimbed stem wood chips, whole-tree chips, logging residue chips or hog fuel (Alakangas et al., 2016, p. 12). Usually forest chips are made from woody biomasses that can't be used other commercial use (Vesisenaho, 2003).

Stem wood chips can be made either from delimbed stem wood or undelimbed ones. In first option stem wood chips are usually called stem wood chips. Undelimbed stem wood chips are usually called whole-tree chips. Stem wood chips are from logging sites or forestry properties either as a by-product of logging or as an energy tree (Vesisenaho, 2003).

Logging residue is the woody biomass that is left after logging and transporting. It includes branches, needless and timbers that are too small or other way unfit for nonenergy commercial use (Vesisenaho, 2003).

Hog fuel from stumps/stump wood chips are made from stumps or thick roots. Collecting stumps for energy is possible in regeneration felling areas or if a forest area's land use is about to change. (Vesisenaho, 2003)

Wood pellets are produced from wood chips. Wood chips are dried, finely ground and finally pressed into pellets. Wood pellets strength is higher energy density comparer to chips. They are preferred if the biofuel is needed to be transported over a long distance. (Wolf, 2013)

Beside forestry biomass, woody biomass includes also used woods and other virgin woods that aren't from forest. Used woods are divided to chemically treated and untreated products and residues. Other virgin woods can mean for example trees from gardens and parks. (SFS-EN ISO 17225-1:en, 2014, p. 9)

2.2 Solid biofuel's properties

Solid biofuel's properties affect fuel's quality for combustion. Calorific value and moisture are important to determine solid fuel's heat energy. Ash, its composition and melting behaviour have many effects to solid biofuels combustion. High density increases solid fuels heat energy per volume. Different kind of densities should not be mixed to each other's.

The importance of each property varies and depends on the fuel type. For more efficient trading ISO standard (SFS-EN ISO 17225-1:en, 2014) was created to classify solid biofuels.

In Table 1, required known properties for some different woody biofuels are presented. If fuel's property (for example bulk density) is required to know (normative), its panel is marked with **N**. If the property is suggested to be known (informative), it is marked with **I**. Blanc panel means property isn't needed to know. Chemical properties are marked with **N/I** because they are normative only if the biofuel is chemically treated. Because solid biofuel's dimension can include various requirements, the requirements are mentioned in the dimensions' columns.

Table 1 Required known properties of solid biofuel (SFS-EN ISO 17225-1:en, 2014)

	Wood chips	**Hog fuel**	**Bark**	**Sawdust**
Dimensions	Main fraction, coarse fraction, max. length of particles, max. coarse sectional area of the coarse fraction **N**	Main fraction, coarse fraction, max. length of particles, max. coarse sectional area of the coarse fraction **N**	Nominal top size, coarse fraction **N**	
Fine fraction content	**N**	**N**		
Moisture content (as received)	**N**	**N**	**N**	**N**
Ash content	**N**	**N**	**N**	**N**
Nitrogen content	**N/I**	**N/I**	**N/I**	**N/I**
Sulfur content	**N/I**	**N/I**		
Chlorine content	**N/I**	**N/I**	**N/I**	**N/I**
Net calorific value or Energy density	**I**	**I**	**N**	**N**
Bulk density	**I**	**I**	**I**	**I**
Ash melting behaviour	**I**	**I**	**I**	**I**
Others			Needed to be stated if bark is shredded or not into pieces **N**	The size of the used sieve for sieving **I**

2.2.1 Calorific value

Calorific value expresses how much material can potentially release heat energy by complete combustion. In Finland Its unit is normally megajoule per mass (MJ/kg) (Alakangas et al., 2016, p. 27), but formulas of ISO use unit (J/g) (SFS-EN ISO 18125:2017, 2017). Calorific value can be presented as a gross calorific value (q_{gr}) or as a net calorific value (q_{net}).

To calculate gross calorific value, the analysis sample with specific weight is burned in a bomb calorimeter under specified conditions. The temperature change is established by comparing the temperature before and after combustion of the sample. Prior to the combustion, water is added to the bomb to create saturated vapor phase. This allows all the water of the sample to be regarded as liquid water after the combustion. With temperature change and effective heat capacity of the calorimeter, the gross calorific value can be calculated with some other value correcting factors. (SFS-EN ISO 18125:2017, 2014, p. 7) ISO's short definition for gross calorific value is "measured value of specific energy of combustion of solid burned in oxygen in a calorimetric bomb under such conditions that all the water of the reaction products is in the form of liquid water" (SFS-EN ISO 16559:en, 2014, p. 16).

In Finland, calorific value is usually presented in a net calorific value form. In net calorific value, released energy of the sample's vaporized water has been taken account. (Alakangas et al., 2016 p. 26) It's main difference comparer to gross calorific value is form of the water after the combustion. The net calorific value at constant pressure (J/g) for dry sample is calculated based on the gross calorific value using formula: (SFS-EN ISO 18125:2017, 2017, p. 29-30)

$$q_{net.d} = q_{gr} + 6.15w(H)_d - 0,8(w(0)_d - w(N)_d) - 218.3w(H)_d$$

$$= q_{gr} - 212.2w(H)_d - 0.8(w(0)_d + w(N)_d) \quad (1)$$

Where

q_{gr}	is the gross calorific value at constant volume (J/g)
$w(H)_d$	is the hydrogen content (% by mass)
$w(0)_d$	is the oxygen content (% by mass)
$w(N)_d$	is the nitrogen content (% by mass)

If the moisture is known, net calorific value as delivered at constant pressure (J/g) can be calculated with formula: (SFS-EN ISO 18125:2017, 2017, p. 29-30)

$$q_{net.M} = q_{net.d} \times (1 - 0.01M) - 24.43 \times M \quad (2)$$

Where

M	is moisture (p-%)
24.24	is the correction factor for enthalpy of vaporization

2.2.2 Moisture

In this thesis moisture is proportional to wet weight. Moisture per wet weight informs how many percentages of total mass of material is water (Alakangas et al. 2016, p. 15). Moisture is an important factor for solid biofuel's quality because solid biofuel's net calorific value is reliant to the moisture. During combustion, water doesn't release energy. It vaporizes which consume energy that usually solid biofuel-based power plant can't use. (Formula 1, 2) Because moisture affects caloric heating value, it's one of the determining factors to estimate the price of woody biofuels. In Table 1 from Chapter 2.2, moisture content is marked as part of classification for every woody biomass type.

Solid biofuels moisture can be measured by drying it. The needed apparatus are drying oven, dishes and trays and balance. First clean trey's weight is measured to nearest 0.1 g. Next the sample's weight is measured in a balance to nearest 0.1 g. The sample should weigh at least 300 g. The trey with sample is placed to a (378.15 ± 2) K oven. The trey is in the oven until the sample's constant mass has been achieved. The used time is not constant, and it depends on particle size of the sample, rate of atmospheric change in the oven and thickness of the layer material. Generally, the drying should not exceed 24 h. (SFS-EN ISO 18134-2:2017:en, 2017, p. 7) Drying in an oven doesn't only vaporise water, but also causes losses of volatile compounds (Samuelsson et al., 2006). After the mass is constant the trey is placed back to the balance from the oven and measured. The moisture can be calculated using formula: (SFS-EN ISO 18134-2:2017:en, 2017, p. 7)

$$\mathrm{M} = \frac{m_2 - m_3}{m_2 - m_1} \times 100 \quad (3)$$

Where

m_1 is mass of the empty container (g)

m_2 is mass of the container and the sample in it before drying (g)

m_3 is mass of the container and the sample in it after drying (g)

2.2.3 Composition of dry matter

Dry matter or dry substance is the mass without any moisture. It can be divided to ash, volatile matter and fixed carbon. It can be also divided to organic and inorganic matters. The amount of each and moisture of solid biomass are determined with proximate analyses, that form one of the two major analytical procedures of biomass. Other group, ultimate analyses determines sample's carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S) and in some cases chlorine (Cl), fluorine (F), and/or bromine (Br). Because composition of biomass is complex compared to other energy sources like coil and oil, its organic and inorganic components are highly varying. (Lestander, 2013) Figure 2 presents composition of biomass dry matter.

Figure 2 Biomass composition (Lestander, 2013)

Biomass is mostly organic matters. Balance between most of organic matters, cellulose, hemicellulose, lignin, extractives, sugars starch and proteins, depend on origin of biomass and affects how much examined biomass contain carbon (C), hydrogen (H), oxygen (O), sulphur (S) and nitrogen (N). These impacts resulting biofuel's energy value, amount of emissions and how combusted solid biofuel wears boiler. Sulphur causes SO_2 emissions

(Basu, 2006, p. 142) and nitrogen is important factor for NO_x emissions. Wood's N to C ration is low, around 0.003 or below. (Lestander, 2013)

When solid fuel is burned perfectly in oxidizing atmosphere, mass that is left is called ash (Raiko et al., 1995, p. 92). Ash is made of inorganic content. It comprises metals and non-metals. Plants can contain substances such silicon (Si), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), phosphorus (P), sulphur (S), chlorine (Cl), aluminium (Al), iron (Fe), manganese (Mn), nitrogen (N), copper (Cu), zinc (Zn), cobalt (Co), molybdenum (Mo), arsenic (As), nickel (Ni), chromium (Cr), palladium (Pb), cadmium (Cd), vanadium (V) and mercury (Hg). Most of these elements are nutrients for plants. Pure wood contains only low amount of inorganic content, around 0,3-0,5 %. For bark it can exceed 10 %. (Lestander, 2013) Amount of ash in waste wood is 1.9 % (Basu, 2006, p.128) Contamination of biomass increase amount of inorganic content. It means usually geogenic materials like soil particles and atmospheric pollutants. Contaminants can carry to solid biofuels during growth, harvesting, handling and processing. Contamination is problem specially for low-value and residual biomass like, straws, branches, tops, stumps or lignocellulosic waste in bio-based industrial processes. (Lestander, 2013)

Volatile matters are the part of the dry solid fuel that vaporize during high heat, quick heating and protection from air. Amount of volatile substances depends on many variables, like temperature, time of heating and pressure. Fixed carbon is mass that remains after vaporization of volatile substances and removing of ashes. (Raiko et al., 1995, pp. 92)

2.2.4 Density

Solid biofuel's density can be expressed more than one way. Bulk density is usually used for biomass loads. It's calculated by dividing the measured mass of load with the space it's put on (SFS-EN ISO 16559, 2014, p. 23). If a bucket is poured full of chips, bulk density of the chips is the total mass minus the buckets mass divided by the buckets volume.

Basic density is calculated by dividing solid biofuel's dry mass weight with the biofuel's green volume. (Alakangas et al., 2016 p. 9) Green volume is volume of wood, with moisture at least enough to saturation point.

Solid density is calculated by dividing the solid biofuel's weight with its volume without the air between the chips. The volume can be measured by solving the amount of water it displaces if the biofuel is immersed in water. (Alakangas et al., 2016, p. 18)

Gross density, alias particle density, is calculated by dividing the solid biofuels weight with its real volume. The real volume excludes volume of pores in a material. (Alakangas et al., 2016 p. 15)

3 SAMPLING AND MEASUREMENT

When a new biofuel load arrives to a biomass power plant, the load is usually analysed to determine its quality. Analyse is done primary to determine biofuel's price, but also for emissions trading or other specific purpose (Alakangas, 2014, p. 34). Most of the time the analyse is done to combination of randomly picket increments of delivered loads. To get reliable results, sampling must be done correctly. Taking samples can be done manually or mechanically. Alternative way to determine load's quality is to measure it with an online method.

After sampling, increments are usually at some point merged to one sample called a combined sample. Combined samples are used to determine solid biofuel's moisture and properties of dry matter (Alakangas, 2014, p. 34). The merged increments are usually from a specific supplier from a defined time period. The increments can also have a same specific fuel type and/or delivery location. A combined sample is usually divided to smaller parts to make it easier to handle. This can be done by quartering method for example. Only some of the divided parts are used for final analysing. Rest of the samples are rejected. (Alakangas, 2016, pp. 46-51) This decreases needed labour for analysing as there is less samples to be handled.

3.1 Correct way to take samples

In a sample-based moisture analyse, sampling is the most vulnerable part of the process. According to Alakangas et al. (2016), it's believed that errors of analysis' results are 80 % because of sampling, 15 % because of processing the samples and 5 % because of the analysis itself. Importance of representation of taken samples is especially important for solid biofuels as it's usually very heterogenetic. More heterogenous the measured load is, more important the representative factor is (Wagner, 2012).

In a good and correct sampling, the object is to get representative samples of the entire load. During sampling each part of the load should have equal chance to get selected. Responsible group of sampling must create a full plan to make sure the sampling is done correctly. (SFS-EN ISO 18135:2017:en, 2017, p. 9) Sampling should be done close as possible of the receiving station and several independent increments should be taken from the entire solid biofuel stream. Sampling is recommended to do when solid biofuel is in motion because stationary biofuels increase segregation. Larger parts of solid biofuel roll down to lower edges of pile and smaller part stay middle and upper top of the pile. (Alakangas et al., 2016 p. 9, 45)

Correctness of sampling can be valued with Theory of Sampling (TOS). TOS is used to determine, if the sampling is done with representativeness. Most important in sampling process is to remove sampling bias. It’s a systematic deviation between results of sampling and true average accuracy. Based on TOS, sampling process can create two kind of errors, incorrect and correct. Incorrect sampling errors are unwanted because these errors create guaranteed sampling bias. These errors are avoidable if the sampling is done right. Incorrect sampling errors are: Increment Delineation Error (IDE), Increment Extraction Errors (IEE) and Increment Preparation Error (IPE). IDE is error that decreases samples representativity because the sampling’s physical extraction doesn’t cover all acquired dimensions to give each part of the total load same chance to be picked. IEE happens when some particle types’ chance to get in the sample are lowered because the sampling equipment rejects these samples (bouncing for example). IPE means errors after extraction, like evaporation and sabotage. Correct sampling errors are errors, that can’t be avoided even with correct sampling. Correct sampling errors are divided in Fundamental Sampling Errors (FSE) and Grouping & Segregation Errors (GSE). Both errors reflect the loads heterogeneity. In TOS, heterogeneity is divided to two parts. FSE increases, when constitutional heterogeneity increases. Constitutional heterogeneity describes materials individual fragments variances comparer to each other’s. GSE increases when distributional heterogeneity increases. Distributional heterogeneity describes how the loads chemical and physical properties varies between its different areas. (Wagner, 2012)

In theory, drying samples in an oven can also create some error. Samuelsson (2006) measured, with analytical method, losses of volatile organic compounds of different kind of biomasses during the oven-drying process. Mostly the losses weren’t significant (mostly under 0.3 % of dry matter). Usually analytical errors aren’t needed to be worry about because they are around 10-100 times smaller than sampling errors (Wagner, 2012).

3.2 Desired accuracy of sampling

Because samples are used to determine value of delivered biofuel loads, the accuracy of sampling is economically important for both parties, a power plant and suppliers. Overall precision (P_L) determines samples accuracy. The overall precision is calculated by using formula: (SFS-EN ISO 18135:2017, 2017, p. 12)

$$P_L = 2 \times \sqrt{\frac{V_i}{N_{SL} \times n} + \frac{V_{PT}}{N_{SL}}} \tag{4}$$

Where

V_i	is primary increment variance
n	is number of increments per (sub-) lot/load
N_{SL}	is number of sub- lots/loads in the lot
V_{PT}	is preparation and testing variance

Primary variance (V_i) and preparation and testing variance (V_{PT}) can be calculated if enough sample-based information is contained from the same type of fuels. Both factors can also be assumed based on two different ways. These assumptions should be verified afterwards if it's possible.

- Assuming V_i or/and V_{PT} is/are based on values of similar materials or previous similar characterization experiences.
- Assuming V_i or/and V_{PT} is/are based on given appendices from SFS-EN ISO 18135:2017 standard. (SFS-EN ISO 18135:2017, 2017, pp. 12-13)

When the wanted P_L is determined, the minimum required number of increments per (sub-) lot/load (n_{min}) should be calculated. Formula 5 for n_{min} is derived from Formula 4:

$$n_{min} = \frac{4V_i}{N_{SL} \times P_L^2 - 4V_{PT}} \tag{5}$$

In some case N_{SL} is changeable factor that can be used to increase P_L. In ISO standard there is determined maximum weight for a (sub-) lot. In manual sampling it's 2 500 tons and in mechanical sampling recommended weight is 5000 tons. (SFS-EN ISO 18135:2017, 2017, pp. 10-11) Weight limit was created for a sea transporting.

In Formula 5, it's assumed that all sub- lots/loads in the lot are the same size. However, sizes of loads vary, and this is needed to take account during sampling. In Finnish Wood fuel guidelines at least two increments are taken per 50 loose m^3. Based on the same guideline for wood and peat loads, one lorry (tractor) requires at least two increments, semi-trailer (<100 m^3) requires at least four increments, tractor-trailer (100-160 m^3) requires at least six increments when two of them are from tractor and four from trailer, and container combinations requires at least two increments to be taken per container. With this amount of increments average moisture's precision of three to five loads is around 3 p-%. (Alakangas & Impola 2015, p. 32)

3.3 Manual sampling

In manual sampling, increments are taken by employees, usually drivers, who deliver the solid biofuel loads. Sampling methods vary between different biomass power plants. For good sampling, ISO request all samplers to be instructed or trained to be able to use the specific needed device or method for sampling (SFS-EN ISO 18135:2017, 2017). During manual sampling, equipment's like sampling box, scoops, shovels, forks, grabs, probes, pipes, frames, hooks and drills can be used for different kind of needs (SFS-EN ISO 18135:2017, 2017, p. 26). The need for a specific equipment depends on the biofuel plant and used method of manual sampling. Manual sampling can be done for example from falling biofuel stream, from a stationary stockpile or from a conveyer belt.

Falling stream-based sampling is a common way to take samples. Usually this is done during unloading the vehicle. (Alakangas et al. 2016, p. 42) In manual sampling of falling stream, a sampling box or equivalent is needed. The sampling box is directed under falling stream and it should cut the cross section entirely. Other solution is to take many increments from various random points. Taking increments manually from falling stream works practically only with slowly moving masses. (SFS-EN ISO 18135:2017:en, 2017, p. 30)

Other common way to take samples is to take increments from a stationary stockpile. This is usually done soon after unloading the load. (Alakangas et al, 2016, p. 43) If sampling is done from a stationary stockpile, it should happen during creating the stockpile or during unloading it. The stockpile is recommended to be visually divided into three horizontal layers. Total number of increments per layer is dependent on the volume ratio between a layer and the stockpile. (SFS-EN ISO 18135:2017:en, 2017, p.28) It's important to take increments from all highs to decrease segregation. Correct sampling from sideview is shown in Figure 3.

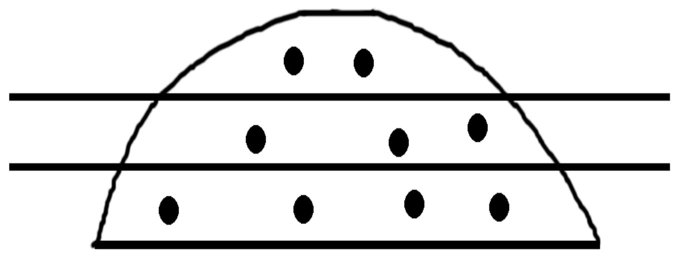

Figure 3 Sampling points of a stockpile (SFS-EN ISO 18135:2017:en, 2017, p. 28)

If sampling is done from a conveyer belt, a sampling frame can be used to separate increment from the stream. Sampling frame consist two parallel metal plates. The plates, that are across to the fuel stream and separated from each other, insulate part of the solid fuel when moved down. The conveyer belt is needed to be stopped during this time. (SFS-EN ISO 18135:2017:en, 2017, p. 17, 30).

Accuracy of driver-based manual sampling seems to depend on solid biofuels type. In Järvinen's (2012, p. 37) report highly heterogenous Finnish logging residue was 4.59 percentage point less humid when sampling was done by driver, comparer to when sampling was done by VTT. When increments were taken from whole-tree chips -loads, there wasn't practically any different (-0.06 pp). In Mustonen's bachelor thesis (2017, p. 27), samples from drivers were 5.3 pp less humid comparer to samples from a robot. Other results were sawdust (-0.7 pp), peat (-1.3 pp) and whole-tree chips (-1.2 pp).

3.4 Mechanical sampling

In mechanical sampling, the sampling is done by machine. It removes possible human errors that manual sampling might include, and it decreases drivers' work. A mechanical sampling can be done by various ways. Falling stream sampling includes usually mechanical driver box with a constant speed. It moves across falling materials and its opening is perpendicular to direction of the falling stream. In cross-belt sampling the machine takes increment from entire cross section of the moving conveyor belt. It also needs to extract sampling all the way to the bottom of the belt. The machine must be strong to maintain the sample inside of it as the rest of the stream moves by it. (SFS-EN ISO 18135:2017, p.24) In mechanical drill sampling, the drill is drilled to the solid biofuel to get random increments. (SFS-EN ISO 18135:2017, pp. 83-86)

At least some mechanical sampling solutions might create challenges that aren't problem for manual sampling. In Järvinen's (2012, p. 31) report, manual and drill based mechanical sampling were compared. Results were mostly close to each other (five of six loads). However, in one load the average moisture was over 10 % higher in increments taken by mechanical sampling than taken by manual sampling. Järvinen speculated that water from previous high moisture loads, might have wet conveyer and mechanical sampling. IEE was also suggested as reason for error as it has been typical problem for mechanical sampling and manual samples seemed to include more large particles.

3.5 Measurement solutions

Different technologies for solid biofuel's measurement are studied. Most of the solutions use radiation. Companies offer commercial solutions to replace traditional sampling methods. Some solutions provide the moisture information quickly, but not immediately. The Senfit BMA Online takes small continuous side stream of the biofuel stream and measures its moisture with microwave-based technology (Österberg, Antikainen and Melkas, 2014, p.29). Bestwood's BAS-700A puts NIR based sensor inside the delivered solid biofuel load and measures its moisture from several places (Österberg et al., 2014, p.35). Two companies offer X-ray based measurement systems. Inray and Swedish Mantex provide online solutions that measure moisture of total load and its impurities (Inray, 2018; Mantex, 2019). Not all alternative solutions are installed close to conveyer. Some commercial measurement solutions are used to replace oven-based moisture determination, not the sampling process. Valmet offers magnetic resonance-based MR Moisture Analyzer for laboratory use (Valmet, 2013). Alternative laboratory analysers give more immediate results than by drying samples with an oven.

3.5.1 Near infrared spectroscopy

Near infrared spectroscopy (NIRS) is an optical method for quantitative and qualitative analysis of materials. It uses wavelengths in range 700-2500 nm. (Järvinen, 2013, p.19) NIRS is used in pharmaceutical sector, food and feed industry and pulp and paper industry. Basing on vibrational spectroscopy, NIRS detects interactions between electromagnetic radiation and the chemical bonds of the matter in the near infrared spectral region and extracts information from this (Skvaril et al. 2017). Near infrared-based measurement doesn't give immediate information about biofuel's elementary composition. Calculations are done by using multivariate methods. The penetration depth of NIRS depends on the measured material, but practically it measures only the surface of solid biofuel. Near infrared-based moisture measurement is also sensitive to temperature changes. (Aulin, 2013)

3.5.2 Microwave

Microwave methods can be based on absorption, phase shift or/and resonance sensor for moisture metering. Most common way is to utilize absorption, that is known as microwave energy attenuation. (Järvinen, 2013, p. 22) Radio frequency spectroscopy analyses microwaves' absorption. Different moistures create different attenuation and time delays that affects to the microwave pulse. The acquired information from this relationship is one factor used in a model for estimating measured biofuel's moisture. For correct analyse, materials density and temperature are needed to know. Radio frequency spectroscopy measures through the entire part of measured material. This increases its credibility with more heterogeneous materials. (Aulin, 2013; Järvinen, 2013, p. 22)

3.5.3 Radiometric measurement

Radiometric measurement can be based on scattering, absorption, natural activity metering, or excitation. In radiometric transmission absorption, irradiated X-ray travels through measured material. It describes materials density. (Järvinen, 2013, p.23) Dual energy X-ray absorptiometry uses two different energy levels for irradiated photons (Aulin, 2013). Neutron activation analysis measures water content by detecting hydrogen atoms from free water molecules (Valmet, 2018). In X-ray fluorescence analysis biofuel's elements are determined based on wavelengths and intensities of X-rays emitted by the material. The material emits X-ray, when it's excited by rays from X-ray tube. (Whiston, 1996, p.166)

Radiometric moisture measurement isn't sensitive to temperature changes or snow or ice in samples (Järvinen, 2013, p.24).

3.5.4 Neutron activation analysis

Neutron activation analysis is used mostly to analyse compounds containing hydrogen. (Timo Järvinen, 2013, p.30). It measures water content by detecting hydrogen atoms from free water molecules (Valmet, 2018). There aren't currently commercial online solutions for solid biofuels based on neutron activation analysis. Österberg et al. (2014) concludes wood and biomaterials being challenging for the technology because these matters are mostly hydrocarbons with a lot of hydrogen atoms.

3.5.5 Common electricity measurement

Common electricity measurement is based on resistance. Changes of biomass moisture affects its electrical properties and because of this, moisture measurement can be based on resistance of dielectric properties of a sample. Resistance-based moisture measurement methods can be done in the radio frequency or microwave range. Other affecting variables to relative permittivity are density variations, ionic conductivity and temperature. Usually resistance-based solutions can measure moisture below 30 %. (Järvinen, 2013, p.25)

3.5.6 Attenuation-based gamma-ray measurement

Lappalainen (1989) presents the principle for attenuation-based gamma-ray measurement, when wood is measured. Utilizing absorption is also most common way in microwave measurement (Järvinen, 2013, p. 22). In Lappalainen's (1989) research note, attenuation-based system measures moisture by using acquired information when the radiation source radiates through the measured material to the detector. The measured material (absorber) causes attenuation to the radiated radiation. The attenuation is exponential if the radiation beam is infinitely narrow, the radiation doesn't diverge (meaning the source is infinitely far), scattered radiation from the absorbing material isn't detect, spectra of radiation beam doesn't change if radiation is monoenergetic, or the absorber is infinitely narrow. Assuming these conditions, and when there is an absorber between the source of radiation and detector, number of pulses can be calculated with formula:

$$N = N_0 \, e^{-\mu x} \tag{6}$$

Where

N_0	is number of pulses when there is only air between source of the radiation and the detector
μ	is a linear absorption coefficient (1/ length unit)

N and N_0 are the information that can be acquired by attenuation-based online measurement system. With this information linear absorption coefficient can be calculated. Leading from Formula 6, linear absorption coefficient can be calculated by using formula:

$$\mu = \frac{1}{N} \times \frac{dN}{dl} \tag{7}$$

Wet wood's linear absorption coefficient depends on absolute dry wood's linear absorption coefficient and linear absorption coefficient caused by water. Absolute dry wood's linear absorption coefficient depends on dry wood's density and linear absorption coefficient caused by water depend on difference between the wed wood's density and absolute dry wood's density. Linear absorption coefficient for wet wood can be presented with formula:

$$\mu_{wo} = a + b \times \rho_{d.w} + (\rho_{w.w} - \rho_{d.w}) \times \frac{\mu_{wa}}{\rho} \tag{8}$$

Where

a and b	are constants that depend on measurement geometry and used energy
$\rho_{d.w}$	is density of absolute dry wood
$\rho_{w.w}$	is density of wet wood
$\frac{\mu_{wa}}{\rho_{wa}}$	is water's mass attenuation coefficient with used energy

Based on Formula 8, $\rho_{w.w}$ can be calculated, if μ_{wo}, a, b, $\rho_{d.w}$ and $\frac{\mu_{wa}}{\rho_{wa}}$ are known. If a, b, $\rho_{d.w}$ and $\frac{\mu_{wa}}{\rho_{wa}}$ stays constant only, μ_{wo} is needed to be determined to calculate $\rho_{w.w}$. If the relationship between $\rho_{w.w}$ and moisture (M) is known, M can be calculated in theory. (Lappalainen, 1989, pp. 7-8, 24)

4 SUPPLY CHAIN OF FORESTRY BIOMASS

Before solid biofuel is combusted in a powerplant, it’s delivered through supply chain. Optimizing forest supply chain is complicate and many researches has been made. Scholz et al. (2018) study analysed 132 forest supply chain related publications. 25 % of those publications were biomass related. Reviewed studies included various optimization methods with different approaches and some similarities. Scholz et al. (2018) writes “Although each model has it’s specific use, generally these optimization models are then applied to define the optimal number, type, and/or location of a new terminal and/or biorefinery in relation to biomass supply, product demand, and the operations in the supply chain.” For example, Campanella et a. (2018) research considers both primary and secondary level forest products. Sosa et al. (2015) study present scenarios where only solid biomass’ with defined moistures were allowed to be used.

If the biofuel comes directly from a forest, the delivery starts from wood purchase. Figure 4 presents regular stages of forestry biomass supply chain. In Finland, supply chain of forestry biomass includes many smaller partners. Most of the wood is collected from private forests and usually harvesting and transporting is done by small entrepreneurs (Hakkila, 2003).

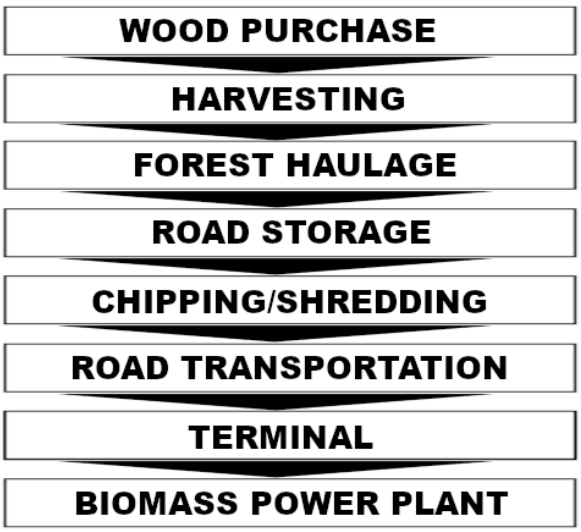

Figure 4 Supply chain of forestry biomass

Supply chain of forestry biomass is believed to benefit from an online measurement. Many supply chain operators saw a real-time feedback of load quality as a positive factor that could help suppliers react to the quality of wood chips. For example, if the moisture of load were noted to be currently too wet, the supplier could start to deliver ordered loads from a different storage (Jahkonen & Ikonen, 2014). A biomass power plant can benefit from developed biomass supply chain when it lowers solid biofuel's purchase price, increases its availability or/and increases its quality (Miktech, 2014).

4.1 Harvesting and forest haulage

During supply chain, it's possible to effect solid biofuel's final quality. In Jahkonen's and Ikonen's (2014) interview, operators in North-Karelia believe that they can affect the quality of solid biomass load as the difference is created with good communication and diligent work. General view of interviewed were that quality of wood chips begins from harvesting, transporting in woods and storing.

To decrease moisture of solid biofuels, the best time to harvest in Finland is in early spring. It can create beneficial results compare to later harvesting because storing time takes advantage of high-pressure deficit of April and May (Nurmi & Hillebrand 2007). However, in practice, most of utilization time of forestry biomass depends on supply and harvesting of industrial wood (Hakkila, 2003). In Finland, most of harvesting of industrial wood is traditionally during autumn-winter time for reasons like summer vacations and spring's mud season (Ranta, 2003). The balance might change. Finnish forest company Metsä Forest aims to increase significantly it's harvesting during unfrozen road time to balance the yearly wood supply. (Metsä Forest, 2018)

After harvesting a forest, remaining logging residue's quality and parameters depend on logging sites. First thinning provides least amount of woody mass. Regeneration felling in spruce stands provide significantly more biofuel for combustion. Most of it is branches, needles and if there is butt rots, refused logs. The amount of logging residue after harvesting depends on tree species, number of trees, the size of stems, the volume of branches and the amount of rot. (Alakangas et al. 2016 p. 67)

According to Sauranen (2003), by pruning logging residues to piles, it's easier to acquire later, efficiency of forest haulage of logging residue increases, and the logging residue's quality is better. In other hand, logging residue piles also decreases efficiency of forest haulage of industrial wood. In Finland the regulatory organisation Luonnonvarakeskus (Luke) offers partly weather observation databased moisture model to determine logging residues moisture during forest haulage. (Luke, 2018)

4.2 Road transporting and chipping/shredding

Road transport moves a solid biomass load from road storage to a biomass power plant. A load can also be transported to a terminal. In a financial standpoint, road transporting is affected by form of delivered solid biomass, it’s bulk density and energy density, transport distance and vehicle. During transportation of forest biofuels, space is usually the limiting factor instead of weight. (Ranta, 2003) Because water increases solid biofuels weight, it’s moisture should affect transportation costs. Hakonen & Laurila (2011) studied, how decreasing moisture affects fuel costs of road transporting. By transporting hardwood chips and diesel fuel price as 1.3 €/l, the fuel cost decreased only a little bit. If amount of load transport is 25 000 km and the moisture decrease 10 %, the fuel saves would be around 1 500 € for the transportation entrepreneur.

In a biomass supply chain, the process is built around location of the chipper (or shredder) because the location decides in what form solid biomass is transported. (Hakkila, 2003) A chipper can be near at a harvesting area, a roadside storage, in a terminal or where the solid biofuel is used. Chipping near at a harvesting area is usually only preferred on load bearing flat ground. Snow is a challenge for near harvesting chipping, so in Finland, it’s better to do during unfreeze road time. Roadside storage chipping is done when solid biomass is moved from road storage to a transporter. The solid biomass is chipped directly to a vehicle. It’s the most basic method. In terminal chipping, biomass is delivered to a terminal, where it is chipped. Shared terminal is practical for small biomass power plants. Chipping in a power plant simplifies the supply chain process. (Kuitto, 2005) If a chipper is in upstream of supply chain, the transportation costs are lower because compactness of chips is around 35-40 %, when for logging residue it’s 15-20 %. If the chipper is close to downstream, maintenance costs of vehicles are lower, and chipping is more efficient. (Sauranen, 2003)

4.3 Storages

Biomass storages can be located close to collection point, intermediate site or at the power plant (Rentizelas, 2013). A road storage is located on roadside, near a harvesting area. It's a temporary storage from where the biomass is transported away by road transportation. Terminals are storages, that includes many solid biofuels loads from many road storages. Sizes of terminals varies, but even smaller ones are much larger than one road storage. In Finland, medium size terminal is 1-3 hectare large (Raitila & Virkkunen, 2017). At minimum, fuel storage is required in a power plant as a safety stock for unexpected situations (Rentizelas, 2013).

Storing is used to ensure solid biofuels availability around the year and it increases the fuels quality. Storing time, geographical location, phase point of the supply chain and form of the biomass are needed to take account when planning solid biofuel's storing in its supply chain (Ranta, 2003). Possible storing solutions difference based on the requirements. Terminal based and fast-track supply solutions provide two different kind of solutions. Large-scale storages between the origin and destination points, terminals, are used as a solution to balance supply of biomass, lower resources, improve quality and when the roadside storing is periodically prohibited due to environmental reason (Raitila & Korpinen, 2017). In fast-track supply, the woody biomass is transported as fresh to a power plant for a significant amount of year, to reduce storage time and costs (Sikanen & Kinnunen, 2017).

To reduce solid biomass moisture to low as possible during storing by utilizing natural drying, studies suggest letting residue dry over a summer and use it before winter. In Filbakk et al. (2011) research in Braskereidfoss, Norway, average moisture content reduction during summer compared to winter was 12 %. In winter the moisture content can increase slightly (Filbakk et al., 2011) because of snow and higher air humidity. In spring, whole tree fuel stocks' moisture can be 3-6 % lower if the stocks are covered during melting of snow (Nurmi & Hillebrand, 2007). Although drying can be optimised based on the seasons, it might not be the best solution in all standpoints. Based on Lauren et alt. (2018) calculations, solid forest fuel harvested in spring at North Karelia is better to use in May if possible. After May, effect of dry matter lost to biofuel's total energy is greater than effect of biofuel's natural drying. Instead of natural drying, biomass can also be dried by using heat energy. In the early 2000's, idea of storing biomass near a power plant and using waste heat for drying purpose was described (Rentizelas, 2013).

Dry matter loss decreases the dry matter of wet woody biomass, during the time it's not utilized (Ashton, 2010). During storage, most important reasons for dry matter loss are living cell respiration, biological degradation and thermo-chemical oxidative reaction (Krigstin & Wetzel, 2016). The amount of loss per time depends on many variables like moisture, temperature, oxygen concentration, and size, form, degree of compaction and location of the solid wood fuel (Routa, et al., 2018). Dry matter loss varies, but in Northern Europe based on experiments, it isn't more than 3 % per a month. ((Filbakk et al, 2011, Routa, et al., 2018).

5 FLUIDIZED BED COMBUSTION OF BIOMASS POWER PLANT

Fluidized bed combustion (FBC) is the most common way to produce heat energy from solid biofuel in a large scale. It is divided to two methods, bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). BFB was invented by Fritz Winkler in 1921. Winkler observed, took measures, filed a patent and build commercial fluidized bed plans. CFB was invented in 1938 by Warren Lewis and Edwin Gilliland. they weren’t aware about existence of BFB that was presented 17 years earlier. (Basu, 2006, pp. 1-3).

The common way to produce energy, is to combust the solid biofuel to create heat steam. With turbine, the energy of steam is be converted to electricity. Some power plants utilize part of heat energy without converting it to electricity. The heat is used partly to industry or to warm houses. Industrial use can mean for example using steam to cook fodder in fodder plant (Herrfors, 2017). Warming houses with energy from thermal power plant is called district heating. The stations that provide, both electricity and heat for use are called combined heat and power (CHP) plants. CHP plants are more efficient than conventional thermal power stations. By utilizing heat, plants efficiency can be close to 90 % when for conventional thermal stations it’s somewhere between 35-60 % (Siemens, 2018; ZBG boiler, 2016).

5.1 Fluidized bed combustion

Fluidized bed doesn’t require much of pre-processing for fuels and it’s suitable to burn solid fuels with various kind of qualities and with strong heterogenous. Its strengths are also cheap desulphurisation and low nitrogen oxides emissions and unburned gases. (Hyppänen & Raiko, 2002, p. 490)

In FBC, solid fuel is burned in a fluidized bed and it moves and mixes continually in the bed. If the fuel’s ash contain is low like in many solid biofuels, the feed is supplemented with sand to compensate the net loss in bed material. (Basu, 2015, p. 309). Fluidized state is created in a boiler when gas is leaded through to granular material layer with right speed. The speed that is required to make particles levitate is called minimum fluidization velocity (U_{mf}). If U_{mf} increases, rising gas bubbles occur in the fluidized bed. This is called bubbling fluidized bed. By increasing the speed more, the gas speed starts to get closer to particles free drop speed. This is called terminal velocity (U_t). In this speed, bubbling fluidized bed transforms to turbulent fluidized bed. The gas bubbles disappear, and particle loss increases. In BFB boilers the gas speed is between U_{mf} and U_t. If the gas speed is more than U_t, more particles is carried with the gas and solids separator is needed. It separates moving particles from the gas and returns them back to reactor. In CFB boilers the speed is needed to be over U_t. (Hyppänen & Raiko, 2002, pp. 490-492) Figure 5 shows different stages of fluidized bed.

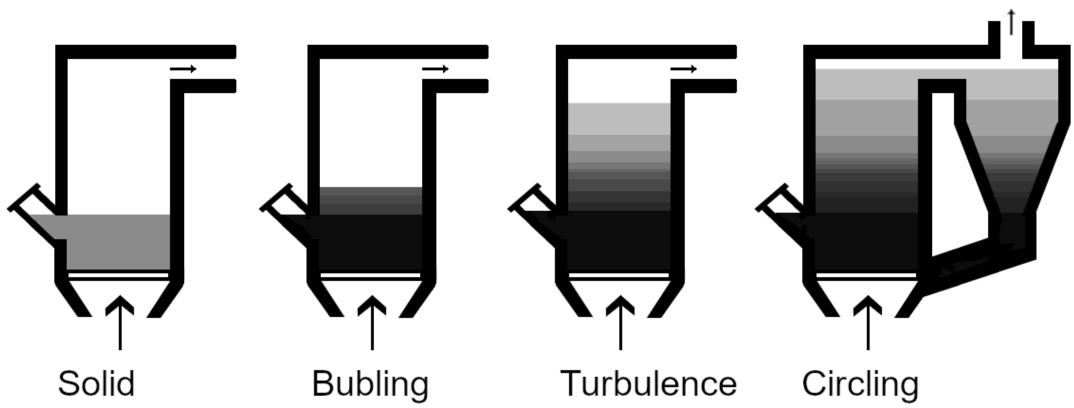

Figure 5 Fluidization velocity's effect to differential pressure and type of flow (Hyppänen & Raiko, 2002, p. 492)

In fluidized bed boiler’s fuel feed system, chipped/crushed fuel is transported by a conveyer to a bunker. From there the fuel is dropped to metering device (screw or belt-weight feeder). Biofuels are challenging for certain feeding systems. Operating biofuels creates problems to solve like, excessive equipment wear, feeding system’s fuel hang-ups and bottlenecks, tramp metal separation challenges and fuel’s varying moisture. (Basu, 2006, p. 211, 341)

5.2 Bubbling and circulating fluidized bed boilers

Fluidized combustion can be done in BFB boiler or CFB boiler. In BFB boiler diameter of the sand particles are usually around one millimetre and velocity is 1-3 m/s. Bed temperature is between 750-950 °C. It can combust solid fuels with higher moisture compared to CFB and because of its simple structure, it’s cheaper. (Hyppänen & Raiko, 2002, p. 490) CFB boilers work much higher speed around 8-10 m/s and particles diameter is under 0.5 mm (Hyppänen & Raiko, 2002, p. 490; Basu, 2016, p. 6). Using CFB boilers allows to use wider range of solid biofuels than BFB boilers (Hyppänen & Raiko, 2002, p. 490).

In BFB system, combustion chamber contains a boiler and lean freeboard above it. Released energy from combustion splits between fluidized bed and freeboard. CFB loop contains furnace or CFB riser, gas-solid separation, solid recycle system and possibly external heat exchanger. (Basu, 2006, pp. 215, 253)

In CFB, air system consumes most of the power. It includes primary air fan, secondary air fan and loop-seal air fan blower. The primary air enters the combustion chamber through the air distributor grate. It blows bottom of the combustion chamber. The second air delivered to bed through ports located around chambers’ periphery and above and above the bed’s lower tapered section. The loop-seal air is blown to loop seal through air distribution grids. BFB air system includes primary air and possibly secondary air. The primary air enters to bed trough a distribution. The distribution spreads the air across the bed to prevent solids dropping into the air plenum. (Basu, 2006, pp. 253-254, 213)

A normal BFB boiler contains three heat exchangers in one steam generation system, economizer, evaporation and superheater. Economizer preheats feedwater close to a saturation temperature, when the water is pumped through it to the drum. Evaporation heats the feedwater to saturated steam by absorbing the combustion heat. Lastly the saturated steam is superheated by the superheater. (Basu, 2005, p. 215, 223) In CFB the water is heated by economiser, evaporator, superheaters and reheaters. After economiser and evaporator, the steam goes through a complex back and forth tube and superheaters. Complexity minimizes tube cost and it’s overheating. (Basu, 2005, p. 257)

5.3 Ash and emissions

From combustion, two kind of waste are created, flue gas and solid residue. Flue gas exits from top of the combustion chamber. It passes through convective section and the stack, and releases to the atmosphere. Solid residue contains bottom ash (also called coarse ash) and fly ash. Bottom ash is the rougher ash that can be drained from the bed by opening the drain valve. Finer fly ash entrains with flue gas. It's collected by economizer hopper or a collection device (Basu, 2005, p. 215). In complete combustion, ash contains only inorganic matters. However, specially bottom ash can contain significant amount of unburned organic matters (Saqib & Bäckström, 2016).

Impurities like soil glass, rocks and metal increase the amount of ash. For biopower plans more ash means more invests to ash handling. (Alakangas et al. 2016, p. 187) It creates undesirable impacts during combustion, like slagging and fouling of heat transfer surfaces. Slagging and fouling are consequences of ash melting that can be categorised to four different stages. The stages are based on temperatures that cause specific melting behaviours:

- deformation temperature (DT)
- sphere temperature (ST)
- hemisphere temperature (HT)
- flow temperature (FT). (Alakangas et al., 2016, pp. 35-36).

Biofuel's ash can be reused. If ash is used for fertilization in Finland, its quality needs to meet requirements of the law (Maa- ja metsätalousministeriö, 2019). Table 2 shows some estimations, how ashes of peat, wood and coal, are compatible for different kind of re-use.

Table 2 Compatibility of ash for different applications (Gango & Kuokkanen. 2018)

Type of ash		**Compatibility of ash**			
Fuel	**Source of ash**	**Forest fertilization**	**Earthworks engineering**	**Mines**	**Cement and concrete**
Peat	Coarse ash	(+)	+++	-	-
	Fly ash	(+)	+	++	++
Wood	Coarse ash	++	+++	-	-
	Fly ash	+++	++	++	(+)
Peat + Wood	Coarse ash	+	+++	-	-
	Fly ash	+	++	++	+
Coal	Fly ash	-	+++	++	+++
+++ = excellent ++ = good + = satisfactory (+) = weak - = no estimate or no use					

European Union has determined limit values of emissions for combustion plants. The limit values are for SO_2, NO_x and dust (particulate) emissions and depends on the plant's thermal input and age. Table 3 presents emission constrains of solid biomass plants when thermal input is at least 5 MW. Emission limit value unit is (mg / Nm3). It presents how much emission can be in one normal cubic meter of flue gas. The calculations are required to be made in conditions of 273.15 K, 101.3 kPa, after correction for the flue gases' water vapour content, and with a standardised oxygen content, 6 % (Directive (EU) 2015/2193, 2015; Directive 2010/75/EU, 2010).

Table 3 Emission limit values of solid biofuel

Combustion plant's size	Medium (5-50 MW)	Medium (5-50 MW)	Large (50-100 MW)	Large (100-300 MW)	Large >300 MW)
Age	Existing	New			
SO_2	200 (1)	200 (1)	200	200	200
NO_x	650	300	300	250	200
Dust	30 (2)	20 (3)	30	20	20
1) If a plant combusts exclusively woody solid biomass, the value doesn't apply 2) If plant's thermal input is equal or between 5 and 20 MW, the limit value is 50 mg/Nm^3 3) If plant's thermal input is equal or between 5 and 20 MW, the limit value is 30 mg/Nm^3					

Existing combustion plant is defined as "a combustion plant put into operation before 20 December 2018 or for which a permit was granted before 19 December 2017 pursuant to national legislation provided that the plant is put into operation no later than 20 December 2018" (Directive (EU) 2015/2193).

5.4 Challenges of maintenance

Maintenance describes all actions used for retaining and restoring a system or product to keep it in preferred condition. It can be divided to two categories, corrective maintenance or preventive maintenance. Corrective maintenance includes all scheduled maintenance. It's used after the system's or product's condition has decreased to restore these conditions.

Preventive maintenance includes all actions of scheduled maintenance. It includes all actions to retain the system or product in a preferred condition. (Blanchard, 1981, pp. 19)

Maintenance cost is sum of many factors from all echelons and the entire life cycle of the system. Some of the boilers' maintenance is preventive and some proactive and it include also breakdown and productivity maintenance. (Basu, 2015, p.326) Formula 6 shows seven main factors that determine the total maintenance cost. (Blanchard, 1981, pp. 352-369) It doesn't include profit loss caused by failures.

$$C_{tot} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 \tag{9}$$

Where

C_1	is personnel and support cost of maintenance. It includes labour costs from corrective and preventive actions of maintenance.
C_2	is cost of spare and repair. The cost is formed from spare and repair parts and consumable materials that are required for maintenance. It includes purchase, actual materials and inventory costs.
C_3	is cost of test and support equipment. It is formed from annual recurring maintenance cost of test and support equipment. It doesn't include operational costs as it is already included in C_2.
C_4	is transportation and handling cost. It includes all sustaining transportation and handling costs of maintenance.
C_5	is cost of maintenance training. It includes training costs of employees that are related to maintenance. The cost is formed for example from instruction time cost, supervision costs and training aids costs.
C_6	is maintenance facilities cost. This factor forms from annual recurring costs of maintenance shops that are related to occupancy and support. The cost includes for example modification and painting.
C_7	is technical data cost. It includes the costs from data that's required to support maintenance of the system.

5.4.1 Failures

In biomass power plants, failures cause economic losses because of property damage and loss of profits. Property damage includes corrective actions like costs of replace parts and cost of extra work of employees. In cases where failure creates unavailability, loss of profits is usually higher than property damage. In De Antonellis S. and De Antonellis M. (2014) study, loss of profits was on average ten time higher than property damage in cases (two biomass and two incinerator power plant) where plant's component failed, and each's total power capacity was between 33-36 MW. Loss of profits are high because biomass is replaced by more costly energy source during the time the biopower can't be used because of failure. Failure time was also significantly long in these cases. Same study's data shows how loss of profit per day can vary. In case 1, Average daily losses were around 71 000 €. In case 5, the average was 15 300 €. In both calculation components' "reparation time" was assumed to be same as total failure time. The total failure time might have been longer.

Frequency of failures can be measured with failure rate. It presents how many failures occur to a system during a specified time:

$$\lambda = \frac{amount\ of\ failures}{specified\ time} \tag{10}$$

With failure rate, reliability can be calculated. Reliability is the probability, that a system works preferred way during a certain amount of time. Reliability depends on failure rate and the defined time of the use of system. When the time and the failure rate are known, reliability can be calculated with formula: (Blanchard, 1981, pp. 26-28)

$$R(t) = e^{-\lambda t} \tag{11}$$

Failure rate isn't usually constant. Typically, it's affected at least by the current stage of system's service life. Figure 6 presents bathtub curve, that show's typical changes of the failure rate during system's service life. Because of debugging, failure rate can decrease at the beginning. After debugging failure rate stays constant. When system's service life's end is getting close, its failure rate starts to increase because of wear out. (Blanchard, 1981, p. 29)

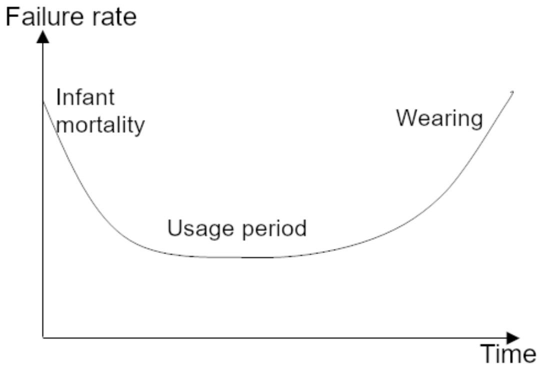

Figure 6 Bathtub curve (Finkelstein, 2008, p. 2)

Many factors affect to system's failure rate and all of them are needed to take account to determine the combined failure rate. If all the factors need to work at together, for the system to work, it's called series networks. If it's enough that only one of the factors is working, it's called parallel networks. If some factors are alternatives and some obligated for the system to work. It's called combined series-parallel networks. (Blanchard, 1981, pp. 31-32)

Failures affect biomass power plants availability. System's availability measures how likely the system would be available at required satisfaction level. Availability can be defined different ways. Inherent availability measures system's probability to operate satisfactorily at any point in time as required when it's support is ideal. It doesn't take account preventive or scheduled maintenance actions, logistic delay time or administrative delay time. It's calculated with formula: (Blanchard, 1981, pp. 66-67)

$$A_i = \frac{MTBF}{MTBF + \bar{M}ct} \tag{10}$$

Where

MTBF	is mean time between failures
$\bar{M}ct$	is mean corrective maintenance time

MTBF can be calculated with failure rate. They are each other's inverse when used time of corrective maintenance isn't included to the failure rate. Corrective maintenance time is the time required to repair a system to restore it operational status. It can include for example detecting the failure, preparation and isolating the fault, disassembly, repair, reassembly, adjustment and verification. (Blanchard, 1981, pp. 28, 35-36)

Achieved availability measures system's probability to operate satisfactorily at any point in time when it's support is ideal. It's close to inherent availability, expect it takes account preventive maintenance. It's calculated with formula: (Blanchard, 1981, pp. 66-67)

$$A_a = \frac{MTBM}{MTBM + \bar{M}} \tag{11}$$

Where

MTBM is mean time between maintenance

$\bar{M}$ is mean active maintenance time

Both MTBM and $\bar{M}$ take account preventive and corrective maintenance. MTBM is meant time between these operations and $\bar{M}$ is mean time of these operations. (Blanchard, 1981, pp. 45, 17)

Operational availability measures system's probability to operate satisfactorily when called upon in an actual operational environment. It's the most reality way to measure system's availability. It's calculated with formula: (Blanchard, 1981, pp. 66-67)

$$A_o = \frac{MTBM}{MTBM + MDT}$$

Where

MDT is mean maintenance downtime

MDT includes all the time when the system is not able to perform. In addition to maintenance time, logistic delay time and administrative delay time are included. (Blanchard, 1981, pp.18) Table 4 shows operational mean availability of some peat or coil power plans from Finland and USA.

Table 4 Mean availability (Räsänen, 1997, p. 79)

Plant	Country	Mean availability (%)
SEVO	Finland	97.2
ENSO	Finland	96.7
PORI	Finland	97.9
OULU	Finland	98.0
KAVO	Finland	98.2
KUHMO	Finland	98.8
ROVO	Finland	97.9
ACE	USA	94.6
UDG	USA	94.1
CAMBRIA	USA	96.4
MORGANTOWN	USA	90.7

5.4.2 Challenges of solid biofuel

Using biomass as fuel requires to take account different factors. Biofuels are generally more reactive than fossil fuels, which increase problematicity of phenomena like bed sintering, slagging, fouling and corrosion. Three of them, sintering slagging and fouling are caused because of alkali, that solid biofuels usually contain a lot. Alkali salts react with silica which is common in fed sand. The reaction creates eutectic mixture of silicate. It's low melts point, 754 ℃ makes the particles sticky. This disturbs the fluidized bed and generate local hot spots which lead to agglomeration and sintering. Fouling constitutes on boiler's tube. It's sticky deposition of ash that reduces temperature of the steam and increases the metal temperature by affecting heat transfer to the tubes. (Basu, 2005, p. 129-130)

In corrosion, surface gets damaged slowly when it reacts with surrounding materials. In fluidized bed boiler, corrosion is caused because of fuels with high chlorine and sulphur content, poor combustion control, high gas temperature, high metal temperature, local reducing atmosphere or tube surface erosion, to external surface. Chlorine corrosion is common in biofuel-based boilers. (Basu, 2015 p.315) Fuels with high chlorine increases corrosion in superheaters. In high temperature steam, when chlorine reacts with alkali metals, low temperature melting alkali chlorides are formed. The alkali chlorides deposit on superheater tubes and reduce their heat absorption. This causes high-temperature corrosion. The temperature of the flue gas when entering to superheater should be lower than ash melting point. (Basu, 2006, p.130) In a fluidized bed boiler, high-temperature corrosion means corrosion in superheaters caused by chemicals and molten phase deposits. Impurities of fuel becomes often to ash deposits. (Caillat & Vakkilainen, 2013, p.209) High-temperature corrosion forces to keep temperature lower in biofuel based fluidized bed boilers compared to coal based fluidized bed boilers. Hupa (2012) writes: “High-temperature corrosion caused by the fly ash is the main reason why the steam temperature and power production efficiency in FBC installations using biofuels are significantly lower than in similar boiler using coal.”

6 INTERVIEWS

Semi-structured interviews were completed with an interview form consisting four parts. Division to four parts was based on the literature review and theoretical frame of this thesis. The parts were following: (1) supply chain of biomass, (2) quality measurement methods of solid biofuel, (3) solid biofuel and (4) combustion of solid biofuel in a boiler. The interview form was tested during the first interview and some questions were changed. The amount time used in each part, depended on the interviewee. Total used time for each interview was around one hour.

Part of questions in the interview form were in a general level so preconceptions of the interviewer wouldn't limit out the potential answers. For example: "What challenges a supply chain (of biomass) contains?" However, some general questions confused interviewees. Many time examples were needed, or a question was ignored. More specific questions of the interview form were based on the topics from theory part. For example: "How seasons and weather are taken account in the supply chain?" Number of questions that weren't written in the interview form increased as more interviews were made. These questions were based on answers of the previous interviewees.

The interviews were done face to face (6), by phone (2) and one was done by Skype. During a interview, the interviewer took notes of what a interviewee said. After the interview, notes were opened to full sentences. This version was sent to back to the interviewee by e-mail to make sure there wasn't misunderstandings. Mostly the full sentence versions were accepted as they were. One interview's written version was changed significantly after the interviewee's feedback. The need was partly recognised even during the interview as the sound quality of phone was bad. Couple of interviewees sent more specific answers to certain questions. In these answers, the messages didn't change much, but they become more informative.

Ten different persons were approached by e-mail and nine of them agreed for an interview. The interviews were done between 8.8. – 12.10.2018. Five of them were power plant presentative, two of them were biomass supply chain presentative and two of them were boiler supplier presentative.

One interviewee was from Estonia and others were from Finland. All interviewees were familiar with Inray's X-ray solution at some level. No interviewee mentioned any other online solution. In automatic solutions, only one company was mentioned by its name, but clearly there was experiences of more than one kind of automatic solution. All interviewees gave permission to use their name. The names and plant related information are found from Appendix 3. In the interviewee result, names aren't used with one exception.

6.1 Supply chain

One of the main focuses of the interviews was biomass supply chain. Questions were focused on supply chain of forestry biomass. Other sources were also mentioned as they also affect supply chain of forestry biomass. Industrial by-product means waste from processing the wood. Most of the questions answered by the biomass suppliers were supply chain related. Representatives of boiler suppliers weren't asked to answer supply chain related questions. Table 5 presents excerpts of supply chain related answers.

When asked directly about challenges of biomass supply chain, most of them were related to winter and storing. An interviewee said the greatest challenge is optimisation of storages. Winters are challenging because of large demand and conditions. It's hard for used technical equipment's. Other interviewee mentioned last winter (2017-2018) being mild, which made transportation difficult. Rainy fall before the mild winter made it even more challenging, as it had decreased winter storages. Based on interviews, most important reason for storing was to create buffers for winter time. One interviewee also mentioned quality management as a reason. If forestry biomass can't be used when it's dry, it's transported to a terminal to keep it dry for winter use.

Most of the biomass was acquired from Finland. Distance radius vary between plants. The max radius was mentioned to be 50, 100, 120 or 150 km. Usually profitably was the reason to limit, how far away loads were brought. Although, one interviewee mentioned how industrial by-product can be delivered from afar as it's necessary to get out of the industry area.

Table 5 Supply chain related answers

	Excerpts from the answers			
About challenges of biofuel's supply chain	*Winters are challenging because of large energy demand. During winters, it's tough for technical equipment's*	*The greatest challenge is to optimise storage*	*The demand isn't steady and forest residue isn't good for storing. Foreseeing is challenging because it's needed to be done around 1.5 year before the solid biofuel is used*	
About where the combusted solid biofuels are brought	*The fuel purchase deals are multi years long. The fuel is acquired in under distant of 100 km, and many times the distant is 100 km.*	*The fuel purchase distance is under 150 km.*	*Forest residues are acquired under 100 km. Other fuels are usually from farther away*	*Around 95 % from fuels comes from Finland and 5 % comes from Russia. The radius is around 50 km*
About communication and feedback between the supply chain and the plant	*In a good communication system, the plant should be informed about upcoming cars, and report threatening congestion to suppliers so it would not be created. Communication should therefore work in the big picture, i.e. between the institution and all the suppliers.*		*An agreement is made with suppliers that includes quality criteria and thresholds. If the limit values are exceeded, feedback is given*	*The faster the feedback, the greater the effect*
	If there are problems, instant feedback is given. #### have an online web-based info system where all the acquired information of solid biofuels is stored. The suppliers have online access to this system to check information of their own biofuel and get this way timely feedback		*Written reclamation can be given, if the goods (solid biofuel) are bad. Sometimes the driver announces himself if the goods he delivered are bad. Bad goods are unloaded in the yard or in extreme cases turned, but this is very rare. If the bad stuff gets more regularly from the same supplier, this will lead to further action.*	
About using storages	*Terminals help prepare for consumption peaks. They are intended to fill with good quality fuel because the mixed and moist fuel evaporates and smoulder (cause fire).*	*In theory, it would be good if the chips could be stored under a roof and dry by their internal heating. In practice, however, storage does not make sense because it generates costs. The only reason for storage is to create buffers.*		*Storage is done for the buffer and by the circumstances when there is not enough demand. Storage is also done for quality management.*
About improving supply chain of solid biofuel	*If the entire supply chain is done carefully, 10% more biomass is obtained. 5% is obtained when entrepreneurs in the chain benefit from lower moisture (attitude change). An additional 5% will be gained when entrepreneurs consider how to get dry as possible biomass*		*Online methods allow you to see quickly if moisture is clearly too high (60%) in the delivered load. This can be reported to the purchaser. Now the supplier can stop bringing solid biofuel from the storage with wet biofuel. Although solid biofuel with 60 % moisture can be recognised also with naked eyes. Practically online measuring doesn't bring much of value in this kind of situation. No load is turned away, because it's too wet, but a wet load can be unloaded to the storage field*	

Communication between a power plant and a supplier is a normal practise, but implementations varies. Some of it is by e-mails and phone callings. If quality is bad, a reclamation is sent. Long term supply agreements help suppliers to predict number of future delivers. In one plant they had an online web-based info system where all the acquired information of solid biofuels stored. The suppliers have online access to this system to check information of their own biofuel. One interviewee underlined need for developing communication system further as its current level is low. The interviewee thought the communication should work between power plant and all its suppliers.

Possibility to use online measurement to develop supply chain was mentioned during some interviews. With load based immediate feedback, supplier can recognise problems of its chain. One interviewee offered bigger picture with some percentages. He believed forestry biomass moisture could be decreased 10 % with better work at supply chain. Five percent is acquired, by making contractors benefit from lower moisture. Other five percent could be acquired if contractors starts to develop their process with constant thinking. However, no interviewer said clearly that with online measurement -based feedback, fuel's moisture can be lowered. Naked eye can also recognise, if fuels quality is bad. The interviewee, who believes possibility to decrease moisture 10 %, underlined importance of forest transport to decrease moisture of solid biomass.

None of the interviewees mentioned, that lower moisture could affect transportation cost. If it was asked separately, it wasn't thought to be meaningful. Some interviewers mentioned dry mass losses and it was one of the reasons not to store solid biofuels over one year. Otherwise, it wasn't much of a factor for interviewers. One interviewee reminded that solid biomass is a second level product and harvesting is done based on needs related to first level products.

6.2 Quality measurement/sampling

Quality measurement/sampling related questions focused on finding differences between manual and mechanical sampling and an online measurement. Questions about possibilities of online measurement were difficult for some interviewees because their limited experiences of them. Table 6 presents excerpts of measurement or sampling related answers.

Manual sampling's strength is its low invest cost and all interviewees agreed on that. There was more opinion variance about operating costs. Mostly it was thought that taking increments doesn't cost anything because it's done by drivers during unloading the load. One interviewee argued that sampling and unloading aren't necessary carry out at the same time or at least it depends on unloading system of the power plant. Analysing samples was considered more important cost factor for power plants. Answers varied from each other's. It was reminded that real cost of analysing samples is hard to calculate as it's only one part of the employee's job. One Interviewee didn't consider it as a cost at all. Other interviewee said labour cost might be around 10 000 €/a. The interviewee estimated that sampling is needed during half of the year and it takes two hours per a day. In third estimation, all fuel reception tasks require around two-person years.

Safety of was seen as one possible problem of manual sampling. Some interviewees mentioned it without asking and if it was separately asked, it was recognized. Manual sampling wasn't said to be dangerous, but it's less safe than mechanical or online sampling. At worst, during his/her sampling, driver can lurch in the gap where solid biomass is unloaded. This can lead to death. Other mentioned harms for drivers were unergonomic work during sampling and dust exposure.

Many interviewees were aware of possibility of errors made by drivers during manual sampling. One interviewee gave an example. During the time they were using manual sampling, sampling results didn't match with the balance calculations and it seemed they were paying too much for delivered solid biofuel. He explained that if the third part drivers are payed based on the energy content of their load, they have an economical motivation to take dry samples. Other interviewee saw the situation same kind of way. The interviewee's company have noticed that if there was a person inspecting when drivers were taking samples, average moisture of samples increased, and moisture were closer to results acquired from a mechanical sampling. Some other interviewees knowledge the possibility of human error of drivers but didn't mention aware or unconscious cheating.

Automatic sampling system's invest cost was thought expensive. Given estimates were 800 000-900 000 €, around one million euros and two million euros. Labour cost was figured to be the same as in manual sampling because analysing is done with same human effort. One interviewee said expenses are higher with automatic sampling system because of its maintenance cost.

Table 6 Sampling and measurement related answers

<table>
<tr><th></th><th colspan="4">Excerpts from the answers</th></tr>
<tr><td rowspan="2">About manual sampling</td><td>Sampling for workers is inorganic, laborious, exposed to dust and, for example, wandering with a shovel in the yard can be a risk</td><td>Simple and affordable. The problem is the representativeness of the sampling</td><td colspan="2">The good thing is that one person is committed to the job. Because of his continuous experience, he can deduce if there is something special in the sample and to report on it. This review is both visual and results-based.</td></tr>
<tr><td>Sampling has been outsourced to the drivers, which could be weakness (because of wrong sampling), but camera surveillance is satisfying. The sampling of drivers does not create costs.</td><td colspan="3">If drivers are responsible for sampling, they may have an economic motive to improve results. In many cases, plants buy biofuel from producers who do not themselves transport but employ a third party. If the driver is paid according to the energy content, the samples should be as dry as possible for them. There have been cases where the driver has brought the samples with them.</td></tr>
<tr><td>About mechanical sampling</td><td>In principle, representativeness should be perfect. Very big investment. In traditional screw or bucket sampling, representativeness can be a problem. Robot sampling is best to take a representative sample, but also most expensive</td><td>The device that was used in the past did not work as desired. The previous load had some remnants that could affect results of the next load's samples. The investment was remarkably expensive</td><td colspan="2">Automatic sampling system was once installed to the bottom of the conveyor, but it was quickly found that it was not working. Sampling was not representative. Someone had to be watching when the cargo changed.</td></tr>
<tr><td rowspan="2">About online measurement</td><td>It's an interesting solution and seems to be fast. It isn't compatible with #### plant.</td><td rowspan="2">The X-ray strength is that it scans the entire batch. The weakness is that you need to know what kind of type (of fuel) is delivered. So, problems can come if the goods you supply are mixed.</td><td rowspan="2">When one #### plants took Inray's device into use, another #### plant started to have worse solid biofuels.</td><td rowspan="2">Inray has been presenting (FuelControl) a few years ago. The solution was too expensive. There is no reliable information of its reliability. There is no standard for online measurements</td></tr>
<tr><td>Ease and safety (about online measurement's strengths).</td></tr>
<tr><td>About potential use of load-specific data</td><td colspan="2">(Data could be used for) improving safety. Removing guest scraps. It makes possible to create a supplier and seasonal forecast libraries. If there is something abnormal in the supplier's delivery, the data can be used as a reference.</td><td colspan="2">Foresight. The data is used to know what kind of biofuel should be around. By knowing what kind of fuel, it should be (normal bulk density) and comparing it to bulk density that is calculated by knowing volume and weight, it is theoretically possible to create an alarm system that reacts to too much deviation.</td></tr>
</table>

One representative mentioned bad reputation of automatic samplers. Two interviewees told that their power plants had used mechanical sampling in the past but stopped it because the sampling was inaccurate. Two interviewees seemed to value accuracy of robotic sampling. Other interviewee also figured robotic sampling being most accurate, but also the most expensive automatic sampler. In theory automatic sampling is more accurate than manual sampling because it takes away the human error. Because both manual and automatic sampling require sample handling by employees, all samples are inspected through human eye. If an employee, notice something unordinary, he can report it to a higher-up.

Four out of the five represented power plants weren’t using an online measurement. For two plants an on-line solution wasn’t considered because of the technical solutions to move biomass in their plant weren’t compatible with an online measurement. Other two plants weren’t interested at least partly because utilization would be too low for both plants. It was said that Inray FuelControl wouldn’t solve anything for the plant. One pointed out that because in online measurement calorific value of solid biofuel is assumed from previous experiences to calculate biofuels energy content, energy calculation isn’t totally accurate. X-ray’s ability to recognise impurities was positive. According to what one interviewee had heard, after Inray’s X-ray measurement system was installed to a plant in Finland, amount of impurities in delivered loads decreased, seemingly because suppliers delivered lower quality loads elsewhere.

One interviewee was using an online measurement and it was Inray FuelControl. The interviewee said the systems strength are its easiness, safety and ability to detect impurities. He also believed the online solution gives image of a progressive company. The interviewee estimated that an online measurement system saves around one-person year amount of work.

Only couple of suggest came, when potential of using load-based moisture data was asked. Large amount of data might help to forecast seasonal supply. With reference data, it could be possible to recognise abnormalities. One interviewee mentioned an alarm system that would inform if loads deviation was too much.

6.3 Solid biofuel and combustion

During interviews, effect of impurities was talked several times. Problematically, meaning the word itself wasn’t clarified during these interviews although its definition can be broad. Impurities can be chemical or external objects like stones and metal. One interviewee divided impurity to chemical impurities and mechanical impurities. For clarity, impurity’s type is marked inside of parenthesis when necessary. The decision, if it was talked about mechanical or chemical, was made during writing the thesis. Table 7 presents excerpts of solid biofuel and combustion related answers.

Interviewees mentioned that combustion process challenges are related to solid fuels quality. Sand can sinter, and little rocks don’t exit from the grate. Corrosion and fouling were mentioned. Chemical impurities were main reasons for combustion maintenance costs. Mechanical impurities affect circulation of fed sand. Two interviewees said (mechanical) impurities affects more to conveyors.

Maintenance problems increase significantly when plants are using fuels not designed to boilers and when generally bad quality fuels are used. One interviewee mentioned how one plant started to combust stumps although the boiler wasn’t designed for stumps. Normally once per year chanced feed screw was needed to be chanced several times more often than before combusting stumps. Other interviewee estimated that low quality fuel could raise maintenance expenses maybe 20 %. During some interviews, solid fuel feeding problems were mentioned. Sometimes solid fuel doesn’t come out of a silo like it should because of freezing or it’s too light. Boiler maintenance costs are significant, but also depend how the calculations are done. One interviewee didn’t give any numbers because of many variables and the total cost depends on, what parts are calculated in boilers maintenance cost. Other said it depends about the used solid biofuels. If recycled wood is only used, maintenance costs millions and is around 10 % of all costs. One estimation for maintenance cost for a boiler, was around 5-7 %. By taking account machine, automation and electricity costs, one interviewee said maintenance costs are two million per year. Other interviewee estimated maintenance costing around 200 000 € per a boiler.

During first interviews, (mechanical) impurities’ effect to conveyers wasn’t recognised to be asked, so the subject was discussed only with some of interviewees. One interviewee listed how metal, ice and large pieces damages scraper conveyor. One interviewee said that if scraper conveyer breaks down suddenly it’s because of (mechanical) impurities. Same interviewee estimated this kind of break down might happen once per five years and fixing it takes around couple of days. It happens most likely during cold season. Consequences of conveyers break down are like shutdown of a boiler, because in both cases solid biofuel is needed to be replaced by alternative energy source.

Table 7 Solid biofuel and combustion related answers

<table>
<tr><th></th><th colspan="4">Excerpts from the answers</th></tr>
<tr><td rowspan="2">About challenges of solid biofuel's combustion</td><td>Variation in fuel quality. Boilers are designed to use a specific type of fuel. The global trend is towards lower quality fuels</td><td>The boilers can handle only biofuels with moisture of 35-55 %</td><td colspan="2">Metals, stones and large amounts of sand. As a result of the problems, the fluidized-bed boilers cease to float. The high amount of fines (under 3 mm) interferes with combustion, and the combustion may be partly in the wrong place</td></tr>
<tr><td>Too fresh chips are problematic due to the high alkaline concentration. Too fresh chips can only be seen by the human eye</td><td>Corrosion, fouling and emissions. In the foreign materials, for example, aluminium and painted wood (lead) are harmful</td><td colspan="2">Emissions must not fluctuate over the limit values. If the biofuel is too bad, the amount of peat should be increased, which will increase emissions</td></tr>
<tr><td>About challenges of handling solid biofuel</td><td>Moisture and size.
In winter, the ability to increase the amount of peat is a contributing factor</td><td>Freezing in winter is the only challenge.
Wet biofuel affects the mixing ratios in the silos</td><td colspan="2">Too dry solid biofuel must be watered. Too big pieces and badly torn shells. Too wet solid biofuel will fall and peel and can freeze in winter</td></tr>
<tr><td>About maintenance cost</td><td>Maintenance costs are approximately (€) 2 million per year. Consists of machine, automation and electrical charges</td><td colspan="2">Fuel quality has a significant impact on maintenance costs. Mechanical maintenance is carried out throughout the year (greasing of parts), but usually once a year the use of the boiler (e.g. for a week) is stopped for larger maintenance, for example replacing worn parts. Using poor fuel could increase maintenance costs by, for example, 20%. This is a very feeling-based estimate</td><td>(Maintenance costs are) about € 200,000 per boiler. Fuel impurities affect the conveyor more than the boiler. The cost of the conveyor is the same as that of the boiler</td></tr>
<tr><td rowspan="2">About failures and shutdowns</td><td>(Boiler was stopped) last in 2011. Since then, we have been driving a better fuel search. There have been problems in some other institutions last winter. The jacket lasts for several days</td><td colspan="2">The goal is to run the plant from summer to summer. Some plants aim for 18-month cycles. In the worst cases, scheduled maintenance is about 4-5 times a year. Costs are largely due to labour costs.
A sudden stop is the biggest disaster. Costs can be € 100,000 per day. Costs arise when the lost production must be replaced by some other energy</td><td>There are rarely surprising shutting downs. Longest one was five days long. We had short fuel supply system failures caused by fuel quality, but they had not caused long-term shutdowns</td></tr>
<tr><td colspan="4">Impurities such as iron and ice are damaging the conveyor belts. Big pieces of wood are also harmful. If the conveyor is broken, use oil instead of fuel. It may take around a few days to get the conveyor back into service.
Thorough conveyors are subjected to careful inspection annually, so if they break down unexpectedly, this is due to impurities or large pieces. This will happen perhaps about once every five years. This is most likely to occur in severe frost</td></tr>
<tr><td>About using online based data for managing combustion</td><td>The information from Inray X-ray could be combined with other data. The information obtained from this may have value</td><td>An on-line method could be used for anticipation and driving planning. If there were any problem, then we could do the analysis afterwards</td><td colspan="2">Moisture prediction does not have much to gain for combustion. In principle, if the humidity were to change rapidly, it could be useful. (How?)
The screw feeds the fuel according to the volume. The rapid change in humidity therefore alters the total amount of water and makes stable driving difficult. The vapor pressure supplied to the turbine must be constant. This is difficult if the fuel supply is not constant</td></tr>
<tr><td>About ash from combustion</td><td colspan="2">Fuel affects the quality and emissions of ash. Impurities affects the reuse and, for example, the reuse of ash from waste fuel is a challenge. Chlorine, nitrogen and sulphur are of interest for emissions. The importance of moisture is small</td><td>Fly ash is generated 3500 tonnes per year. 174 000 tonnes of fuel are burned per year</td><td>(Handling costs are) quite small. Includes shipping costs and a bit some other. Ash is taken to the shooting range.</td></tr>
</table>

Answers about shutdowns and failures in biopower plants varied. Some interviewee said there weren't any shutdowns because of fuels, when other said that in theory all of them are related to fuel. Unexpected shutdowns were rare. In one plant, sudden long-term shutdown happened last time in 2011. After that, quality standards of delivered solid biofuel were increased. Other Interviewee had same kind of story. After 2008, decreased demand of biofuel gave possible to develop supply chain and use only better biomass suppliers. Mentioned reasons of shutdowns were related to fuel feed system. One interviewee said there are some supply system related failures per year causing short breaks. Potentially shutdown can last days and be expensive for the power plant. One general level estimation for profit losses was 100 000 € /day. Other interviewee said losses caused by shutdown is a six-digit number during winter.

Measuring solid biofuel moisture before its combustion was mentioned by many interviewees. An online measurement system could be used to predict moisture changes of solid biofuel before it's combusted. One interviewee explained that when solid biofuels moisture changes, it affects system's feeding, and this can cause unstable fuel feeding for a moment. Other interviewee believed that combined information from X-ray measurement system and from combustion proses could give valuable information. The interviewee mentioned how information of X-ray could also be used afterward to analyse occurred problems. One interview didn't believe measuring moisture before combustion would be much of use because it would only help if biofuel's moisture would chance rapidly. The interviewee didn't think biofuel moisture usually chances fast enough.

All plants had found a solution to reuse at least part of ash from combustion. Ash was used for forest fertilizer and delivered to a shooting range. In these cases, most of the costs came from transporting the ash. One interviewee said ash transportation costs are around 10 €/ton, but if the ash is delivered to landfill, expenses folds 7-10 times. One plant estimated ash handling costs to be around 100 000 €/a including fly ash and bottom ash. One interviewee confirmed fly ash is composed of chemical impurities and bottom ash is made of mechanical impurities and fed sand.

7 IMPACTS OF ONLINE MEASUREMENT

Possible impacts of X-ray measurement system were inspected based on the literature review and the semi-structured interview. Under review are X-ray's effects to solid biofuels supply system, accuracy of determined moisture, safety, maintenance of power plant, ash handling costs and labour costs of sampling. Limitations are presented.

7.1 Online-system based feedback

An online measurement system can give instant feedback to suppliers of biomass/fuel. In feedback, two (or more) dynamical systems are connected to each other's in a way that when other changes the other chances as well. This causes a loop. Dynamical system is a system that changes over a time. Feedback is used to correct the difference between desired and actual performance. By using dynamic system to measure output of another dynamic system, feedback decreases uncertainty. (Åström & Murray, 2008, p. 1) Figure 7. shows feedback where supply chain of biomass load is dynamic system 1, and an online measurement system, and the data it provides to suppliers, is dynamic system 2.

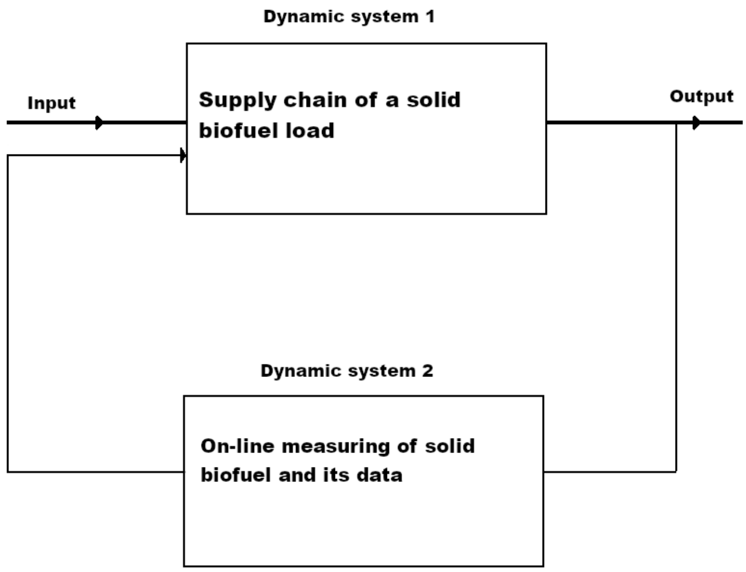

Figure 7 Online measurement -based feedback

A biomass power plant can benefit from developed biomass supply chain when it lowers solid biofuel's purchase price, increases its availability or/and increases its quality (Miktech, 2014). Based on these benefits, desired performance is: always available and affordable as possible solid biofuel with low as possible moisture and without impurities. Optimising biofuel supply chain is balancing between these needs. Weather and solid biomass properties are affecting circumstances. After feedback from the online measurement system, corrective actions are required. Based on the interviews and the literature review, some corrections could be possible.

Increasing effort. Idea, that different participants of the supply chain can affect the solid biofuels quality with own effort, received more confirmation from the literature review and the interviewees. However, the supply chain is a complex system and includes many parties. A biomass power plant can motivate its direct biofuel suppliers with energy based paying of solid biofuel, but the impacts are limited if other parties of supply chain aren't motivated. There are hopes and suggest measuring solid biofuel/biomass at many different stages to increase results of a supply chain (Sikanen et al., 2017). Developing control system is however balancing between costs and benefits.

Storing biomass. Storing is already used to decrease moisture, and studies prove early spring as best time to start it (Nurmi & Hillebrand 2007). In Finland harvesting of logging residue depends on harvesting of industrial wood limiting optimal timing of storing. Storing balances biomass supply, but dry matter losses make many solid biofuels bad for a long time storing. Most importantly, storing creates capital costs. An online measurement system might provide some of the needed information, to calculate optimal storing balance for different kind of situations.

Chancing sources of biomass. Solid biofuel loads come from different sources. Because of varying constrains and circumstances, the quality of these loads difference from each other's. In cases where load's quality isn't enough for required standards, the biopower plant can inform the fuel's supplier not to bring any biofuel from the same source, alias storage. This idea was mentioned during the interviews, but practical real-life example wasn't given.

Road transportation costs of solid biofuel are major and affects how far away the fuel is transported. Main reason is solid biofuels low energy density. By lowering the total moisture of transported solid biofuels, transportation costs should decrease. Based on the interviews, this isn't thought to be factor for decision making at all. Hakola & Laurila (2011) study also shows that at least fuel saves from lower moisture isn't a major economic benefit.

7.2 Increased accuracy of fuel trade

Driver based manual sampling can give too low average moisture for delivered solid biofuel loads. Specially logging residue sampling is challenging, due to its large heterogeneity (Järvinen, 2012, p- 37; Mustonen, 2017, p. 27). In theory, the drivers have economical reason to take dry as possible samples. Some interviewees had examples/experiences supporting their doubts.

If manual sampling results are too humid comparer to real moisture of the delivered loads, plants can save with X-ray measurement assuming it's more accurate and gives less humid results. The yearly economic benefits depend on, how much the average moisture result differs between driver based manual sampling and X-ray measurement, average price of the solid biofuel and how much of it is delivered per year. Plant's yearly saves from measuring higher moisture can be calculated with formula:

$$S_a = (q_{net.d} - q_{net.m1}) \times P_J \times m_a \times \Delta M \qquad (16)$$

Where

$q_{net.d}$	is net caloric value at constant pressure (J/g) for a dry sample
$q_{net.m1}$	is net caloric value as delivered at constant pressure (J/g) when the moisture is one percentage
P_J	is solid biofuels price (€/J)
m_a	is yearly amount of delivered solid biofuel to the plant (g),
ΔM	is change of moisture (%)

$q_{p,net,m1}$ is calculated by using Formula 2 and ΔM is difference between results of manual sampling and online measurement. Formula 14 can be presented as:

$$= (q_{net.d} - (q_{net.d} \times ((1 - 0{,}01 \times 1) - 24.24 \times M)) \times \frac{P_{MWh}}{3.6\times10^{9}} \times m_a \times (M_{x.m} - M_{m.s})$$

Where

24.24	is correction factor for the enthalpy of vaporization
P_{MWh}	is solid biofuels price (€/MWh)
$M_{x.m}$	is solid biofuel moisture from X-ray measurement system (%)
$M_{m.s}$	is solid biofuel moisture from manual sampling (%)

Based on Formula 14, Table 8 presents different scenarios. It shows saves can be significant for a biomass power plant if it can change its driver based manual sampling more accurate way to determine solid biofuel moisture.

Table 8 Potential saves if average measured moisture increases

Logging residue chips without needles		**Plant A (50 000 t/a)**			**Plant B (100 000 t/a)**			**Plant C (250 000 t/a)**		
	Moisture change	19 €/MWh	20 €/MWh	21 €/MWh	19 €/MWh	20 €/MWh	21 €/MWh	19 €/MWh	20 €/MWh	21 €/MWh
20.4 MJ/kg (Pine)	1.0 pp	60 t €	63 t €	67 t €	121 t €	127 t €	133 t €	301 t €	317 t €	333 t €
	3.0 pp	181 t €	190 t €	200 t €	362 t €	381 t €	400 t €	904 t €	952 t €	999 t €
	4.6 pp	277 t €	292 t €	306 t €	555 t €	584 t €	613 t €	139 t €	1 459 t €	1 532 t €
19.7 MJ/kg (Spruce /birch)	1.0 pp	58 t €	62 t €	65 t €	117 t €	123 t €	129 t €	292 t €	308 t €	323 t €
	3.0 pp	175 t €	185 t €	194 t €	351 t €	369 t €	388 t €	876 t €	923 t €	969 t €
	4.6 pp	269 t €	283 t €	297 t €	538 t €	566 t €	594 t €	134 t €	1 415 t €	1 485 t €

Highest ΔM (4.6 pp) is assumed from VTT report (Järvinen, 2012). X-ray measurement system is assumed to be perfectly accurate. Lower ΔM are more cautious assumptions. Depending on the scenario $q_{net.d}$ of logging residue chips without needles is either 20.4 MJ/kg (pine) or 19.7 MJ/kg (spruce and birch) (Alakangas, 2016, p. 63). P_j is based on Finland forest chips current price 20 €/MWh (Tilasto: Energian hinnat, 2018) and two scenarios, one, where the price goes up, and one, where the price goes down. m_a is assumed to different a lot between each scenario as the amount of combusted solid biofuel can vary largely between power plants.

Formula 16 based sheet was made with Excel. It can be used to calculate potential saves if the solid biofuel moisture changes, because of more accurate measurement. The sheet is presented in Figure 9.

Table 9 Saves of more humid measured biofuel

				Net caloric value at constant pressure for a dry biofuel ($q_{net.d}$)						Change of		
		NUMBER	UNIT	Own estimation	Use own estimation?	In use		Solid biofuel price (P_{MWh})		determined moisture ($M_{x.m}$ - $M_{m.s}$)		Saves (S_a)
Solid fuel type 1:	**Logging residue chips**	50	%	19.7	**YES**	19.7	MJ/kg	20	€/MWh	4.6	% point	282 938 €
Solid fuel type 2:	**NO NEED TO MEASURE**	50	%	0	**NO**	0	MJ/kg	20	€/MWh	0	% point	0 €
Solid fuel type 3:	**NO NEED TO MEASURE**	0	%	0	**NO**	0	MJ/kg	20	€/MWh	0	% point	0 €
Solid fuel type 4:	**NO NEED TO MEASURE**	0	%	0	**NO**	0	MJ/kg	20	€/MWh	0	% point	0 €
	Total (must be 100)	100	%								Total	282 938 €
Amount of delivered solid biofuel to the plant (m_a)		100 000	t/a									

7.3 Safety

Interviewees mentioned potential health and safety issues during manual sampling comparer to mechanical sampling or online measurement. In website of Finnish workplace accident investigation (Työpaikkaonnettomuuksien tutkinta, TOT) reports (TVK, 2018), there wasn't mention of sampling-based accident in recent years. In one accident driver fell to unloading pit, but not because of sampling (TVL, 2010). Falling to a pit was mentioned as a possible risk during sampling in one interview. Exposure to dust is health issue when employees handle biofuel. Report from Koppejan et. al (2013) focuses health and safety aspects of solid biofuel during its storage, transportation and feeding. Organic dust generation from biomass increases when solid biofuels moisture is low, air flow is high, there isn't enough containment to prevent dust to move around and/or agitation of solid biofuels. Sampling of solid biofuels isn't mentioned in this report. Potentially, online measurement seems safer than manual sampling as its use doesn't require work near solid biofuels. With same principle Laitinen (2015) suggest the best way to avoid dust exposure during sampling is to use mechanical sampling. Safety impact of an online measurement system depends on the plant's current sampling practices. When radiation based online measurement system is used, its radiation safety is needed to be qualified. In Finland radiation safety is supervised by Radiation and Nuclear Safety Authority (STUK, 2019).

7.4 Maintenance and profit loss save

Based on the interviews, by developing solid biofuel supply chain, plants in Finland has been able to decrease amount of impurities in biofuel loads. Partly reason is current restrained biofuel demand. This increases the quality of used fuels and decrease the benefits of recognizing impurities in solid biofuel by using X-ray measurement system. The situation seems however largely vary between different plant even if interviewees were happy with their own situation.

Mechanical impurities cause failures specially to fuels supply and feed systems. Räsänen's study (1997) includes examples of how impurities can cause failures in coal and peak based thermal power plants, like stones or metal plate in a rotary feeder or stones in a conveyer. Inray's X-ray online measurement system might help to decrease amount of impurities with feedback and increase biomass power plants mean availability. Recognizing impurities could also help to clean out the impurities if other used technologies could provide removing. This should decrease plant's failure rate and increase its mean availability. Cost of preventive maintenance would decrease if annual maintenance could be made less frequently. Increasing mean availability is economically impactful for a plant because it decreases profit loss. Profit loss is caused by lower contribution margin as normally during a failure, combusted solid biofuel is replaced by more expensive fuel (oil for example). If X-ray decrease plant's failure rate and increase mean availability the saves could be calculated with formula:

$$S_{tot} = (P_{f.2} \times \eta_{f.2} - P_{f.1} \times \eta_{f.1}) \times F_{d.e} \times t_o \times \Delta A_o + \Delta\lambda \times t_o \times C_{p.d} \tag{17}$$

Where

$P_{f.2}$	is price of the replacing fuel (€/MWh)
$\eta_{f.2}$	is energy product efficiency when replacing fuel is used
$P_{f.1}$	is price of the normally used fuel (€/MWh),
$\eta_{f.1}$	is energy product efficiency normally
$F_{d.e}$	is plant's average power during a failure (MW)

t_o is system's total operation time (h)

ΔA_o is difference between mean operational availability after using X-ray and mean operational availability before using X-ray

$\Delta\lambda$ is difference between failure rate before using X-ray and failure rate after it's in use

$C_{p.d}$ is average property damage cost per a failure (€)

Formula 17 based sheet was made with Excel. It can be used to calculate how much a plant could save if the number of failures decreases. Figure 10 shows a picture of the sheet.

Table 10 Decrease of cost of failures

VARIABLES	NUMBER	UNIT
Plant's average power during a failure ($F_{d.e}$)	63	MW
Defined operating time (t_a)	8400	h
Utilization of the plant (not including failures)	95.9	%
Decrease of amount of failures	17	%
Price of the normally used fuel ($P_{f.1}$)	20	€/MWh
Price of the spare fuel ($P_{f.2}$)	31.5	€/MWh
Energy product efficiency normally ($\eta_{f.1}$)	90.0	%
Energy product efficiency of spare fuel ($\eta_{f.2}$)	90.0	%
Average property damage cost per a failure $C_{p.d}$)	5 000	€
	Before X-ray	After X-ray
Number of failures	3	2.49
Mean corrective maintenance time	4	4.00 h

	Failure rate (λ)		MTBF		Inherent Availability (A)	
Before X-ray	0.0004	1/h	2796.0	h	99.9	%
After X-ray	0.0003	1/h	3369.5	h	99.9	%

Saves							
Profit loss		Damage cost		Total cost		Cost per a year	
1 330	€	2 557	€	3 887	€	3 887	€

Example calculations based on Formula 17 weren't made for this research as it would require too many assumptions. Digits in Figure 8 aren't based on secondary data or the interviews.

7.5 Ash handling costs

Cost of ash handling depends amount of total ash, it's transportation cost per mass, and disposal site cost. Disposal site cost depends if the ash can be reused. Reusability depends on its chemical structure. There isn't a lead to estimate how much online measurement could decrease ash production from combustion. Total cost in Pursiala's power plant was estimated to be around 100 000 €/a. Other interviewee's rough estimation for ash transportation cost was 10 €/ton. If it isn't reused, total cost of ash is 7-10 times more. Saqib and Bäcström's study (2016) includes information about daily bottom and fly ash production in certain Swedish plant. Table 9 presents secondary data from Saqib and Bäcström's study.

Table 11 Examples of daily ash production

Facility	Capasity (t/d)	Boiler	Waste Fuel (%)	Bottom ash	Fly ash
Högdalen	750-800	CFB	Industrial waste	45	45
Händelö P13	360	CFB	Wood chips	13	24
Eskilstuna	NA	BFB	Tree branches + bark + wood shaving + willow (55:25:15:5)	21	10

Information from Table 9 and acquired estimations from interviewees are used to create example results of ash handling costs. The results are presented in Table 10.

Table 12 Ash handling saves

Plant	Högdalen (CFB)		Händelö P 13 (CFB)		Eskilstuna (BFB)	
Daily bottom ash/fly ash (ton/d)	45/45		13/24		21/10	
Cost (€/ton)	10	70	10	70	10	70
Bottom ash handling cost (€/a)	164 250	1 149 750	47 450	332 150	76 650	536 550
1 % change (€/a)	1 643	11 498	475	3 322	767	5 366
Total ash handling cost (€/a)	328 500	2 299 500	135 050	945 350	113150	792 050

Bottom ash handling costs are separated because, there's dependence between mechanical impurities and amount of bottom ash. Bottom ash is usually made from mechanical impurities and fed sand. One interviewee described, how problems caused by mechanical impurities are avoided by increasing fed sand's circulation, meaning increase of the mechanical impurities could also increase amount of fed sand in the bottom ash. By effecting amount of mechanical impurities in solid biofuel, online measurement could decrease amount of bottom ash.

7.6 Labour costs of sampling

Interviewees' views varied about how much sampling requires labour. In theory, an online measurement system decreases amount of labour because less sampling related work is required comparer to manual or mechanical sampling. If samples are taken manually, it requires labour during sampling and drying samples. Usually sampling is done by drivers. Because it's done at the same time as unloading the load delivered by the driver, it isn't considered as a cost for plants. Drying samples is done by the plant's labour. Online measurement can also create some new work, like monitoring X-ray results.

How much sampling requires labour, depends on a plant and its needs. If the plant wants only to know daily average moisture per supplier, the amount of labour is probably reasonable. Increments taken by driver are mixed together and only part of this combined sample is used as a labour sample. Presumed a plant gets solid biofuel delivers from four different suppliers in a day. Two of the suppliers, A and B, deliver six loads. A delivers fuel type X (woodchips, delivered with bark). B delivers three loads of X type of fuel and three loads of Y (sawdust from conifer) type of fuel. Two other suppliers, C and D, deliver four loads. C delivers fuel type X. D delivers two loads of fuel type X and two loads of fuel type Y. The plant has agreed with its suppliers to measure daily moisture of each suppliers' loads. Fuel types are also separated so there is total of six combined samples per a day. The plant and suppliers have also agreed daily samples precision (P_L) being at least 2 p-%. Primary variances (V_{i_x} = 12.5 p-%, V_{i_y} = 6.0 p-%) and preparation and testing variances ($V_{PT\_x} = 0.059\ p-\%, V_{PT\_y}$ = 0,06 p-%) are assumed from SFS-EN ISO 18135:2017. The amount of total needed increments can be calculated from Formula 5. Table 11 presents results of different scenarios. The amount of daily combined samples is six.

Table 13 Number of increments for a daily average moisture

	Supplier A	Supplier B		Suppliers C	Supplier D	
Fuel type	Woodchips (X)	Woodchips (X)	Sawdust (Y)	Woodchips (X)	Woodchips (X)	Sawdust (Y)
Number of loads (N_{SL})	6	3	3	4	2	2
Required number of increments per load (n_{min})	3 (2.1)	5 (4.3)	2.0	4 (3.2)	7 (6.4)	4 (3.1)
Total amount of increments	18	15	6	12	14	8

Usually pricing of delivered solid biofuel is based on much longer time periods than a day. In Formula 5, its assumed that size of the loads are identical. In practice, size of loads can vary. If same amount of increments are taken from different sized loads, the smaller loads are overrepresented. If the solid biofuel systematically difference between smaller and larger loads, causes this sampling bias for the results of solid biofuels moisture. In VTT guideline, the load size is taken account at some level and amount of increments vary between 2 to 6 depending on the type of the vehicle (Alakangas & Impola 2015, p. 32)

If the plant wants to know moisture of each load, needed labour increases significantly. More increments are needed to be taken by drivers because N_{SL}=1 (sub- lots/loads in the lot). Combined samples wouldn't be daily based, but load based. Presumed same conditions as in Table 11, Table 12 presents results, if moisture of each load is required to know.

Table 14 Number of increments, when loads aren't combined

	Supplier A	**Supplier B**		**Suppliers C**	**Supplier D**	
Fuel type	Woodchips	Woodchips	Sawdust	Woodchips	Woodchips	Sawdust
Number of loads (N_{SL})	6	3	3	4	2	2
Required number of increments per load (n_{min})	14 (13.3)	14 (13.3)	7 (6.4)	14 (13.3)	14 (13.3)	7 (6.4)
Total amount of increments	84	42	14	56	28	14

Amount of taken increments increases significantly. Combined samples are made per a load meaning (6 + 3 + 3 + 4 + 2 +2) 20 combined samples are made per a day.

In power plant's perspective, number of combined samples determines amount of work. In a case where only daily combined samples are made, amount of labour can be low. If more specific information about loads is required, much more work is needed. The variations (V_i , V_{PT}) can be much higher, than what it's used in Table 12 (or 11) calculations. In VTT report (Järvinen, 2012) during winter in Finland, V_i was calculated to be 26.80 p-% and V_{PT} was 1.88 p-% (regardless of the season) for whole-tree chips. In this case if P_L = 3 p-% for load, then $n_{min} = 73$. Practically, sample precision can't be as accurate as 2 p-% and/or combined samples shouldn't be only a single load based.

Excel sheet was created to calculate required amount of increments or load based precision. Figure 10 shows a picture of the sheet.

Table 15 Required number of increments

VARIABLES	NUMBER	UNIT
Number of loads (N_{SL}):	4	pcs
Primary increment variance (V_i)	26.8	%
Preparation and testing variance (VPT)	1.88	%
Required precision (PL)	3	%

RESULTS	NUMBER	UNIT
Requiret number of increments per a load	3.8	pct
Total number of increments	16	pct
Load based precision	6.0	%

FUEL TYPE	Vi	VPT
Forest residue, Finland, yearly average (VT	24.16	1.88
Forest residue, Finland, winter (VTT)	30.36	1.88
Whole-tree chips, Finland, yearly average	11.71	1.88
Whole-tree chips, Finland, winter (VTT)	26.8	1.88
Woodchips, including bark (nominal top si	12.5	0.059
Sawdust from conifer (ISO)	6	0.06
Bark from Scots pine (nominal top size: 1(	8	0.68
Logging residue from conifer (nominal top	10	0.73
Straw from wheat in bales	100	3.06

8 CONCLUSIONS

Solid biofuels are used in biomass power plants to produce energy. Each solid biofuel load's value depends on its total energy. The total energy of a load can be calculated if it's weight and net calorific value as delivered are known. To calculate net caloric value as delivered, its moisture is needed to know. Common way for plants to solve moisture of delivered solid biofuel loads, is manual sampling. Manual sampling requires labour, it's slow and representativity of samples are criticized because of solid biofuels large heterogeneity and challenges to acquire correct sampling (Fernandes-Lacruz & Bergström, 2016; Wagner, 2012). Online measurement system is alternative solution for sampling.

The aim of this thesis was to research the benefits of an online measurement system for biomass power plants. The comparison was done mostly to manual sampling as it's the common way to estimate moisture of solid biofuel loads. The aim was acquired by a literature review and a semi-constructed review. Five different benefits of X-ray based online measurement system were presented with some calculations.

An online measurement system measures solid biofuel moisture in real time. The benefits are connected to the limits of manual sampling. An online measurement measures whole load, not only small parts. Immediate information could help suppliers (Sikanen et al., 2017) and increase process control and performance optimization of a power plant (Skvaril et al., 2017). A commercial X-ray based measurement system recognizes impurities like stones and metals (Inray, 2018; Mantex 2019) providing other potential advantages.

Biomass supply chain includes many participants that can affect final products quality but have no financial reason to provide best results. An X-ray based online measurement system can detect problematic biofuel sources and provide moisture feedback to supply partners. It offers one source for an instant feedback, but only about the final product. Best way to decrease forestry biomass moisture would however be done by increasing the effort at the beginning of the supply chain during harvesting and forest haulage. An online measurement system can be one source to measure supply chain.

Sampling is very vulnerable for incorrect errors when highly heterogeneous solid biofuels are measured by sampling. Some interviewees recognized the problem, where increments taken by drivers create sampling bias and average moisture of combined samples is lower as it should be. Failed samples can be a significant cost for a plant. A plant pays extra if sampling results are too dry comparer to biofuel's real moisture. In Finland, sampling bias for logging residue can be 4.6 pp. (Järvinen, 2012, p. 37) or even more (Mustonen, 2017, p. 27). Based on 4.6 pp, if a plant buys 100 000 tons of logging residue chips (without needles, spruce) per year at the current price, the plant pays around 566 000 € extra for its suppliers. Not all sampling methods are the same and sampling bias presumably vary between biomass power plants. If alternative methods, like Inray FuelControl, can provenly provide lesser sampling bias, this can create significant savings for many plants.

Online measurement can increase employee's safety, by decreasing amount of sampling. Manual sampling can expose the driver to physical risks, like falling to unloading pit. Serious accident was mentioned in one interview, but there wasn't any mention of sampling related accidents in Finnish workplace accident investigation report (TVK, 2018). Dust exposure is a risk for employees that are handling solid biofuels.

An X-ray measurement system can recognise impurities like stones and metals. If this information can be exploit, it would decrease amount of failures. The benefits could be calculated by knowing average profit loss (€/h) during failures and how much an X-ray measurement system increases power plant's availability and decreases failure rate.

Mechanical impurities (stones, metals) affect amount of bottom ash produced during solid biofuels combustion. If amount of mechanical impurities decreases by using an X-ray measurement system, it affects bottom ash expenses. If bottom ash is reused, potential saves are limited. If a biomass power plant produces bottom ash 45 tons per a day, one percentage decrease of produced bottom ash would save 1 643 €/a for the plant. If the ash isn't reused, one interviewee estimated ash handling costs to increase around 7-10 times comparer if it is reused.

Labour cost of sampling is hard to determine because it's one of employee's many tasks. It's also hard to calculate, by using ISO standard (SFS-EN ISO 18135:2017:en), how many increments are needed to take from each load to get specific accuracy of daily (or any time period) moisture. This is because sizes of the delivered loads vary. Load size is needed to take account, or it is possible to have measurement bias where some loads might get overrepresented. In VTT's recommendation, load size has been taken account at some level (Alakangas & Impola 2015, p. 32). If a plant requires accurate information of moisture from individual solid biofuel loads, large amount of increments is required. Woodchips delivered with bark load requires 13.2 increments for the samples precision to be 2 p-%, when primary variance is V_{i_x} = 12.5 p-% and preparation and testing variance is V_{PT_x} = 0.059 p-%. In Finland variances can be much higher meaning even more increments for many loads would be required. Practically, sample precisions can't be as accurate as 2 p-% and/or combined samples shouldn't be only a single load based.

8.1 Limitations

The thesis studied potential benefits of using an online measurement system. Although many weaknesses of manual sampling were found, it doesn't necessary prove Inray FuelControl could resolve them. The basic principle of attenuation is presented, but FuelControl's accuracy or precise operating principle isn't much of discussed. The accuracy is hard to discuss as each different type of solid fuel requires its own formula and calibration. X-ray measurement system's accuracy increases when more specific information of the fuel is acquired.

The Interviews were informing, but some interview results were limited due to limited experience of the interviewer. Not all interviewees wanted to share all asked information, but mostly cooperativeness of all interviewees was great.

Inray advertises that FuelControl can decrease amount of emissions (Inray, 2018). This area wasn't much of discussed with interviewees. The possible benefits would be likely connected to measuring solid biofuel moisture before its combustion. In power plants, the interest is to keep emissions below certain level (emissions per produced energy).

8.2 Suggest for further research

X-ray measurement system can recognise impurities like stones and metals, but currently there isn't cases or acquirable data that could be used to inspect real benefits. Studying reliability change of a biomass power plant before and after using an online measurement system, could be one way to approach this problem.

Current ISO (SFS-EN ISO 18135:2017:en) standard for calculating accuracy of sampling isn't ideal for road deliveries as it doesn't account how varying sizes of delivered loads can affect each loads representativity. It might be good idea to study if quality of biofuel loads difference systematically from each other when load size varies.

One of subjects was to inspect, if an online measurement system could increase process control and performance optimization of a power plant. Measuring solid biofuels moisture before combustion could create saves, when online information could stable the fuel feeding and effect this way combustion or give data that could be used to explain occurred combustion related problems. The discussion exists, but not much information was found for this thesis. There seems to be more experience is the coal industry. Process control and performance optimization of solid biofuel requires more case-based studying.

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APPENDIX 1: ORGINAL INTERVIEW QUESTIONS

Interviewee

Name:

Job title:

Company:

Plant

Name:

Location:

Power:

Spent fuel:

Boiler:

Production:

Quality measuring methods

SUPPLY CHAIN OF BIOMASS

What challenges a supply chain contains?

From where the combusted solid biofuel is brought and what are the factors that decide this?

What kind of communication there is between the supply chain and the plant? Is there quality feedback?

How quality measuring of solid biofuel affects the supply chain?

How quality of solid biofuel affects a supply chain?

How seasons and weather are taken account in the supply chain?

How storing is used to affect quality of solid biofuel and total cost of the supply chain?

QUALITY MEASURING METHODS OF SOLID BIOFUEL

What are the impactful factors, when the methods to measure quality of solid biofuel are decided?

What are the problems, the benefits and costs of measuring quality by using:

Manual sampling?

Automatic sampling?

Online measuring?

Are the benefits of chosen quality measuring being tracked? How?

How quality data of solid fuel per load could be used in addition to pricing?

Are there benefits of measuring quality, that can’t be measured with money (e.g. safety, imago)?

SOLID BIOFUEL

What are the challenges of processing solid biofuels?

How the value of a solid biofuel is calculated/decided? How is calorific value calculated?

What factors are needed to take account to decide whether the use of solid biofuels with too bad quality is profitable?

COMBUSTION OF SOLID BIOFUELS IN A BOILER

What are the challenges of combusting solid biofuels?

What is or could be the role of quality data of solid biofuel to operate the boiler?

How accurate is the determination of amount of energy in combusted solid biofuel (by observing the balance)?

How much are the maintenance costs of the boiler?

How usually, why and with what consequences the use of the boiler is stopped?

What are the handling costs of the ashes?

APPENDIX 2: INTERVIEWEES' INFORMATION

Interviewee				Plant					
Name	**Tittle**	**Company**	**Interview date**	**Name**	**Location**	**Power**	**Used fuels**	**Boiler (s)**	**Sampling/measurement methods**
Hulkkonen, Seppo	Technolgy director	Andritz Oy	11.10.2018	Andritz Oy is a large international supplier for the pulp and paper industry. It provides systems, equipment and services including biomass boilers. (https://www.andritz.com/pulp-and-paper-en/locations/andritz-oy)					
Lahtinen, Lasse	Production Manager	Etelä-Savon Energia	14.8.2018	Pursiala's power plant	Ételä-Savo, Finland	Electricity 60 MW. District heating 130 MW	Woody biofuels, peat	BFB and CFB	Manual and half-automatic sampling and Inray FuelControl
Laine, Mika	Production Manager	Suur-Savon Sähkö	4.9.2018	Savonlinna's power plant	Ételä-Savo, Finland	Electricity 17 MW. District heating 20 MW. Process steam 20 MW.	Plywood chips (59%), logging residue (21 %), peat (7 %), industrial by-products (12 %)	BFB	Manual sampling
Nieminen, Miikka	Develop-ment Manager	Stora Enso	7.9.2018	Develops and produces wood and biomass-based solutions for range of industries. (https://www.storaenso.com/). Its solid fuel supply chain in Finland delivers biofuel mostly for its own plants, but also to other plants.					
Pekkola, Peter	Manager, wood energy	Metsä Forest (part of Metsä Group)	24.9.2018	Metsä Forest is a wood supply and service company, that works with forest owners and wood industry (https://www.metsaforest.com).					
Seppälä, Peter	Production Manager	Kuopion Energia Oy	30.8.2018	Haapanie-mi's power plant	Pohjois-Savo, Finland	HP2-BFB: Electricity 70 MW. District heating 200 MW. HP3-CFB: Electricity 50 MW. District heating 100 MW	Industrial by-products, logging residue, peat	BFB, CFB	Automatic sampling
Silvennoi-nen, Jaani	Manager, facility and process solutions	Valmet	28.8.2018	Develops and supplies technology, automation and service for pulp, paper and energy industry. Offers BFB and CFB boilers. (https://www.valmet.com/)					
Tamm, Andrus	Member of the board	Utilitas	6.9.2018	OÜ Utilitas Tallinna Elektrijaam	Talinna, Estonia	1st power station: Thermal energy 67 MW. Electricity 25 MW. 2nd power station: thermal energy 76 MW. Electricity 21 MW	Wood chips, milled peat	1st: BFB 2nd: 3 X moving grate furnaces	Manual sampling

Ylä-Kotala, Jarkko	Energy Procure-ment Manager	Kotkan Energia Oy	27.8.2018	Hovisaa-ri's power plant	Kymenlaak-so, Finland	65 MW	Logging residue (25 %), industrial by-products (25 %), milled peat (25 %), others (25 %)	BFB	Manual sampling