

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

School of Energy Systems

Energy Technology

Measuring wood based biomass quality

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ABSTRACT

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This Master's thesis studies the suitability of an on-line moisture measurement for UPM Caledonian Paper CHP plants fuel receiving. The object is to validate the functioning of the recently installed X-ray based moisture measurement, and to evaluate the accuracy of current moisture determination procedure.

The literature part of this thesis describes woody biomass: its composition and characteristics with an emphasis on moisture and its implications on boiler operation. Woody biomass is rich in chlorine compared to coal. Waste wood typically includes substances such as lead and zinc, which are linked to corrosion. Mechanisms of bed agglomeration, deposit formation, corrosion and erosion linked to combustion of biomass are described. Different technologies for biomass moisture measurement are presented.

Experimental part shows that in general the X-ray measures average moistures with an acceptable accuracy. There are however certain fuel types that are measured incorrectly and require new calibrations. Further fine tuning is required. X-ray measured moisture seems to correlate with average fuel bed thickness on conveyor – the thicker the layer the higher the moisture measured. Thus, compensation or evening out of fuel thickness is needed. The current use and design of Caledonian fuel receiving do not allow continuous load specific measurement to be conducted. The samples used for fuel pricing, sampled by driver or operator, appear to give acceptable results based on data and empirical evidence accumulated. The composite sample of fuel entering boiler silos appears to be measured with current procedure higher in moisture (5 percentage points) than it most likely is.

TIIVISTELMÄ

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Puuperäisen biomassan laadun mittaaminen

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Tässä diplomityössä tutkitaan erään on-line kosteusmittauksen soveltuvuutta UPM Caledonian Paper -tehtaan CHP-voimalaitoksen polttoaineen vastaanottoon. Tarkoitus on varmentaa vasta asennetun röntgeniin perustuvan kosteusmittauksen toimivuus. Laitteiston soveltuvuutta polttoaineen vastaanoton designiin arvioidaan. Lisäksi työssä arvioidaan nykyisin käytössä olevan perinteisen kosteusmittausprosessin tarkkuutta.

Kirjallisuuskatsauksessa esitellään puubiomassan koostumusta ja ominaisuuksia painottaen kosteutta ja polttoaineen sisältämän kosteuden vaikutusta kattilan toimintaan. Puuperäinen biomassa sisältää enemmän klooria kuin hiili. Kierrätyspuu tyypillisesti sisältää lyijyä ja sinkkiä, jotka ovat yhdistetty korroosion muodostumiseen. Puupolttoaineisiin liitettävän petin aglomeraation, kerrostumien sekä korroosion ja eroosion muodostumista kuvaillaan työssä. Lisäksi työssä kuvaillaan erilaisia pääosin ainetta rikkomattomia kosteusmittausmenetelmiä.

Kokeellisen osion perusteella röntgenmittaus mittaa yleisesti kuormakohtaiset keskiarvokosteudet hyväksyttävällä tarkkuudella. Tietyillä polttoainetyypeillä ja -jakeilla röntgenillä mitatut kosteudet erosivat merkittävästi todellisista kosteuksista. Laitteiston lisäviritys ja osittainen kalibrointi ovat tarpeen. Röntgenillä mitatut kosteudet vaikuttavat korreloivan polttoainepatjan keskimääräisen korkeuden kanssa – mitä paksumpi kerros polttoainetta liukuhihnalla on, sitä korkeampia ovat röntgenillä mitatut kosteudet. Tätä virhettä voidaan korjata joko tulosta kompensoimalla tai tasaamalla hihnan polttoainekerrosta. Caledonian nykyisen polttoaineen vastaanoton operointi ja design eivät mahdollista kuormakohtaista kosteusmittausta. Kuljettajan tai operaattorin ottamat näytteet, johon polttoaineen toimittajan saama maksu perustuu, näyttävät antavan hyväksyttäviä tuloksia kerätyn datan sekä empirian perusteella. Päiväsiiloja ennen kattilaan menevästä polttoainevirrasta otettu kokoomanäyte vaikuttaa noin 5 prosenttiyksikköä kosteammalta kuin polttoaine luultavasti on.

FOREWORD

This Master's thesis was done for UPM Caledonian Paper between January and July 2017. The experimental part was completed in Scotland, and the start and finishing of writing in Helsinki.

At first, I want to express my gratitude for UPM Caledonian Engineering, Eddie my boss and Reetta who both helped me so much with practicalities of my thesis. I genuinely hope that my work comes for good use in Caledonian. My instructor Antti deserves a big thank you for all the support and guidance. Thank You Esa H. for good improvement suggestions and ideas for my thesis and your enthusiastic approach. Sirpa, my career role model, you deserve also a big thank you for all the support. My professor Esa V. has been very supportive and involved. This thesis would not be the same without Inray and Janne, Elisa, Olli and Mika. Thank you for all the help, support and information.

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ABBREVIATIONS

Th	Thermal
CHP	Combined heat and power
DR	Digital Radiography
DXA	Dual Energy X-ray
HHV	Higher heating value
LHV	Lower heating value
MRI	Magnetic Resonance Imaging
N/M/FIR	Near/Middle/far Infrared
NDT	Non-destructive testing
NMR	Nuclear Magnetic Resonance
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PGW	Pressure groundwood
RF	Radio frequency
ROCs	Renewable Obligations Certificates
RWW	Recycled Wood Waste
WID	Waste Incineration Directive
wt%	Weight percent

1 INTRODUCTION

The share of renewable energy generation has increased, and not least due to efforts to curb climate change. Wood and other solid biomass accounted for 40 % of renewable energy generation in the EU in 2015 as presented in **Figure 1**. The use of renewables has increased with a rate of 4,3 % annually. (Eurostat. 2017) The EU's ambitious plan to cut greenhouse gas emissions by 40 % from 1990 levels before 2030, and aims to act as the global climate leader, steer to further increases in bioenergy use. Countries have their own schemes to make use of renewables economically viable by subsidies of different sort.

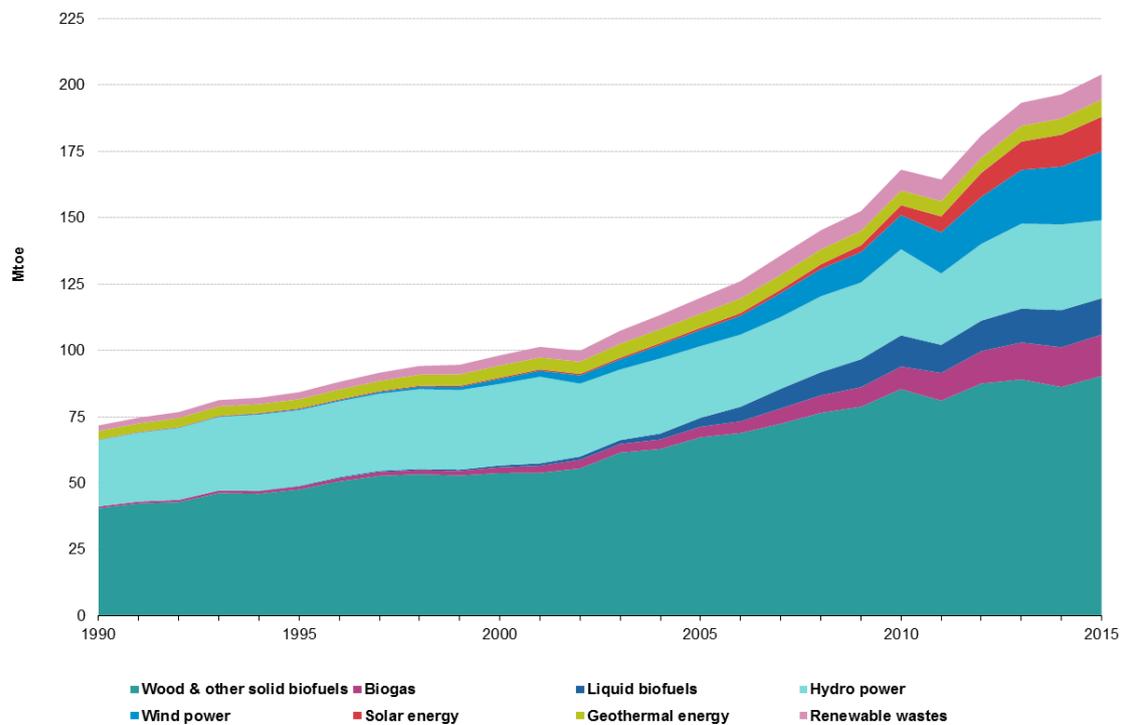


Figure 1. Primary energy production from renewables by source (Eurostat. 2017).

The increased bioenergy generation has created a demand to measure biomass quality and particularly moisture thus there is a market for measurement applications. Fuel costs of bioenergy generation accounts by estimate for half of all operating costs. The non-destructive, and on-line measurements are gaining market share but traditional sampling remains the main testing method for biomass moisture and quality. The advantage of on-

line and other rapid testing methods is the instant or almost instant moisture results, whereas traditional oven dried samples take 24 hours to be analyzed. The NDT often measures the whole object while sample size is limited and addresses only a fraction of a heterogeneous biomass batch. Oven drying only measures moisture but many NDT applications such as those based on radiography can also detect foreign objects such as rocks and metals.

The experimental part of this thesis was carried out in UPM Caledonian Paper CHP plant's fuel receiving. The CHP plant supplies the paper mill, producing paper of on-site PGW and bought chemical pulp, with electricity and steam. The CHP plant has Metso Hybex BFB boiler, the live steam parameters are 90 bar, 510 °C and 34 kg/s, and the heat output is 90 MW_{th} (UPM. 2014). The power plant uses woody biomass and effluent sludge from paper mill as fuel. The CHP site is presented in **Figure 2**.

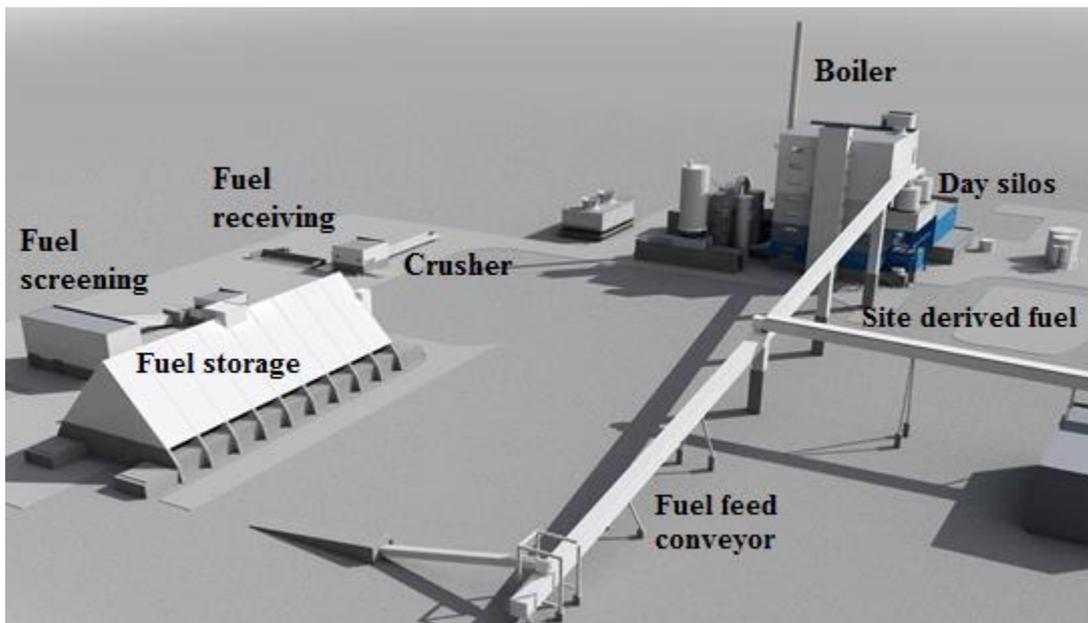


Figure 2. Caledonian CHP area (UPM. 2014). Modified picture.

The aim of this thesis is to verify that an X-ray based moisture measurement measures the biomass moisture correctly. The suitability of the measurement equipment to the fuel receiving is evaluated with alongside an evaluation of the current sampling procedure.

2 WOODY BIOMASS

The EU defines biomass as the biodegradable fraction of products, wastes and residues of biological origin. Forestry is included in this description. Biodegradable fraction of industrial and municipal waste is also considered biomass. (2009/28/EC) Sustainability criteria has previously only been set to apply for biofuels in gaseous or liquid form and bio liquids. The Commission now proposes that solid biomass used in heat and power generation should also have sustainability criteria. Only biomass complying with sustainability criteria would be considered as "zero emission". The current regulations only apply to biofuels used within transportation. (COM(2016) 767) Sources of woody biomass are presented in **Figure 3**.

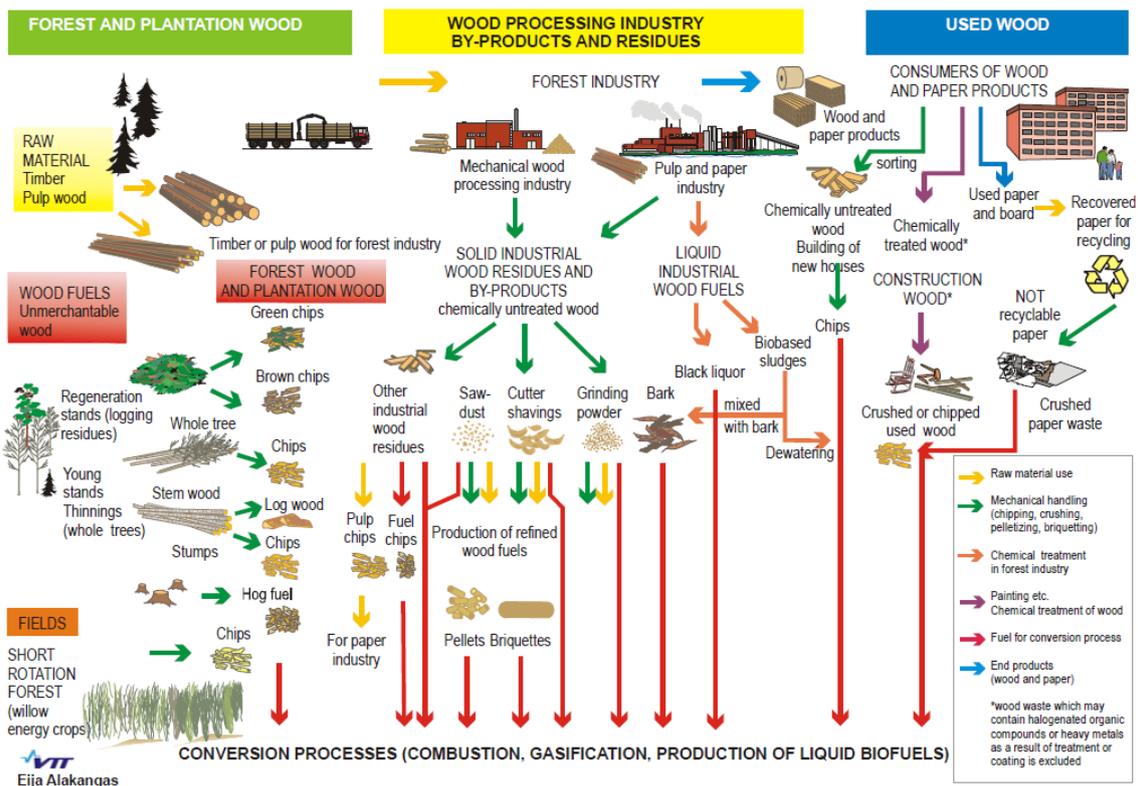


Figure 3. Woody biomass resources. (Alakangas, 2005)

2.1 Virgin wood and residues

This section describes woody biomass types relevant for the Caledonian CHP plant. Virgin wood and different kinds of residues are described. Waste wood has its own section 2.2.

2.1.1 Arboricultural arisings

Arboricultural arisings refer to biomaterial that was removed as part of tree surgery, management of municipal parks and verges of roads and railways (Ofgem. 2016).

2.1.2 Forest residue

Forest residue is wood that was left in forest either after logging or thinning. According to Ofgem it includes all raw materials collected from forests. This includes materials such as tree tops, branches, brash, clippings, trimmings, leaves, bark, shavings, wood chips and saw dust from felling. (Ofgem. 2016) Some needles may be present but are unwanted substances for boiler due to their high ash and chlorine contents. Moisture content for fresh forest residue is approximately 50-60 wt%. (Alakangas et al. 2016) Moisture content of forest residue has a varying range depending on the state of the drying process. Soil is often attached to forest residue.

2.1.3 Bark

According to Ofgem guidelines in the context of renewables obligations bark is either categorized as forest residue or arboricultural arising depending on where the residue is generated. (Ofgem. 2016) Bark is also a side product of pulping and mechanical forestry.

Bark is a residue, that is created during skinning of wood used for production purposes. Bark has a decent heating value due to considerable amount of lignin it includes. Bark has a high moisture content of about 70 %. The ash contents are likewise high, 1.8 wt% dry basis for pine and 3.4 wt% dry basis for spruce. In contrast, the ash content for chips made from whole unskinned wood is ~0.5 wt% dry basis. The high moisture, and ash

contents weaken barks fuel properties that can be improved by mixing it with other fuels. Bark is heterogenic and may cause problems in fuel handling. (Alakangas et al. 2016)

Bark fuels tend be high in silica. In coastal regions sand enters the surface layers of wood by wind transport. During skidding of wood especially in rainy conditions the surface layers pick up sand and clay. (Mcgowan et al. 2010)

2.1.4 Stem wood

Stem wood, later referred to as fuelwood, has a low ash content of 0,5 wt% dry basis for softwood. Moisture content for pine is 45-50 wt% and for spruce 40-60 wt%. (Alakangas et al. 2016) Timber or pulp wood or other high-quality wood is primarily used in process industry e.g. pulp or at sawmills for manufacture. If unsuitable for previously mentioned activities or otherwise excess higher quality wood can be used in heat and power generation.

2.1.5 Sawmill Residue

Sawmill residue is saw dust or other woody material including small offcuts and bark produced during processing of wood at a sawmill (Ofgem. 2016). Ash contents for sawmill residue is low, with bark 1.1 wt% dry basis and 0.08 wt% dry basis for non-bark pine sawdust. Moisture is low accounting for 5-15 wt% for dried lumber and 50-55 wt% for undried. (Alakangas et al. 2016) Depending on the sawmill process moistures can reach 65 wt%.

2.2 Waste wood

European Commission sets a priority order in waste prevention and management legislation and policy in following hierarchy: prevention, preparing for re-use, recycling, recovery and disposal. Waste itself is defined as any substance or object which the holder discards or intends or is required to discard. (2008/98/EC)

The current Renewable Energy Directive says little about waste wood other than fuels produced of it. The proposed renewed directive mentions biomass fuels from waste and residues in a context that suggest that they do not have to fill the sustainability criteria but only greenhouse gas saving criteria. That applies also for wastes and residues that first were processed to a product and then used as a fuel. (COM(2016) 767)

The Waste Incineration Directive (WID) is a directive setting guidelines for thermal treatment of waste wood. The aim of the WID is to limit and prevent negative effects on environment that may relate to pollution of air, soil or water or on human health caused by gasification, pyrolysis and incineration. (The Waste and Resources Action Programme. 2012) WID excludes power plants combusting wood waste with the exception of wood waste which may contain halogenated organic compounds or heavy metals as a result of treatment with wood preservatives or coating, and which includes in particular such wood waste originating from construction and demolition waste. (2000/76/EC) This means that if there is no evidence of chemical treatments or paint WID compliance would not be required when waste wood is utilized for energy generation. However, it has to be demonstrated that the wood waste was not treated. (The Waste and Resources Action Programme. 2012)

Renewable energy policies and in UK e.g. the Renewables Obligation effect the use of waste wood. Waste wood can include fossil derived compounds but only biomass is eligible for Renewable Obligation Certificates (ROCs) thus generators are required monthly to demonstrate the biomass and fossil derived portions of the fuel as a percentage of total energy content (Ofgem. 2013). In brief Renewables Obligation requires power suppliers to increase the proportion of renewable electricity. Obligation is reached either by presenting ROCs or by contributing to the buy-out fund. Operators can obtain ROCs by accreditation and meeting the ROC issuance requirements. Later the buy-out fund is redistributed to generators in proportion of number of ROCs the supplier has presented. (Ofgem. 2015) Prices for ROC's and buy-out fund are shown in Table 1.

Table 1. ROCs and buy-out price.

Obligation period (1 April - 30 March)	Buy-out price, £	Obligation, ROCs/MWh
2013-2014	42.02	0.206
2014-2015	43.30	0.244
2015-2016	44.33	0.290
2016-2017	44.77	0.348
2017-2018	45.58	0.409

Demand for wood waste in energy generation has risen due to policies encouraging the use of renewables. Due to support in form of subsidies, biomass industry has an advantage over other industries buying and using wood waste in production. (NL Agency. 2013) Besides being CO₂-neutral, recycled wood has a market demand due to a relatively low price. For instance, in Sweden between 2005 and 2009 recycled wood was 40-60 % cheaper per MW than forest residue. (Enestam et al. 2011a) Currently in some parts of UK power generators do not pay for waste wood. In practice, as will be described later in this and chapter 3 combustion of waste wood may have serious implication on the boiler. The inexpensiveness of the waste wood makes it economically justifiable to have shorter operating life of boiler parts that then need to be replaced prematurely.

2.2.1 **Class ification of waste wood**

This section introduces the grading and origins of waste wood. Wood waste grades range from A to D:

- Grade A: “clean” recycled wood. Includes solid softwood and hardwood, packaging waste, cable drums and process off-cuts from manufacturing. Usually reused as material e.g. in panel industry or fuel manufacture for pellets and briquettes.
- Grade B: industrial feedstock. Contains up to 60 % of A grade material plus building and demolition wood. Used for industrial wood processing like manufacture of panel products.

- Grade C: fuel grade. Wood used as biomass for energy generation. Can include grade A and B wood and e.g. fencing products and flat pack furniture. High amounts of panel products such as chipboard and plywood occur. Allowed non-wood contents prior to processing include paints and coats, glass, plastics and metal.
- Grade D: hazardous waste. Special disposal facilities are required. Wood in this category includes transmission poles, fences, railway sleepers and cooling towers. (Defra. 2012)

Only grade A and B are used at UPM Caledonian CHP. Grade A usually refers to pallet wood. **Figure 4** shows Recycled Wood A (right) and Recycled Wood B (left). As can be seen grade A is cleaner, has a more consistent quality and particle size.



Figure 4. Recycled wood grade B (left) and grade A (right).

Grades A-C are all used for energy generation e.g. clean wood waste is used in pellet production alongside sawdust, energy crops and forest thinning. Waste wood has traditionally come from construction and demolition activities. (NL Agency. 2013)

2.2.2 Origin

UK is a significant producer of waste wood, most of which is derived from construction and demolition activities. In 2010 the waste wood arisings were 4,33 Mt. 0,55 Mt was in the market for Biomass/Energy and 0,38 Mt was Export Biomass. Altogether demand in UK was estimated to be 3,2 Mt making the recovery rate 74 %. (Defra. 2012) The London region is a big producer of recycled wood.

One supplier of recycled wood grade B was visited 7.4.2017. **Figure 5** shows wood waste ready for shredding. There is no cover at yard thus if in wet weather the wood piled on concrete may soak some moisture. Ferritic and non-ferritic metals are removed from the waste wood. The wood is shredded as shown in **Figure 6**



Figure 5. Waste wood waiting at yard for shredding.



Figure 6. Shredding of waste wood.

The waste wood is shredded to a particle size of 10-70 mm. Smaller matter is separated and sold as animal bedding. Particles with a diameter > 70 mm are returned to be re-shredded.

2.2.3 Properties

Waste wood is low in moisture and includes impurities such as plastics, and may have been treated chemically. Waste wood is typically more corrosive than virgin wood due to contaminants like paint or plastics which increase the level of chlorine, zinc and lead in the fuel (Alipour et al. 2014). Sodium and sometimes sulfur contamination levels are elevated relative to those found in virgin wood. Zinc and lead originate often from surface treatments that are estimated to account for 70 % of zinc, and 80 % of lead. Plastic accounts for approximately 10 % of lead, and 14 % of zinc is likely from galvanized metal. (Enestam et al. 2011a) A comparison of waste wood and virgin wood is shown in **Table 2**. As can be seen moisture is low compared to virgin wood. Ash contents seem to be higher adding up 15 %.

Table 2. Wood composition. (Alipour. 2013).

Parameter	Waste wood	Waste wood (Min-Max)	Forest wood
Total moisture (wt%)	23	11-39	48
Total ash (wt% dry)	5,8	3,2-15	2,7
C (wt% dry ash-free)	52	50-56	53,1
N (wt% dry ash-free)	1,2	0,12-1,5	0,31
S (wt% dry ash-free)	0,08	0,04-0,3	0,04
Cl (wt% dry ash-free)	0,06	0,04-0,22	0,02
K (wt% in ash)	2	1,0-2,6	7,6
Na (wt% in ash)	1,4	0,6-1,9	0,86
Zn (mg/kg in ash)	10393	2420-184167	2047
Pb (mg/kg in ash)	544	140-28611	63

The pollutants and contaminants found in waste wood lead to increased deposit formation. Also, the possibility for notable concentrations of heavy metals exist. (Alakangas et al. 2015) Boilers combusting waste wood have an increased risk of fouling and corrosion of furnace walls, superheaters and economizers. These have been linked with chlorine, zinc and lead found in deposits but also sodium and titanium have been detected. Waste wood is also associated with the formation of molten metal in the bottom of the boiler. (Enestam et al. 2011a)

content is over 5 %. (Grammelis et al. 2011) In Caledonian waste wood as received has a moisture content of 15-35 %. Typical values for moisture content for solid biomass and other fuels are presented in **Table 3**.

Table 3 .Fuel moisture contents (Alakangas et al. 2016)

Fuel	Moisture wt-%
Coal	8-14
Heavy oil	<0,1
Light oil	0.01-0.02
Peat	35-47
Forest residue	50-60
Sawdust	45-60
Bark	40-70
Stem chips	40-55

3.1.2 Volatile content

Volatile content for wood is high accounting for 80-90 % dry basis mass. Volatiles are made of hydrogen, oxygen, nitrogen and sulphur. (Alakangas et al. 2016) Most of the heat formed during combustion of biomass is due to volatiles. Volatiles burn fast because of the rapid release rate in high temperatures leading to high reactivity. (Grammelis et al. 2011) Fuels containing larger shares of volatiles also combust in lower temperatures than fuels with lower volatile contents. Due to the rapid ignition, they burn faster and more completely than fuels with less volatiles. (Huhtinen et al. 1994)

3.1.3 Ash content

Ash contents are defined as weight percentages for dry basis fuel. Wood contains ash typically less than 3 % bark being the richest in ash content. A typical value for wood ash content is 0.4 %. For comparison coal contains 11 % ash. (Huhtanen et al. 1994)

Ash contents for wood are typically low. For biomass, the quantity of ash tends not to be an issue but the quality of it is. Unlike coal, biomass ash includes alkali metals and silica. These may lead to boiler issues such as agglomeration that can cause availability problems and force to unit shutdowns due to bad fluidization. (Grammelis et al. 2011)

3.1.4 Fixed carbon

Fixed carbon is the carbon residue (char) that does not exit with the devolatilized material. Wood contains typically 11.4-15.6 % of fixed carbon dry basis. (Alakangas et al. 2016)

Porous biomass chars have a high reactivity compared to coal. This can be explained by the high internal specific surface area and catalytically important ash forming elements (Hupa et al. 2016). Huang et al. (2009) studied char reactivity by adding metal catalysts. Their findings suggest that the catalysts increased char reactivity in order K, Na, Ca, Fe, and Mg. This phenomenon is presented in **Figure 8**.

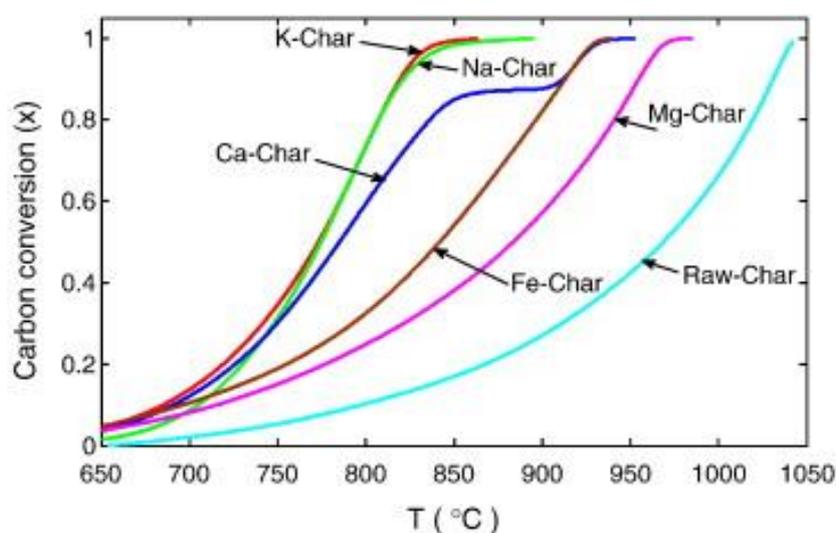


Figure 8. Char reactivities as a function of temperature with added metal catalysts. (Huang et al. 2009)

3.1.5 Chlorine content

Chlorine vaporizes during combustion and forms amongst others HCl and alkali chlorides. Alkali chlorides may induce fouling, superheater hot corrosion, and formation of HCl and dioxins. (Grammelis et al. 2011). There are two major ways for dioxin formation: carbon, oxygen and HCl build it in convection part of the boiler in temperatures 200-400 °C or dioxin precursors react on fly ash surface in temperatures 300-800 °C while Cu and Fe act as catalysts. Formation of PCDD/Fs can be inhibited

with use of sulphur and nitrogen. The additives can be added before the convection part. Such additives as ammonia or urea are used to restrict NO_x -emission thus synergies. (Aurell et al. 2005) Combustion of treated wood is one of the most important sources of dioxins (Lavric et al. 2003). Typical values for wood fuel chlorine content range 0.01-0.03 wt%, daf. Higher chlorine contents are found in waste wood. (Kassman. 2012). Waste wood can include plastics and plastics are rich in chlorine, PVC having the highest concentrations of up to 5 wt% (Coda et al. 2001).

3.2 Heating value

Heating value is one of the most important properties of biomass regarding design calculations or modelling of thermal conversion systems. (Sheng and Azevedo. 2004) Energy content is dependent on the woods chemical composition thus carbon and hydrogen compounds are determinant for the energy content (Alakangas et al. 2016). For solid fuels such as wood heating value cannot be calculated by elements since they typically include oxygen compounds, that react with other fuel components. For that reason, heating values for solid fuels must be measured (bomb calorimeter) or approximated with correlations that may differ by results considerably from measured values. (Raiko et al. 2002) **Figure 9** plots heating value as a function of moisture content. As can be seen water content effects heating value significantly.

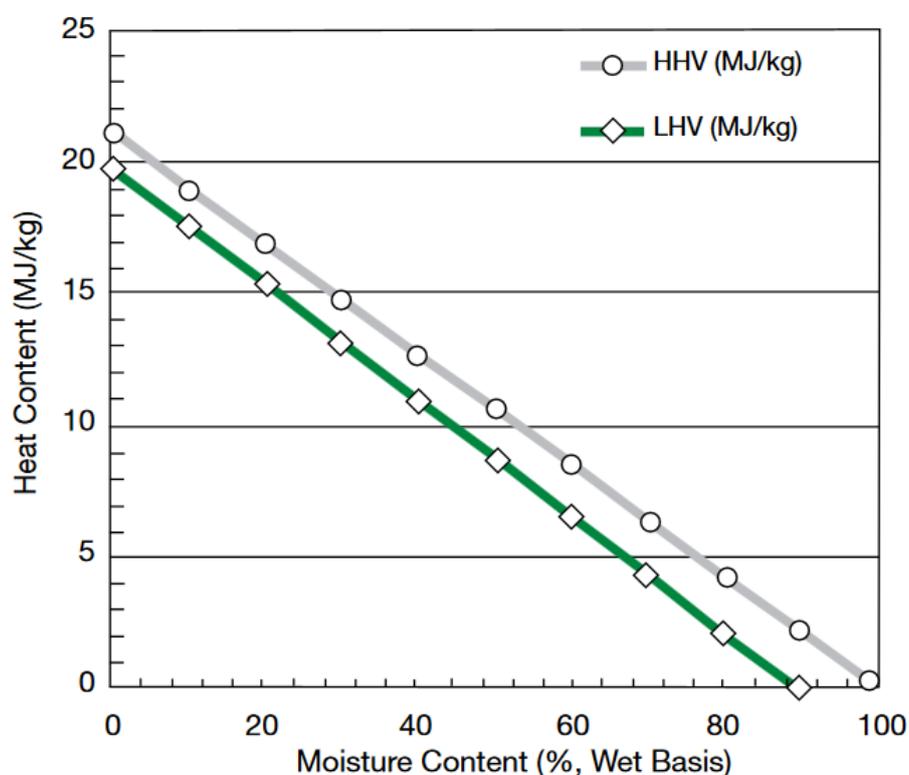


Figure 9. Relationship between moisture content and heating value. Plotted for lower (LHV) and higher heating value (HHV). (Ciolkosz. 2010)

3.2.1 Higher heating value

Higher heating value is the heating value which assumes water to be liquid after combustion. This means that the water vaporizes but is then condensed and the energy released can be recovered thus combustion process heat output is increased. This is not the case for actual boilers since part of heat is lost with flue gases so more usable heating values can be obtained by using the lower heating value. (Huhtinen et al. 1994)

There are many correlations available with high accuracy if compared to investigator's own data. Samples that the correlations base on are limited leading to not that high accuracies in general. Sheng and Azevedo studied estimation of higher heating value of biomass from basic analysis data by correlations based on proximate, ultimate or chemical analysis. Proximate analysis, that is the easiest and most used characterization

method for biomass, uses weight percentages of moisture, volatile matter, fixed carbon and ash. They found that the correlations based on proximate analysis data were poor but proposed a correlation between ash content dry basis and HHV. An ultimate analysis based on weight percentages of C, H and O is generally more accurate than those based on proximate analysis. As the contents of carbon or hydrogen increases the HHV seems to increase too. The equation proposed by Sheng and Azevedo, that gave 90 % accuracy, is shown in equation 1. The HHV correlation based on chemical analysis was found to be poor due to the variation in chemical composition and component properties of biomass. (Sheng and Azevedo. 2004)

$$\text{HHV} = -1,3675 + 0,3137C + 0,7009H + 0,0318O \quad (1)$$

Channiwala and Parikh (2002) searched for a unified correlation for estimating HHV of fuels in liquid, solid and gaseous state. The best correlation with on average absolute error of 1.45 % and bias error of 0.00 % according to their finding is show in equation 2.

$$\text{HHV} = 0,3491C \cdot 1,183H \cdot 0,1005S - 0,1034O - 0,0151N - 0,0211A \quad (2)$$

Looking closely at the equations 1 and 2 it seems that hydrogen has significant effect on HHV. About half of dry basis wood consists of carbon and ~6 % is hydrogen. (Alakangas et al. 2016) **Figure 10** presents molar ratios of hydrogen and oxygen to fuel carbon. The variation of hydrogen-coal ratio does not seem particularly large considering the large range of biomass the data included. (Jenkins et al. 1998)

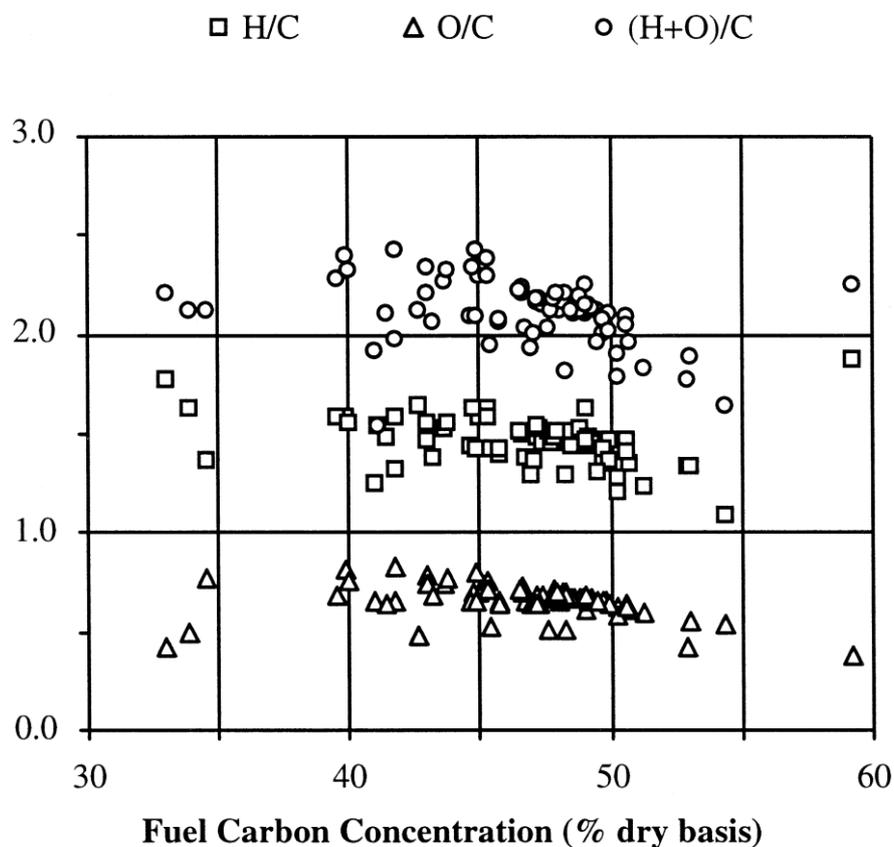


Figure 10. Molar ratios of hydrogen and oxygen to carbon. (Jenkins et al. 1998)

3.2.2 Lower heating value

Lower heating value (LHV) is calculated by subtracting heat of vaporization from the heating value. (Raiko et al. 2002) Since that heat is not recovered by condensation LHV gives a more suitable value for solid fuels. (Huhtinen et al. 1994) Moisture content of wood varies based on the type but also storage and harvesting time matters (Alakangas et al. 2016).

3.3 Fuel quality implications

Variation and impurities in fuel quality present several implications for the boiler, for the environment, and also cause issues related to fuel handling (Alakangas et al. 2015). Waste wood may include metals, glass and plastic, which unless used as coating or paint, can be mechanically removed. Also for power plants receiving waste wood from several

suppliers it has proven difficult to monitor the quality – it may be un-clear what the waste wood actually includes as received, thus contamination detection is vital.

3.3.1 Mechanical issues

Mechanical issues may be caused by glass or metal objects on conveyers or screws of the fuel handling system (Alakangas et al. 2015). Most of the availability issues are related to fuel handling (Vakkilainen. 2010). Fuel high in moisture e.g. bark tends to cause blockages.

3.3.2 Technical issues

Technical issues are in this case defined as operational issues that are linked to agglomeration, deposit formation and corrosion or erosion. Focus is in heat transfer surface damage.

Deposit formation, corrosion and erosion are problems at Caledonian CHP. They are mainly attributed to combustion of chlorine rich waste wood and to high moisture content of biomass which increases the flue gas flow that accelerates the deterioration. The problems have mainly been associated with boiling surfaces and flue gas channels but economizers appear to be in good condition.

3.3.2.1 Agglomeration

Bed agglomeration is an ash-related problem in Bubbling Fluidized Bed (BFB) boilers. Temperatures that are higher than the softening temperature of fuel ash have been linked to result in agglomeration of bed particles and subsequently in defluidization of the bed. Low-melting-point of fuel ash and bed particle coating layers are suggested as crucial routes to the initiation of bed agglomeration. (Moradian et al. 2016) Larger particles are created due to agglomeration leading to local hotspots that further aggravate the agglomeration (Grammelis et al. 2011). The mechanisms of agglomeration are not well understood. It is unclear whether agglomeration is simply due to molten alkalis that bind

ash particles together and/or by chemical reactions between alkalis, ash components and bed materials in high temperatures. (Montes et al. 2016)

Figure 11 presents time to agglomeration as a function temperature or bed material diameter. The graphs suggest that higher bed temperatures and larger bed material diameters increase agglomeration speed. The latter is consistent with formation of hotspots.

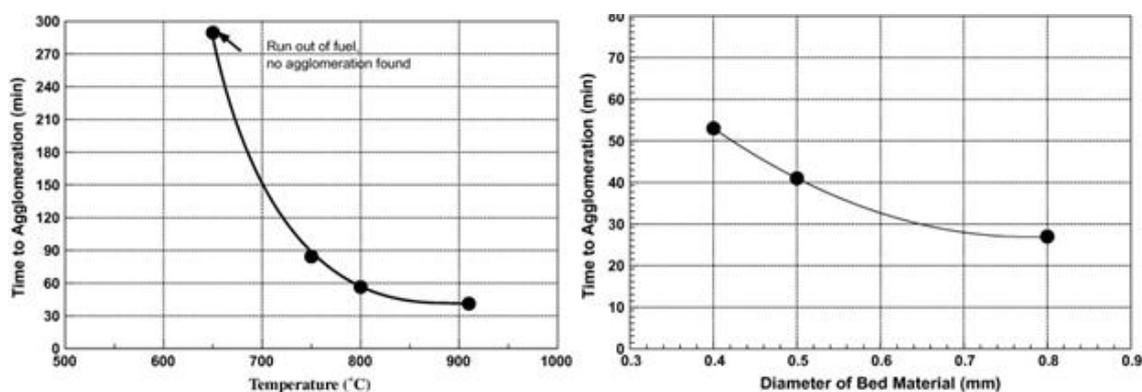


Figure 11. Time to agglomeration in relation to temperature and bed material particle size (Chungjiang et al. 2011)

Waste wood tends to be rich in alkalis. Sand is typically used as bed material and includes quartz 25-100 wt%. Quartz is known to form alkali calcium silicates with ash of alkali-rich fuels. Unfluidizable material such as gravel, glass and metal can disturb the fluidization to a point where fuel particles and char rise in temperature locally above that of deformation of sand particles. (Silvennoinen et al. 2013)

Agglomeration can be detected by temperature gradient or by pressure drops in the bed. Early detection enables corrective measures. However corrective measures do not always help but preventative approaches should be adopted. One strategy is to prevent bed agglomeration by the use of additives like dolomite or limestone. Two underlying mechanisms for these additives are: fuel ash dilution leading to reduced sticky ash layer on bed particles or fuel alkalis reacting with additives forming higher melting point compounds resulting in reduced agglomeration (Van Eyk. 2005). Fuels can be

preprocessed to lower the level of contaminants like alkalis. Alternative bed materials can be used in order to achieve higher melting temperatures. Reduction of bed temperature by dropping combustion temperature might reduce the vaporization of alkali salts resulting in reduced agglomeration. (Basu. 2006)

3.3.2.2 Boiler deposit formation

Deposit formation is related to fuel and ash composition (Alakangas et al. 2015). Slagging refers to dirt on furnace area where main mean of heat transfer is radiation. Slagging layers are typically thick and the appearance is molten. Fouling refers to dirt on heat convection surfaces such as heat exchange tubes. The temperatures of fouling are lower and the ash layer is in solid form. (Raiko et al. 2002)

Consequently, heat transfer rate is reduced due to deposition. Slagging and fouling affect the overall boiler availability and efficiency. Depositions can be removed with soot-blowing from superheater tubes, and cleaned mechanically during outages. Alkali compounds, sulphur and chlorine are involved in deposition and corrosion phenomena. Slagging and fouling are known to cause corrosion. While depositions can be removed, corrosion is permanent affecting the lifetime of the equipment. (Grammelis et al. 2011)

3.3.2.3 Corrosion and erosion

Corrosion may occur when the protective oxide layer on tube walls and other surfaces are attacked by chlorine or sulphur containing compounds. A new non-protective layer with defective structure is formed. The layer can be scaled off thus further corrosion is possible. Corrosion can occur through gas phase reactions e.g. Cl_2 and NaCl , with metallic boiler surfaces or through solid and molten chloride reactions. Also, sulphates are prone to induce corrosion but rather uncommon for BFB due to low-sulphur-content fuel. (Grammelis etn al. 2011)

Combustion of wood waste may lead to excess corrosion (and deposit formation) on furnace walls, superheaters, and economizers. Especially alkali chlorides play a

significant part in high-temperature corrosion. Zinc and lead chlorides, according to evidence, increase corrosivity of deposits. As the melting point of deposits is decreased the surfaces risk molten-phase corrosion. (Silvennoinen et al. 2013)

Conventional methods to curb high-temperature corrosion have included boiler design such as superheater placement and tube arrangement and chose of materials. Additives containing sulfur, sulfate or aluminum silica have also been used to reduce superheater corrosion by altering flue gas properties. Co-firing with coal or sludge seems to work in the similar manner. (Silvennoinen et al. 2013) Superheater corrosion is the main reason why steam temperatures must be kept lower in biomass boilers than in coal fired ones. Corrosion induced by alkali chlorides is the best-known cause of superheater corrosion. (Hupa et al. 2016)

There is a relationship between erosion rate and velocity of the particles. As the particle size grows the rate of erosion related loss increases. (Pronobis and Wojnar. 2013)

Whether corrosion attributes to erosion or the other way around is discussed. Corrosion may enhance erosion or erosion enhance corrosion or both. Erosion is often linked to corrosion and referred to as erosion-corrosion (E-C) (Wang 1995, Mishra et al 2014, Kumar et. al. 2015). E-C is a major way of high-temperature degradation of fireside boiler tubes. It is believed that corrosion products deposit on boiler surfaces and simultaneously flue gases erode these corrosion-product deposits. The E-C leads to continuous thinning of tubes that may lead to rupture. (Kumar et al. 2015) Fly ash E-C of superheater, reheater and economizers is a serious problem in biomass boilers and depends on fuel characteristics and additives, operating conditions and boiler configuration etc. Flue gas velocity and amount and quality of ash e.g. abrasiveness and corrosiveness have been linked to material degradation. (Wang. 1995)

3.3.3 Financial aspects

Fuel costs make up 45 % of the total costs in electricity generation by wood combustion (Vakkilainen et al. 2012). EU evaluates that costs of feedstock account for around 50 %

of bioenergy costs (European Commission. 2017). Significant fuel costs give energy generators an incentive to pay for the energy content. This makes measurement of moisture content and foreign object concentrations economically feasible.

All mechanical and technical issues are also financial. Availability issues in the worst-case lead to stops in operation thus less revenue from power generation. Boiler deposit leads to less efficient heat transfer which contributes to inefficient utilization of fuel energy content. Severe corrosion demands change of equipment. More so environmental issues are financial issues. Cleaning of flue gases, and ash removal are costs.

3.3.4 **Reasons to monitor**

Fuel moisture, and in some cases foreign content, is measured generally for price determination and perhaps further to base fuel price on energy content. A basic problem is to get a rapid and accurate estimation of fuel moisture content during receiving. Instrumental biomass moisture measurement has proved difficult since water is trapped inside porous material, cell structures, cells and fibers. Moisture is also spread unevenly. Thus, standardized oven drying method remains the most widely applied moisture measurement. (Järvinen. 2013)

Moisture effects boiler operation in several manners. High moisture increases flue gas flow, increases fan power need and may speed up abrasion. Moisture in general decreases the heating value (Huhtinen et. al. 1994). Thus, knowledge of moisture content is important. Moisture data could be used to enhance boiler operation by sorting or mixing biomass by energy content (or moisture content) in order to have a steadier bed temperature.

Wood may include foreign objects such as rocks and pieces of metal. These are separated if possible, metals with magnets and rocks with rollers. Foreign objects increase the rate of ash creation leading to higher costs for ash management. By entering the boiler, they may e.g. speed up agglomeration and deposit formation.

As mentioned in chapters 2.2.3 and 3.3.1 there are other damaging substances in woody biomass than moisture, recycled wood being perhaps the most problematic. To monitor glass, metals, glue and paint, it would be feasible that these fuel flows could be rejected or used in smaller portions. Foreign matter content might also be used as a pricing criteria.

4 MEASUREMENT METHODS FOR FUEL QUALITY

There is an increased demand for wood fuel quality measurement. Different and broader selection of biomass is utilized for energy generation. This creates a need for fuel quality control and assurance. Forestry biomass is often wet and can include considerable amounts of foreign objects such as soil, and during winter snow.

Moisture content is recommended to be tested from each load or part load in Finland, where weather conditions have a huge effect on moisture. That testing frequency is not applied through-out Europe due to diminished importance of moisture content (Salvola, 2014). Other measures such as chlorine content, net calorific heating value and ash content can be monitored in monthly basis if not more frequently needed. (Alakangas et al. 2015b) More frequent sampling might be needed to comply with renewable schemes and subsidies to be granted.

The reasons to measure the moisture content and heating value are fuel price determination and combustion control (Nyström, 2006). The traditional sampling method is time consuming. Adding that biofuels are heterogenic so in order to get a good characterization of the biofuel excessive sampling would be required. (Torgrip, 2017)

4.1 Conventional measurements

Conventional fuel quality measurements are based on samples that are collected mechanically or manually. Limited sample size and non-continuity are characteristic for conventional fuel quality measurement. Most widely applied method is the gravimetric method.

4.1.1 Samples and guidelines for sampling

Most inaccuracies in fuel analysis originate from the sampling stage. Wood fuels are heterogeneous which makes collecting samples meeting criteria for good sampling, meaning each particle should have equal opportunity for selection in final sample,

difficult. Due to this mechanical sampling from moving fuel e.g. from conveyer should be preferred. Most preferably collected sample should come from falling fuel stream like conveyer or unloading of the truck. (Alakangas et al. 2015b) **Figure 12** shows possible executions for fuel sampling from a moving fuel stream.

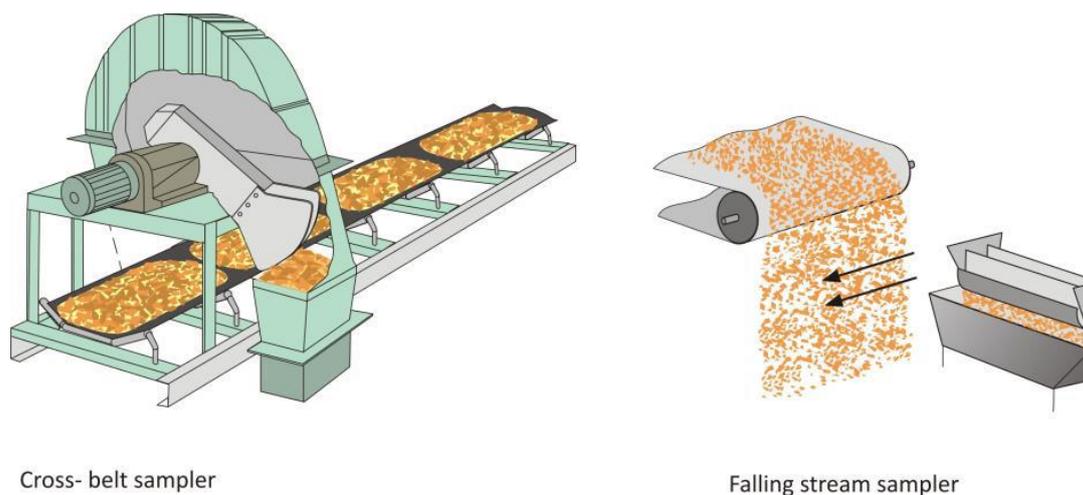


Figure 12. Mechanical sampling techniques. (Alakangas et al. 2015b)

Manual sampling is still a widely used method for pricing of wood fuel. Manual sampling can occur from stationary fuel from back of a truck, fuel stream during unloading from the rear dump vehicle or immediately after dumping or from the storage space. If already unloaded samples should be taken from truck specific loads. Several samples need to be taken in order to get a good presentation of the fuel since wood fuel segregates during dumping. Coarsest particles land in the bottom, finest matter at the top and middle of the pile. (Alakangas et al. 2015b) In Caledonian it is estimated that the operator takes approximately 50 % samples and the driver the remaining 50 %, both from back of a truck.

The overall precision of moisture measurement by sampling for a load is dependent on the number of samples collected and on how many loads are tested. This correlation is shown for logging residue in **Figure 13**. If you test two loads taking two samples from

each, the overall precision is 6 %. If you increase the number of increments per load to 6 the overall precision is 3.5 %.

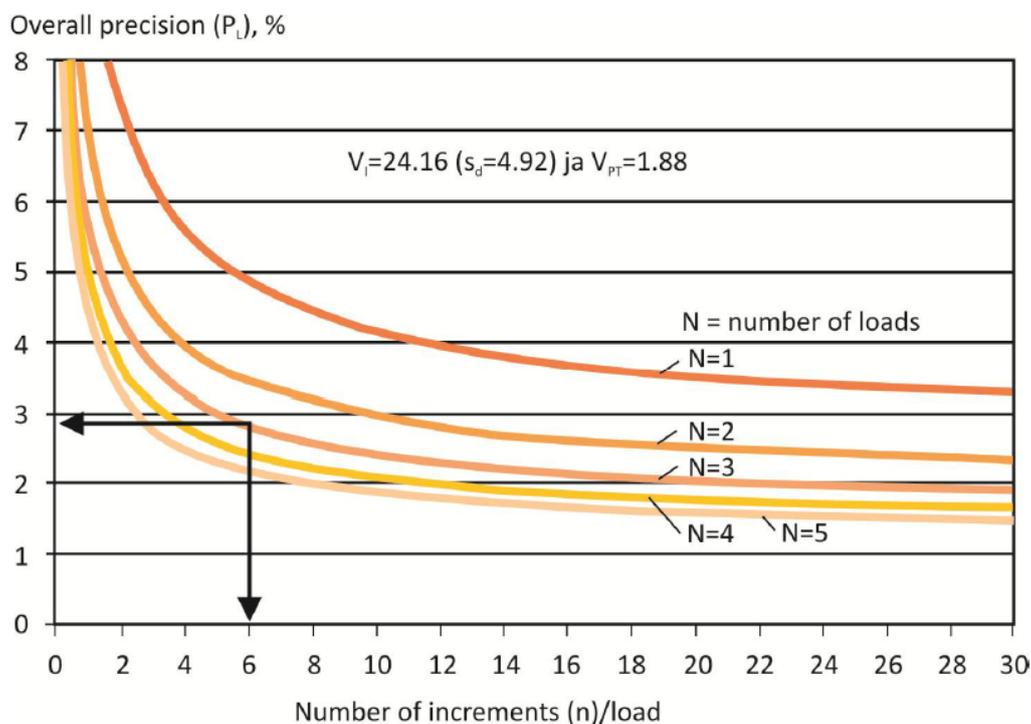


Figure 13 Dependence of overall precision and the number of increments per load for logging residue. (Alakangas et al. 2015b)

4.1.2 Gravimetric method

Gravimetric method is commonly used and accepted widely as the industrial standard. It is time consuming, taking typically at least 24 hours. (Hultnäs et al. 2012) The method is also called oven-drying. The error for oven-drying is below 2 %. The sample is weighed wet, the fuel sample is dried, and is weighed again. Moisture content can be obtained with equation 3. (Huhtinen et al. 1994)

$$MC = \frac{m_w}{m_w + m_d}, \quad (3)$$

where	MC	is moisture content
	m_w	is the weight of water obtained by subtracting dry weight from original sample weight
	m_d	is the dry weight of the sample

As mentioned earlier moisture content can be used when the composition of fuel is known to calculate the heating value with experimental correlations. The net calorific value as received can be obtained with equations 4 and 5. (Alakangas et al. 2015).

$$Q_{\text{net,d}} = Q_{\text{gr,d}} - 212.2w - 0.8 \cdot [w(\text{O})_d + w(\text{N})_d], \quad (4)$$

where	$Q_{\text{net,d}}$	is the net caloric value on dry basis [kJ/kg]
	$Q_{\text{gr,d}}$	is dry basis calorific heating value [kJ/kg]
	$w(\text{O})_d$	is dry basis hydrogen content in fuel [wt-%]
	$w(\text{N})_d$	is dry basis nitrogen content in fuel [wt-%]

$$Q_{\text{net,ar}} = Q_{\text{net,d}} \cdot \left(\frac{100-\text{MC}}{100} \right) - 0,02443 \cdot \text{MC}, \quad (5)$$

where	$Q_{\text{net,ar}}$	is the net calorific value as received [kJ/kg]
	0.02443	is a correction factor for the enthalpy of vaporization for water at 25 °C

4.1.3 Calorimetric method

To obtain heating value, a bomb calorimeter can be used. A small amount, approximately 1 g of an air-dry sample is weighed, and analyzed. It is burned in oxygen atmosphere in a bomb calorimeter placed in water. The heat released is measured. Now the calorific heating value for dry basis can be calculated with equation 6 when moisture content of the air-dry sample has been measured.

$$Q_{gr,d} = Q_{gr,ad} \cdot \frac{100}{100+M_{ad}}, \quad (6)$$

where $Q_{gr,d}$ is dry basis calorific heating value

$Q_{gr,ad}$ is calorific heating value in analysis moisture (air dry)

M_{ad} is the analysis moisture content of the air-dry sample

Further the net calorific heating value for dry basis sample can be obtained with equation 7. This can then be used to calculate the heating value for fuel as received with Eq. 4.

$$Q_{net,d} = Q_{gr,d} - 0,02443 \cdot M \quad (7)$$

where M is water content in percentages created by dry basis
fuel hydrogen reacting

4.2 Nondestructive and on-line testing

Nondestructive testing (NDT) including radiography such as X-ray and ultrasonic have five distinctive features applying to all technologies used:

1. Energy in suitable form and distribution is supplied to the test object from an external source.
2. Energy distribution within the test object is modified as a result of its variation in material properties or discontinuities
3. A sensitive detector detects a change in energy and intensity

4. Energy intensity from measurement is recorded or indicated from the detector in a suitable form for interpretation
5. Indications are interpreted and (the corresponding serviceability of) the test object is judged (Bryant et al. 1985)

There is no general all-purpose NDT that could be applied to every kind of material or structure. Every testing application has to be based on good knowledge of the objects nature and function plus conditions of its service. (Bryant et al. 1985) It is characteristic sampling that the serviceability of that part is destroyed thus only limited number of samples can be collected rather than testing whole components or materials which can be done with NDT. (American Society for Nondestructive testing. 2016)

All methods mentioned later may not be applied to continuous measurement but rather be used to test samples. Combinations of different NDT techniques are used or have been tested for biomass quality measurement. A combination on X-ray fluorescence (XRF) and quantitative DXA (Dual-energy X-ray absorptiometry) has been tested for moisture, ash content, and heating value determination (Torgrip et.al. 2017).

Nondestructive testing offers a possibility for continuous monitoring of biomass and besides moisture content information of fuel properties such as energy content and occurrence of foreign objects can be obtained.

4.2.1 X-ray

Matter is bombarded by a stream of electrons, electrons from inner orbital of an atom are ejected and outer electrons move to fill the open positions near nucleus from high to low energy state. X-rays are emitted. As the X-ray beam hits the specimen three basic phenomena may result: absorption, scatter or fluorescence. (Bryant et al. 1985)

Apart from a source some kind of detection equipment is needed. Detection is a result from electrons (photoelectric and Compton) resulting from the photon absorption event (Bryant et al. 1985). Techniques applied are: film radiography, computed radiography,

computed tomography and digital radiography (DR). DR “digitalizes” the radiation passed through the measured object and the image that is created can be displayed on a monitor in seconds. Three principal detection techniques used are amorphous silicon, charge coupled devices and complementary metal oxide semiconductors. (American Society for Nondestructive Testing. 2016) This thesis focuses on DR that enables real-time continuous monitoring.

Besides X-ray gamma can also be used to test objects. Gamma is generally used for thicker or denser materials (American Society for Nondestructive Testing. 2016). Thus X-ray may be more usable for biomass measurement with the advantage that current from X-ray machine can be switch of and radioactivity lost immediately. Lighter safety measures are allowed than in a case of a permanent radiation source.

4.2.1.1 X-ray absorptiometry analysis

Photon absorptiometry has several advantages: the radiation is penetrating and snow or ice do not disturb the moisture measurement. Photon absorptiometry is sensitive to density of material being tested. (Kullenberg. 2010)

Figure 14 shows a schematic construction of an x-ray machine for absorptiometry analysis. X-ray absorptiometry is the measurement of the number of photons that pass through a sample (Torgrip. 2017). In basic terms the result is dependent on the density found in the sample. Foreign objects for instance are detected by density variation.

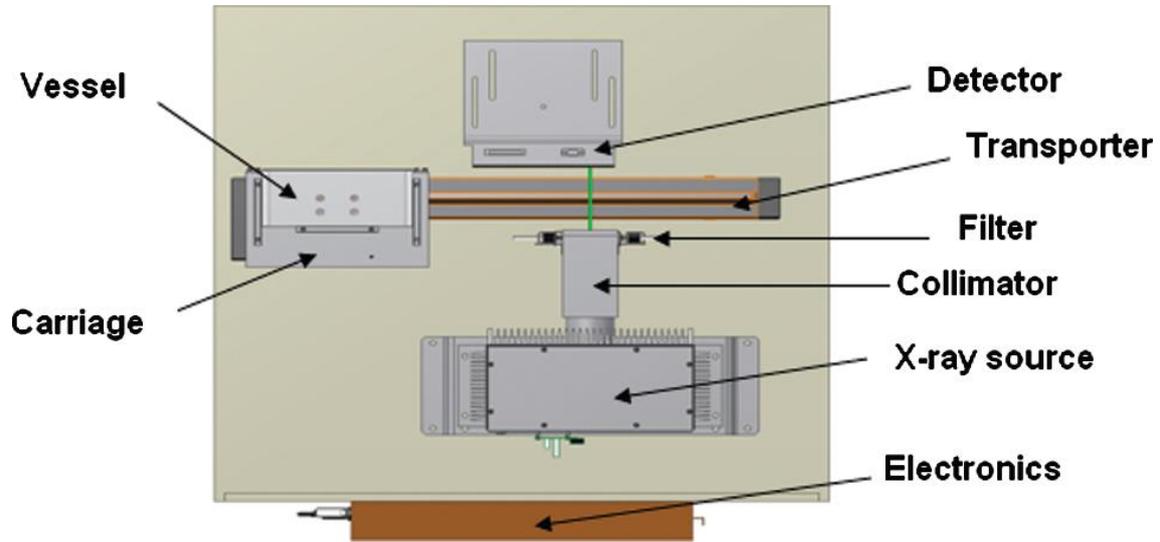


Figure 14. Schematic of an X-ray machine. (Kullenberg et al. 2010)

Equation 8 shows how X-rays interact with matter. The principle is that attenuation occurs so the calculations are based on that phenomenon. Further if the attenuation coefficients for different dry fuels and water are known and knowing moisture adds the attenuation, moisture content can be calculated (Inray. 2016).

$$\frac{I}{I_0} = e^{-(\mu/\rho) \cdot x}, \quad (8)$$

where

I	is attenuated intensity of photons
I_0	is intensity of photons emitted
μ/ρ	is mass attenuation coefficient
x	is mass thickness that is derived by multiplying thickness

DXA has been studied for fuel moisture content measurement (Hultnäs et al. 2011, Tanaka et al. 2012, Kullenberg et al. 2010, Kim CK et al. 2015) Dual-energy X-ray emits photons generated by two different voltages, e.g. 15 and 40 kV so photon energies are different. DXA is based on relationship between the variation in mass attenuation

coefficient with energy of photons and elemental composition. Besides total density also constituent substances can be distinguished by comparing the two X-ray radiographs created by different voltages. (Tanaka et al. 2013)

4.2.1.2 X-ray fluorescence

X-ray fluorescence (XRF) technology can be described as the simultaneous measurement of the abundance and energy of the emitted fluorescent photons from atoms irradiated by X-rays. Emitted photons have energies unique and characteristic for each chemical element so the spectral peaks are element specific. XRF can both quantify and identify different elements in a sample. XRF is insensitive to temperature or state of aggregation. (Torgrip et al. 2017)

XRF has been studied for measuring biomass and ash quality. Salvola studied suitability of a portable XRF analyzer for recovered waste wood (RWW) and fly ash quality control in 2014. According to Salvola's study XRF was more suitable and accurate for detection of heavier elements e.g. lead, but lighter elements could also be detected. XRF requires homogenous samples and since moisture affects the accuracy, samples shall be dried first. The portable device suited well for ash quality control but proper calibration e.g. for plastic is required. Also the heterogeneity of RWW proved to be a difficulty. (Salvola. 2014)

4.2.2 Optical methods

Infrared absorption has been applied widely on moisture measurement. Infrared methods are categorized based on the wave length used and are called NIR (near infrared), MIR (middle infrared) and FIR (far infrared). The most commonly used absorption wave lengths are 700-2500 nm that fit into NIR spectrum. Typical commercial application use a few, 2 to 8 wave lengths, of which one or two measures the moisture and the rest compensate for errors and noise. Modern NIR measurements that use line-detectors can detect hundreds of wave lengths thus the whole spectrum can be measured and more

information about the material obtained. (Järvinen. 2013) The penetrability of IR is weak thus it is used to measure the surface moisture.

NIR penetrates further into biological matter. (Lestander et al. 2008) NIR is suitable for moisture content determination since water shows strong absorption bands with the wavelengths used. Samples do not have to be prepared, in order to use NIR that provides real-time data. NIR requires careful, time-consuming calibration to a reference method so NIR suits measurements where a large number of batches is tested. (Corredor et al. 2011).

Figure 15 presents a schematic of the operation of a NIR setup.

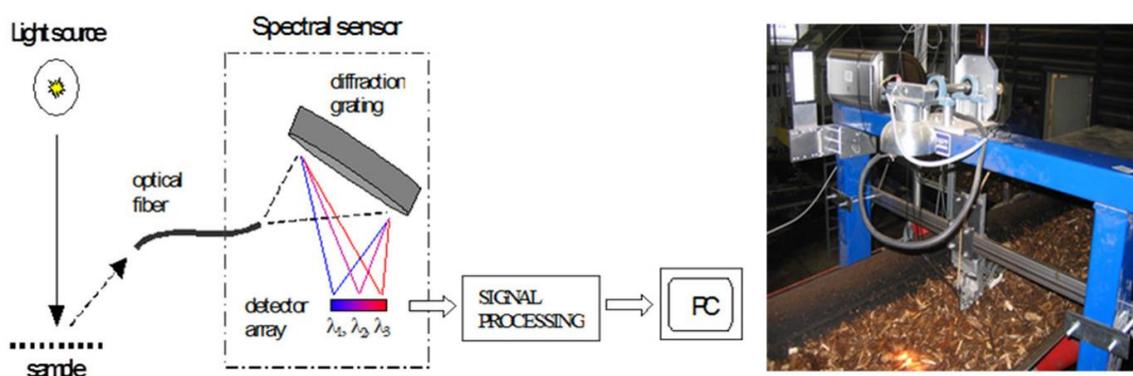


Figure 15. Schematic of NIR and a picture of moisture measurement of forest residue. (Järvinen. 2013)

4.2.3 Microwaves

Microwaves can be used in several ways to determine biomass moisture content. The most typical method is to measure the wave attenuation. The penetration method is non-sensitive for surface moisture but cannot measure material that has snow or ice in it. The penetration method where attenuation is measured gives the average moisture for biomass when both thickness and density of the measured material is known. (Järvinen. 2013)

Microwave resonance can also be used to determine moisture content continuously. The method is independent of material density. Microwave resonance technology is based on an interaction between electromagnetic waves and material particles. Water is detected

by decreasing microwave resonance and the half-width of resonance curve increasing. (Corredor et al. 2011) Microwave can be utilized for on-line moisture measurement. A basic microwave moisture measurement set up is show in **Figure 16**.



Figure 16. Schematic of a microwave moisture measurement equipment for biomass. (Bethold Technologies. 2017)

4.2.4 Magnetic resonance

Magnetic resonance in this case referred to as nuclear magnetic resonance (NMR) is based on the phenomenon that a nucleus has a nuclear magnetic moment and if the nucleus is placed in a magnetic field, the precession movement in relation to the field can be calculated. The method is most sensitive to hydrogen thus materials high in hydrogen can be measured with NMR spectroscopy. NMR is based on the interference between nuclear magnetic moment and an external magnetic field. The sample is exposed to electromagnetic field. The sample will then absorb the energy at a certain frequency that equals nuclear precession movement. Materials conducting electricity are unsuitable for the technology since creating a sufficient RF field inside the object is difficult. (Järvinen. 2013)

Figure 17 is shows a schematic of a MR moisture measurement. The device consists of a magnet with coil, enclose, and a tray to take the sample for measurement. An RF coil that sends and receives pulses is needed to make the measurement, alongside an RF pulse generator and RF receiver. A computer is connected to RF receiver and RF pulse generator to obtain data. (Barale et al. 2002, Järvinen. 2013) For field conditions NMR with an open magnetic field can be used but that weakens sensitivity and resolution. Still the technology is accurate for biomass moisture determination. (Järvinen. 2013) Calibration is valid for several biomass types and mixes with exception of fatty and ferromagnetic materials which cannot be tested. No material specific calibration is needed. (Silmu. 2014) MR can be utilized for on-line moisture measurement. Magnetic resonance imaging has also been studied for woody biomass moisture determination.

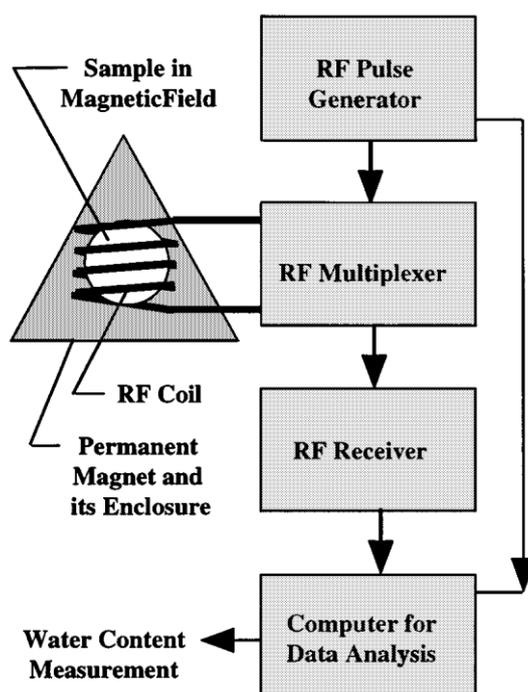


Figure 17. MR moisture measurement device. (Barale et al. 2002)

4.2.5 Neutron applications

Neutrons can be used for radiographic testing in a similar manner as x-ray and gamma. An intense beam of low energy neutrons is directed to an object. Neutrons penetrate most metals but are attenuated by organic materials and water due to high hydrogen content. Thus, organic material can be seen from the object studied. (American Society for Nondestructive Testing. 2016) A schematic of a neutron application for moisture measurement is presented in **Figure 18**.

According to JHV Physics, a Finnish start-up neutron transmission, prompt gamma neutron activation analysis and gamma fast and slow neutron transmission technologies could be used for wood moisture content determination. (JHV Physics. 2017) Neutron technology can be utilized for on-line measurement.

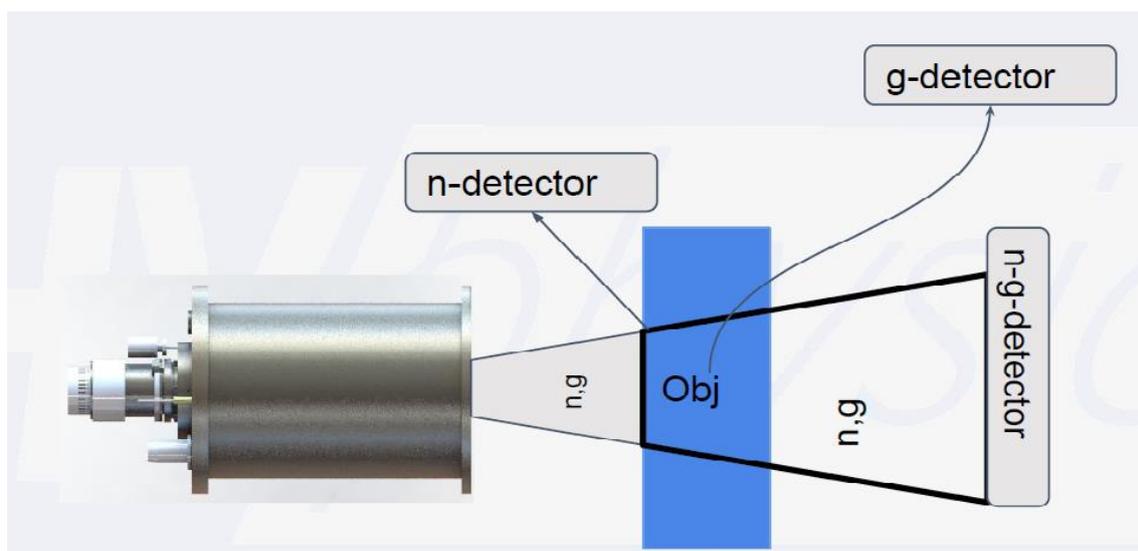


Figure 18. Schematic of a measurement technique based on gamma neutron activation. A combination of techniques is used to provide better data. (JHVPhysics. 2016)

4.2.6 Electrical methods

Capacity has been exploited to determine woody biomass moisture. A sample of a size of a few liters is used as a dielectric of a capacitor. Water has a high permittivity compared to dry wood so moisture content can be measured. Large linear range of the calibration is

an advantage. (BioNormII.) Dielectric testing is a capacity measurement in which dielectric constant is obtained by calculating how much the capacity of condenser rises compared to air if the sample is placed between plates. The dielectric constant for water is 80 whereas it is 2.5-6.7 for dry basis wood. A sensor can be placed on a conveyor or in a silo where it touches with the material measured. Compressible material is pressed to fixed volume. Automatic temperature compensation can be utilized. This method can be used for measurement of up to 50-60 % moisture contents. Frozen material cannot be measured. (Korpilahti et al. 2010) A capacitance moisture measurement is presented in **Figure 19**.



Figure 19 .An example of the capacitance method. The biomass is pressed to standard density thus measured capacitance only changes with moisture. (Korpilahti et al. 2010)

Impedance can be used to determine biomass moisture. The technology is based on electrical impedance spectrometry, and can be used to measure material properties particularly moisture content and water fluxes. The sample is stimulated with alternating current of small amplitude. (Chilcott et al. 2010) Several frequencies up to approximately 1 MHz can be used. The technology is interesting, because it can measure material properties below surface, and with spectral analysis moistures can be measured even during unfreezing. (Korpilahti et al. 2010)

4.3 Errors in moisture content measurement

There are several factors that affect the accuracy of a woody biomass quality measurement. For gravimetric method, the biggest risk of error is with the representativeness of a sample, and for NDT or on-line measurements generally the calibration of the equipment is the bottle neck.

4.3.1 Gravimetric method

The biggest error with gravimetric method derives from the limited sample size and sample quantity or representativeness of sampling. While a typical truck weight in Caledonian for instance is 15 000-30 000 kg the sample that is oven dried weighs approximately 300 g. This means that only a fraction of the load is tested. It is estimated that 80 % or above of accuracy is dependent on representativeness of a sample rather than on handling or moisture measurement. (Järvinen. 2013) During handling proper storage of the fuel is vital, containers or plastic bags in which the samples are placed in, must be properly closed.

Errors may be caused by the place or method of sampling. A falling fuel stream is mixed, and samples should be taken from moving fuel. However often sampling is in practice done from back of a truck from stationary fuel. When dumped wood fuel is segregated. (Alakangas et al. 2016). Segregation of fuel particles also occurs during transportation. Limited representativeness of a sample e.g. limited particle size may induce error.

4.3.2 Nondestructive and on-line testing

There are some circumstances that are problematic to all other technologies except the gravimetric. Density and particle size of woody biomass and moisture vary, and frozen material can be difficult to measure. Even with most developed techniques absolutely accurate results cannot be obtained. Many of the technologies demand more or less constant measurement conditions. (Korpilahti et al. 2010)

An on-line moisture measurement may scan the whole fuel batch e.g. truck load thus good “sample” representativeness. The NDT devices used are typically calibrated to work in certain temperatures and with known bulk densities and fuel types (Silmu. 2014). If conditions are not those that the calibration is based on, error might be induced. One source of error is heterogeneity of the fuel. If there is huge variation in the fuel e.g. unexpected particle size or moisture different from calibrated values, distorted results may occur.

There is a huge difference between frozen and unfrozen material properties. This is a problem when using impedance, capacitance, RF or microwaves for moisture content determination. With impedance, this can be overcome with spectral analysis. (Silmu. 2014) Frozen material is a common error factor for some NDT but has in-practice limitations for gravimetric method too since according to experience fuel with ice is seldom sampled.

5 FUEL RECEIVING AND HANDLING

Fuel handling at a power plant site generally consist of fuel receiving, storage, transportation and pretreatment for combustion. (Huhtinen et al. 1994) Specific conditions at each site are necessary to be evaluated so optimal solutions vary between power plants. For solid biomass, the most important characteristics regarding handling are moisture content and particle size. (Mcgowan et al. 2010) Flexibility is needed since often several wood-based fuels with different characteristics are combusted together. This chapter describes basics of fuel handling design for power plants using woody biomass.

Figure 20 presents fuel handling from receiving to boiler. Number 1 is the receiving station where trucks unload the biomass, 2 is the fuel preparation which may consists of crusher, and stone and metal removal. 3 is storage and 4 presents boiler dozing and feeding. (BMH Technology. 2017)

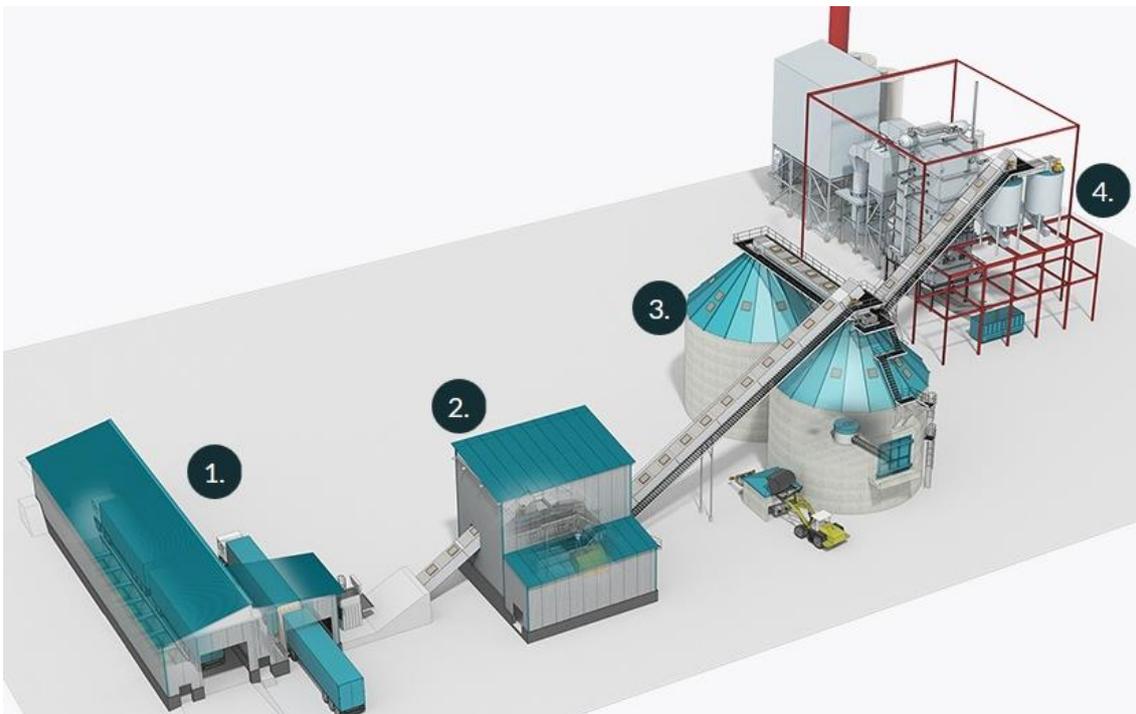


Figure 20. Fuel handling from receiving to boiler (BMH Technology. 2017).

5.1 Receiving station

The most often used mean of transportation to deliver wood fuel is by truck. Biomass can also be delivered by train or ship. (Lindberg et al. 2012) Receiving consist of a receiving station and its operations, and functions rather automatically.

5.1.1 Receiving pocket

Fuel trucks are weighed before and after unloading of biomass in order to measure the amount biomass delivered. Samples are taken as the end-point-users payment often depends on the quality of the fuel delivered. (Lindberg et al. 2012) Usually drivers register their load, the truck is weighed, unloaded to the receiving station and the empty truck is weight.

Trucks empty the already chipped or crushed biomass to the receiving pocket. Unloading can be performed from rear end or side of a truck. If dust is not an issue the receiving hopper can be uncovered with no roof or walls. However, to avoid rain or snow cover is recommended. (Lindberg et al. 2012) The size of the pocket varies and the design may allow several trucks to unload simultaneously. In larger plants, the biomass is not stored in the receiving pocket, but is transported mechanically to storing silo immediately.

5.1.2 Chipping and crushing

If a truck delivering large particle size biomass, such as forest residue or stem wood, is equipped with a crane, it can lift the wood directly to the conveyer leading to the chipper. Metal detectors should be used before the chipper since foreign objects may cause damage. Biomass crushers are less sensitive to metals and stones than chippers but metal detection is encouraged. (Lindberg et al. 2012) There may be more than one crusher e.g. primary and secondary crusher to obtain acceptable particle size.

5.2 Storage

Storage at the plant site is required in order to assure constant operation (Van Loo et al. 2008). A recommended minimum for storage is fuel for 2-3 days of operation. Wood fuel can either be stored covered or uncovered. Storage under roof is preferred for prepared biomass e.g. chipped wood in order to protect the fuel from wet weather. Also, environment can be protected if the fuel is stored in a silo since dust emissions to surrounding areas are decreased. (Lindberg et al. 2012)

Issues like fuel degradation and the possibility of self-ignition have to be considered, if wood chips and bark with moisture content of 20-30 wt% is stored long term in piles. Biomass piles should not be compacted since this can lead to local spikes in moisture leading to increased risk for self-heating. Due to the same reason piles should include homogenous material. (Van Loo et al. 2008) Risk for degradation and especially self-ignition is small at plant site since storage times are short.

5.2.1 Yard

Wood chips, sawmill residue or other pretreated fuel can be unloaded to and stored at the yard, but this is not an encouraged action. Logs are often piled in wait of crushing or chipping and bundles of forest residue or other non-fully pretreated biomass may also be stored at yard.

5.2.2 Storage silo

The biomass fuel enters the storage silo. Two types of storage silos are most commonly used in the Nordics, the circular silos, that are equipped with a cantilevered radial screw reclaimer or something equivalent, and A-framed silos. (Lindberg et al. 2012)

An A-framed silo is used typically if large storage volumes are required. It is equipped with a linear screw reclaimer or similar. Fuel should be supplied from the top and center

of the silo. There is a shuttle conveyer that distributes the wood fuel along the length of the silo. (Lindberg et al. 2012)

5.2.3 Boiler silo

Day silos or boiler silos are the last storage units before the boiler. The purpose is to level out and assure the fuel feed into the boiler. The capacity of the boiler silo(s) corresponds to approximately 1-2 hours of operation. (Hakkila. 2004)

5.3 In-plant transportation

In plant transportation is mainly automated and done by conveyors. Moving logs or piled wood fuel is typically done with tractors or other man driven vehicles. Mixing of different fuels can occur at several stages during in-plant transportation. Dust emission control has to be implemented if need either with separate collectors or by transportation design (Lindberg et al. 2012).

5.3.1 Conveyer transportation from receiving to boiler silo

For transportation from the hopper chain reclaimers can be used. If only chips are handled screw type devices are applicable. (Lindberg et al. 2012) Also a combination of walking floor and screw conveyer is used. (Van Loo et al. 2008)

Notable for in-plant transportation is limited space. Several types of conveyers can be used mainly depending on the plant design, biomass type and capacity needed (Lindberg et al. 2012). Angles for some conveyors are limited. Chain type conveyer can allow angles up to 90° but belt conveyors are not suitable for larger inclines, the maximum being 15°. Belt conveyors are cheap, can be used for long distances and allow weighing equipment to be installed easily. (Van Loo et al. 2008, Lindberg et al. 2012)

The fuel is screened for metals, rocks and other large particle size objects before entering the storage silo. For metals magnets both self and non-self cleaning are used if the fuel is

transported by belt conveyer. (Lindberg et al. 2012) Heavier objects like stones can be removed by trembling the fuel stream. From storage silo the fuel stream is transported to boiler silos with conveyors.

5.4 Fuel during storage and transportation

In order to guarantee constant biomass quality when different types of biomass are combusted mixing is an option. Mixing may occur in several stages during in-plant transportation and storage. The first mixing possibility is the fuel pit, where several trucks may unload simultaneously. It may also be that fuels from different origin e.g. from the fuel pit and from crusher enter the same conveyer. The aim may be to mix the different biomass varieties as evenly as possible or separate the fuel in piles based e.g. on their heating value, A-framed silo allow both approaches. When the biomass is transported by a conveyor to day silos by the boiler additional mixing may occur. For instance, if there is a paper mill some rejects or bark and chips from debarking may be added to the top of the biomass on the conveyer. Some mixing occurs inevitably in the boiler silo.

5.5 Caledonian fuel receiving and handling

At Caledonian Paper ready chipped fuel: mixed biomass, sawmill residue or recycled wood is unloaded to a fuel pocket. There is space for four trucks to unload at the same time but only three outermost from pit exit are used. There is a chain conveyer at the bottom that moves the fuel that exits the pocket from the other side to be transported by a conveyor belt. The receiving station and chip pit conveyor are shown in **Figure 21** and **22**.



Figure 21. Fuel receiving station.



Figure 22. Chip pit chain conveyors and the pit exit.

Crushed stem wood exits the crusher to conveyor belt, prior to biomass from fuel pocket. Conveyor transportation at Caledonian starts from crusher and receiving pocket that takes the fuel via metal detection, rock removal and secondary crusher to A-framed silo. There is storage space for fuel supply for 2-3 days. The fuel is mixed as evenly as possible. A screw takes the fuel to a conveyor belt and the stream goes through second metal detection. Prior boiler silo sludge from paper mill, and bark and chips from debarking is added to the mix that enters boiler silos. Boiler silos fit a supply of approximately of 1 hour 30 minutes. The Caledonian fuel handling is shown in **Figure 23**.

UPM-Kymmene (UK) Ltd, Caledonian Paper CHP1

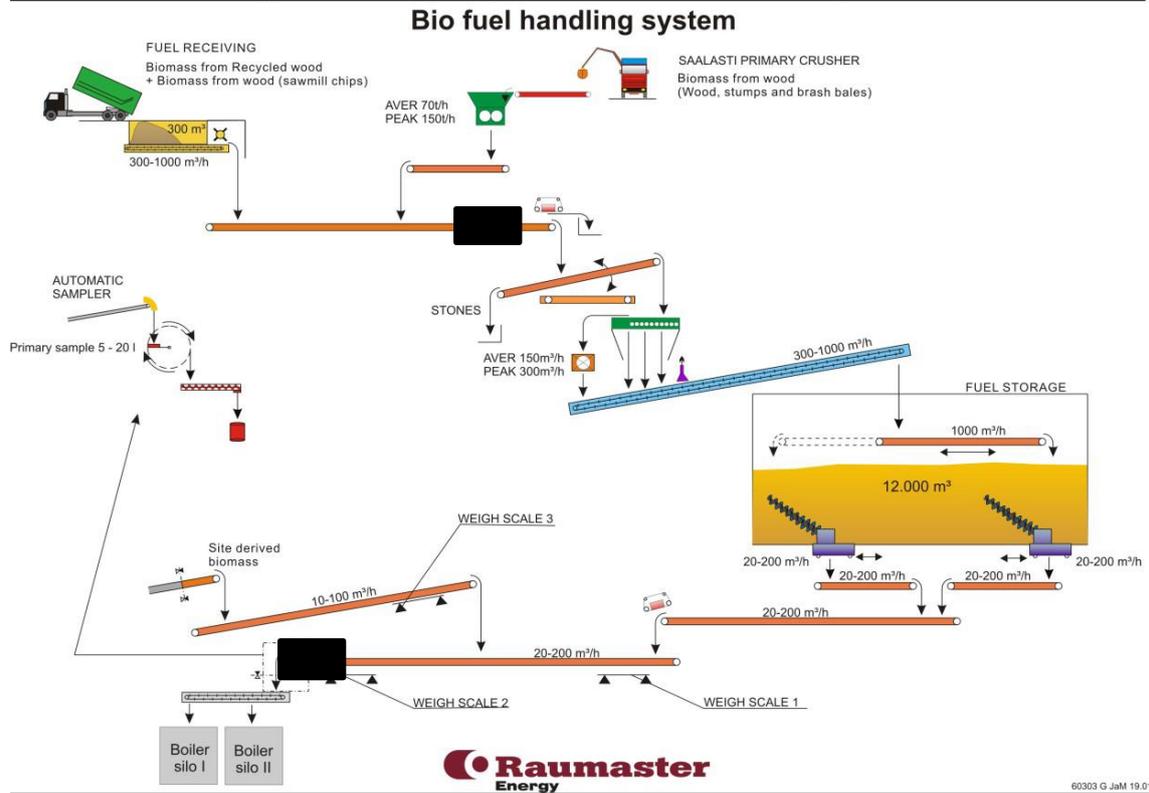


Figure 23. Caledonian fuel handling from receiving to boiler silos. (UPM Caledonian Paper)
The black box in fuel receiving presents the position of the X-ray unit studied. The latter black box is the position of the second X-ray unit.

6 SUITABILITY OF AN ON-LINE MEASUREMENT

There are some obstacles at Caledonian Paper to fully utilize an on-line moisture measurement. The investment cost of an on-line measurement tends to be significant compared to operational costs. If the equipment is used as a mean for price determination every load should be measured. Advantages of a constant on-line measurement include:

- Immediate moisture data
- The whole batch is measured – no sample representativeness issues
- Moisture content of biomass in storage is known
- Possibility to a load energy content calculation
- If agreed obtained moisture or energy content data can be used as base for fuel price
- Automation to a high extent

On-line measurement allows whole batches to be measured instead of one sample per load, which is the current practice run in Caledonian. Also, instant load specific energy content can be evaluated. Risk of intentional or unintentional sampling selectivity from supplier side is diminished. If low-quality fuel high in moisture is received, it is immediately known, and actions can be taken: it can be rejected or stored separately for further use. The current moisture determination with oven-drying gives results first after 22 hours, thus after analyzing, the fuel is mixed in storage or already combusted.

Boundary conditions for an on-line measurement include in practice:

- Measurement of one load at a time
- Fuel bed thickness within boundaries thus limitations on pit conveyer operation
- Limitations on particle size and type variation for each separately measured fuel type (calibration)
- Limitations in fuel density variation other than those based on moisture (calibration)

6.1 Caledonian receiving and fuel handling

There are three major challenges at Caledonian Paper to fully utilize a constant, batch specific on-line moisture measurement. The first is the receiving station, the second is timing of fuel deliveries and the third is the crusher operation. Caledonian fuel receiving and handling were presented in **Figure 2** and **Figure 23**.

6.1.1 Biomass need

Based on figures from 2016 weekly need of chipped biomass is about 4000 t and stem wood about 2000 t. This figure does not include site derived bark, chips and effluent sludge from paper mill. **Table 4** shows biomass and fuel wood deliveries in 2016. May was the outage month and April had 172 hours of downtime so they are excluded from the average.

Table 4. Monthly biomass deliveries in Caledonian 2016.

Month	Recycled wood [t]	Mixed biomass [t]	Sawmill residue [t]	Chipped biomass, all [t]	Fuel wood [t]
Jan	7217	4846	3811	15874	9022
Feb	7583	5011	6023	18617	7682
Mar	8221	6283	7037	21541	12952
Apr	4874	3981	4134	12990	3626
May	3599	2801	3552	9951	2505
Jun	6959	4942	6150	18050	6126
Jul	6930	4856	5458	17243	6947
Aug	6846	6209	4197	17251	8994
Sep	6340	6357	6240	18933	7934
Oct	6907	5723	5854	18484	6711
Nov	7594	5737	5901	19232	9729
Dec	7419	4583	4519	16521	13754
Average	7202	5454	5519	18174	8985

6.1.2 Receiving station

The Caledonian receiving station allows three (four by design) trucks to unload simultaneously. More than one load in the chip pit at a time risk mixing. Fuel at the bottom tends to leave the pocket first, especially if of heavier, wetter type. The design and current use of the receiving pocket makes load specific moisture measurement with x-ray difficult if not impossible.

Figure 22 showed the Caledonian fuel pocket and its two conveyers that move the fuel towards pocket exit and conveyer belt. The speed of conveyors vary generally 20-60% of the maximum, being slower when the crusher is on. **Figure 24** shows the situation where biomass has piled on the pit exit. If the fuel level is above the top of the exit mixing occurs since the fuel at the bottom is pushed through the exit first.



Figure 24. Piling of biomass at chip pit exit.

6.1.3 Timing of biomass deliveries

Biomass is delivered to Caledonian mostly on weekdays between 6:00-19:00. **Figure 25** shows biomass deliveries per day excluding fuelwood in 2016. A median value for daily loads was 35 deliveries per day, maximum daily load count was 51 (SD=10,5).

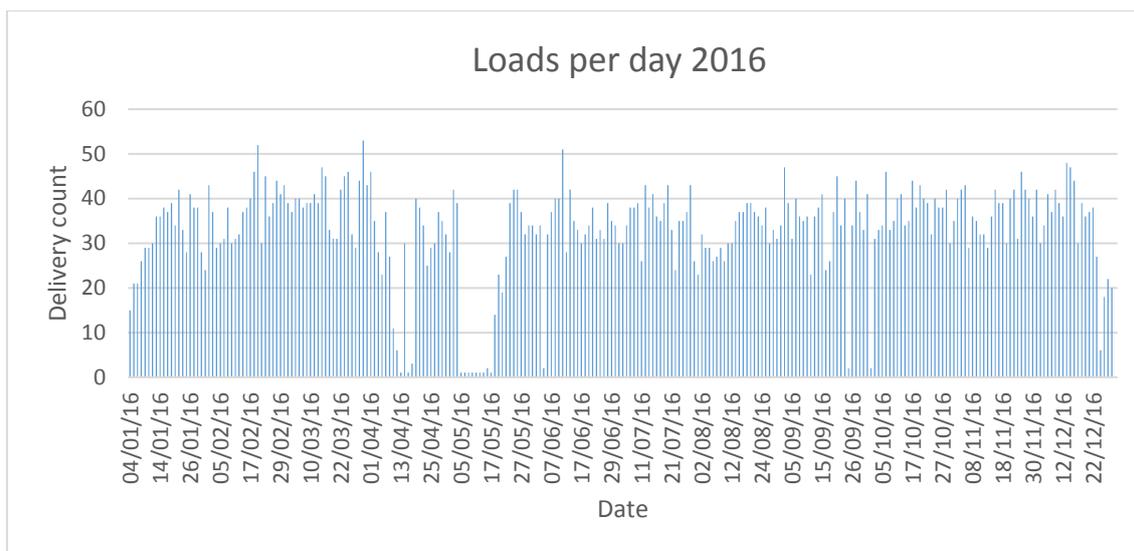


Figure 25. Daily biomass delivery counts in 2016.

Figure 26 shows biomass deliveries excluding fuelwood divided for hours in 2016. There seems to some difference on weekdays: Monday mornings are quiet since less biomass is prepared on weekend and on Friday mornings tend to be busier than afternoons due to the approaching weekend. The count of deliveries in 2017 is expected to decrease somewhat due to drier fuel in comparison to 2016.

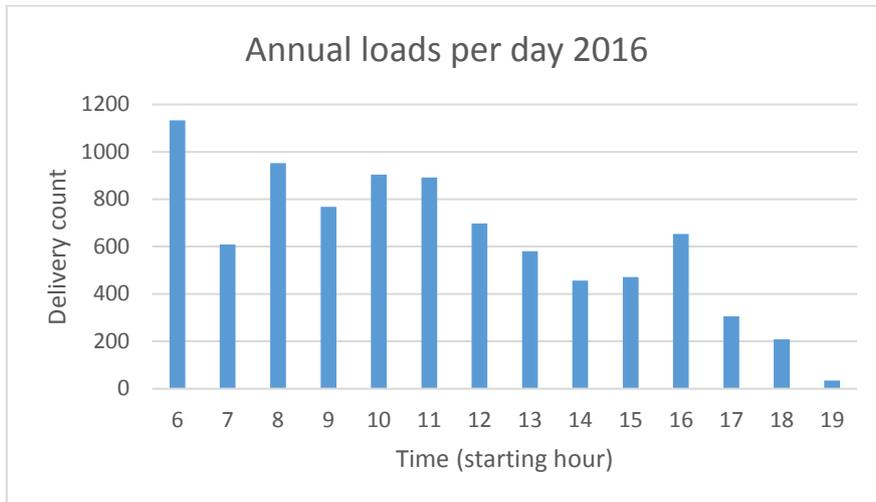


Figure 26. Delivery counts per starting hour in 2016.

At 6 o'clock opening there seems to be a rush hour and afternoons tend to be less busy than mornings but daily variation is significant. Several trucks arriving at same time means mixing is likely to occur in the chip pit. **Figure 27** displays deliveries by every starting hour for a selected day, 15.1.2016, with 39 deliveries.

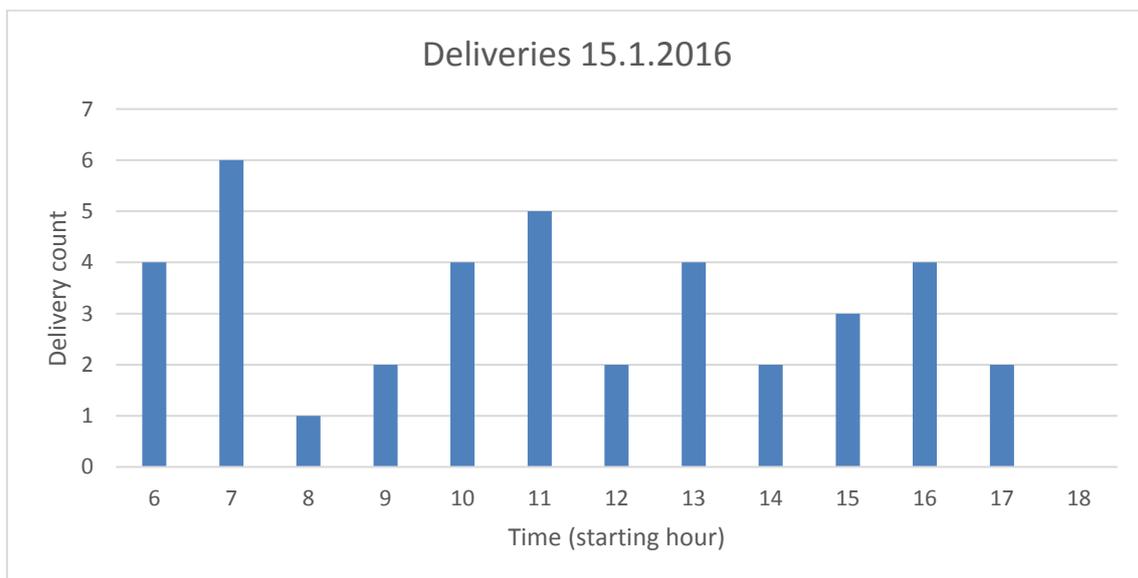


Figure 27. Delivery count per starting hour 15.1.2016.

6.1.4 Crusher

Crushed stem wood from the crusher enters the conveyor prior to the biomass from the receiving pocket. This means that there is crush below the ready chipped biomass when the fuel passes the X-ray measurement thus, it is difficult to obtain reliable moisture results. **Figure 28** shows where crush and biomass from fuel pocket enter the conveyer belt, crush first and then biomass. The moisture of crush varies based on wood origin. In April 2017 alone measured stem wood moistures varied 30-60 % between individual samples.

In order to measure the moisture correctly with current X-ray configuration load specifically, crush should not enter the conveyor when chipped biomass is measured. In principal crusher is run also during days, preferably in hours with few biomass deliveries. Stem wood crush has a constant quality and has a lower moisture content than mixed biomass and sawmill residue in general, and is used to improve and even out the biomass quality.



Figure 28. Biomass from crusher and chip pit entering the conveyor for transportation to storage.

6.2 Fuel receiving optimization

In order to fully utilize the X-ray moisture measurement some changes are needed in fuel handling. This chapter gives a quick glance at these options and discusses how the X-ray could most efficiently be exploited with current design and operation.

6.2.1 Receiving station

In order to measure each separate load, the fuel pit cannot be full because the biomass mixes. Load specification requires one truck unloading at a time with caution to inhibit mixing. That would require some adaptations: automation and scheduling of deliveries.

Figure 29 shows the receiving station. The fuel pit could be separated to unloading sections that are controlled. The control would be based on 1) location or absence of biomass in the pit, 2) instruction signs to unload e.g. with green and red lights or 3) plates that divide the sections and prevent mixing.



Figure 29. Fuel receiving station (chip pit).

Use of only section 1 (furthest from conveyer belt) would allow the next truck to unload with a relatively small risk of mixing if the second unloading is started after the first load has passed section 2. This would require some kind of detector to be installed e.g. laser

or similar. Fuel type identification is necessary. Even with good timing, use of one single unloading spot would be insufficient to fulfill the daily biomass need.

Use of both delivery spots 1 and 3 might be a feasible option to somewhat speed up the fuel receiving. Estimated time saving is 10 minutes, compared to use of one single spot, but there is an advantage only when the pit is empty. Emptying the load to spot 1 would be possible right after the unloading to pit 3 has ended with small risk of mixing. There is a higher risk of piling of biomass by the exit in using spot 3 than with the use of spot 1. Automation for unloading section control and fuel type identification are both necessary.

6.2.2 Timing of deliveries

In order to measure each arriving load, scheduling of deliveries is required. There are commercial, management tools available such as Protacons Once. One option would be that the supplier or individual drivers would schedule the deliveries by booking a time slot for their deliveries.

Timing of deliveries may have advantages for truck drivers. If the scheduling works correctly it would eliminate waiting times. Unloading of a truck takes approximately 10 minutes, and more if the pit is full or there are several trucks dumping simultaneously. Waiting times at the yard can reach up to one hour. Waiting times may become prolonged if all or almost all slots are booked, and one or several trucks use someone else's unloading slot.

Let us assume that the fuel receiving is open 6:00-19:00, there is only one load in the pit at a time, and one dumping takes 10 minutes, and additional 20 minutes for the fuel to exit the fuel pit. This would allow 26 measurements a day which is too few. If different fuels were allowed in the pit simultaneously with caution to inhibit fuels mixing, 10+10-minute slots might work. This would allow 39 measurements per day which in practice is still not enough.

6.2.3 Crusher

A theoretical option would be to separate the crusher from the conveyor and allow the crush to enter the conveyor after the measurement. This would however be costly, and require large alterations. This design would make X-ray moisture measurement of crush impossible without a new unit.

The x-ray system could be developed to not account for or subtract crush under the chipped biomass. In order to do this the thickness of crush bed and its characteristics should be known.

Crusher could be operated outside fuel delivery hours. This requires a change in current fuel handling operation hours. If crushing is performed at different times than biomass deliveries arrive, and no alterations are made to operation of the A-framed silo, a less mixed and less constant quality fuel may result. Implications on boiler operation due to biomass moisture and impurities in recycled wood are possible.

If use of the crusher was altogether abandoned and replaced with supplied wood chips flexibility would be lost. Crusher can be run when best suitable and also outside of biomass delivery hours. Delivered wood chips would increase the pressure on delivery scheduling. The stem wood is stored in yard thus, good availability.

6.2.4 Scenario as usual,

Scenario as usual refers to X-ray monitoring of some loads without alterations to fuel receiving. This includes selective measurement of certain deliveries e.g. from a supplier whose deliveries are expected to need closer inspection of moisture content. There are two main ways this could be arranged:

- 1) **Temporary yard storage prior moisture measurement.** Load meant to be measured is dumped in yard storage, for example in the shed shown in **Figure 30**. Several loads do not fit in shed thus if there are several loads to be measured some

have to be placed at the yard without cover. The loads can then be measured when most suitable.

- 2) **Immediate moisture measurement.** Other fuel deliveries are stopped, and loads selected for measurement dumped to the empty fuel pit separately, and measured immediately upon arrival.



Figure 30. Temporary storage for chipped biomass.

Table 5 is a summary of the two options with evaluation of benefits and disadvantages. Additional requirements which the selective measurement would create are also listed.

Table 5. Benefits, disadvantages and additional requirements if X-ray equipment is used without changes to fuel handling.

Option	Benefits +	Disadvantages or additional requirements -
1) Temporary yard storage prior moisture measurement	<p>Other deliveries are able to operate as usual, no additional waiting required.</p> <p>X-ray measurement can be done when most suitable: as scheduled or when there is no other traffic, and the fuel pit is empty.</p>	<p>Biomass on yard, and especially uncovered, is undesirable due to risk of rain, dust emissions and for safety reasons.</p> <p>During conveyor stops or when there are several e.g. above 5 trucks in the fuel yard, it may be feasible to unload biomass to yard. This induces risk of mixing or space issues.</p> <p>Raised fuel costs. Excess work for operators with guiding the drivers and moving fuel to the pit.</p> <p>Safety aspects with increased traffic in fuel receiving.</p>
2) Immediate moisture measurement	<p>Immediate moisture results.</p> <p>Fuel measured as received.</p>	<p>Scheduling of deliveries or without controlled arrivals to yard congestions are likely.</p> <p>Requires guidance from operators for drivers who can unload and when.</p>

7 TESTING WITH X-RAY

Inray Fuel is an X-ray based on-line measurement of biomass quality that analyses moisture and foreign matter concentrations. The operating temperature range is -10...+45 °C. The limit of lowest fuel bed thickness is 500 mm. (Inray. 2016) **Figure 31** shows the system basics. The measurement is based on radiation absorptiometry: X-ray beam is emitted, penetrates matter and attenuates, and hits the detector. Real-time data includes X-ray image, moisture, foreign matter and volume of measured biomass. The fuel characteristics such as moisture is derived by analyzing the X-ray image.

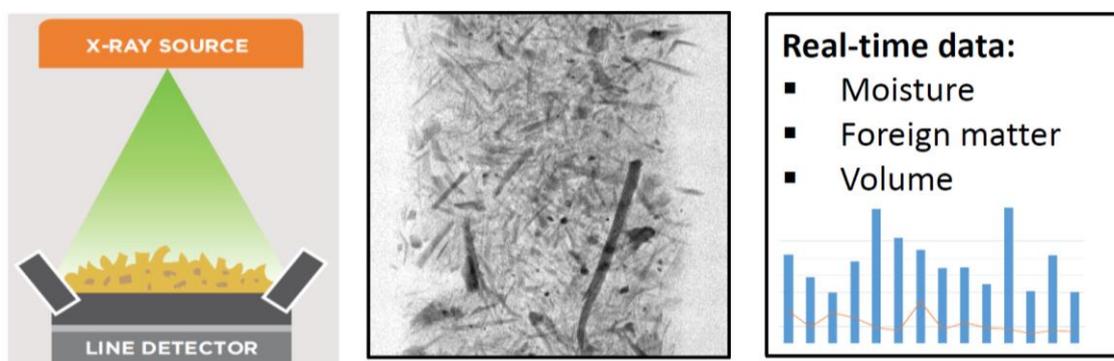


Figure 31. Inray Fuel measurement basics. (Inray 2016).

7.1 System description

The measurement is based on different X-ray radiation absorption of materials. The location of the X-ray unit was shown in **Figure 23** as a black box. It hangs above the conveyor belt. The X-ray unit is shown in **Figure 32**. **Figure 33** presents the detector that is located under the conveyor belt straight under the X-ray unit.



Figure 32. X-ray tube box with laser.



Figure 33. Detector under conveyer belt.

7.2 Testing description

The testing of the X-ray moisture measurement was carried out between 2.-22.6.2017. Suppliers were informed about tests being carried out during the period, but they did not know which specific deliveries would be measured. This should reduce the risk of selection of higher quality loads. The fuel moisture varies seasonally, and during the testing there had been a drier period thus loads selected for measurement may have been drier than deliveries in general. Due to time constraints, the focus was on wet fuels: mixed biomass and sawmill residue but some batches of recycled wood were measured too.

7.2.1 Fuel types

Mixed biomass is a blend of forest residue and other residues and stem wood. One source consists on estimate of 30 % greenwaste, 30 % forest residue, 15 % bark and 15-25 % of whitewood and sawmill residue. The other consists of arboricultural arisings, forest residue and a variety of sawmill residues from several locations. **Figure 34** shows the two types of mixed biomass.



Figure 34. Two different types of mixed biomass. The first picture presents a more composted type while the second tends to richer in chips.

Sawmill residues arrive from different sites and vary in type. Some of the sources include varying amount of bark and/or saw dust. Chip size varies, some have a thickness of above 1 cm and some just a few millimeters. Sawmill residue is high in moisture, generally 50-60 %, but there are also pre-dried chips with a moisture content of 30-35 %. Sawmill Residue types are presented in **Figure 35**.



Figure 35. Different sawmill residues used in Caledonian.

Recycled wood is divided into two categories: A and B. Different sorts are presented in **Figure 36**. There is large variation in particle size in recycled wood B ranging from dust to over 70 mm in diameter.



Figure 36. First two pictures are of Recycled wood grade B with and without dust, and the third presents grade A.

Table 6 sums up fuel types by source. The table also includes a short description of biomass from each source measured.

Table 6. Detailed description of fuel types.

Fuel type	Source	Description
Mixed Biomass	Blantyre	Slightly decomposed matter, forest residue, different wood residues and round wood.
	Avonbridge	Arb arisings, forest residue and variety of sawmill residues.
Sawmill Residue	Dunkeld	Chips of varying kind
	Cardross	Chips, bark and sawdust
	Auchengate	Chips and modest amount of bark
	Troon Mill	Dried chips
	Lockerbie	Ultrathin chips from debarking, and modest amount bark.
Waste Wood	Recycled A	Pallet wood, grade A
	Recycled B	Mostly construction waste, grade B

7.2.2 Measurement and sampling phase

Each tested load was measured with X-ray and sampled. The measurement lasted for approximately 15 minutes, of which 9-12 minutes was used for sampling, and taken into account. So, for comparison 9-12 samples were gathered, one each minute. Initially the aim was to measure each load for 12 minutes and take 12 samples but due to fuel bed thickness issues, it proved impractical. The issue with fuel bed thickness is discussed in more detail in section 8.2. Samples were placed in resealable plastic bags.

The sampling spot was 50 m after the X-ray measurement thus time cap between measurement and sampling is approximately 30 seconds. **Figure 37** shows the sampling spot that allowed sample collection from a falling fuel stream.



Figure 37. Sampling spot with a falling fuel stream.

7.2.3 Sample analyzation

Samples were oven dried. Each sample was placed in a metallic tray. One sample should weigh 300-350g. Samples were then dried for 22 hours in 105 °C. Each metal tray was weighed empty to subtract it from results, and with wet and dry sample in order to calculate the moisture content. Dry density was measured as well.

8 TEST RESULTS

Chapter 8 presents results from testing trial 2.-22.6.2017. Measurement data for each measurement can be found in Appendix 1. One sample corresponds to one minute of measurement. Figures for fuel wood (stem wood crush) measurement in comparison to samples from April 2017 are presented in Appendix 2.

8.1 Moisture comparisons based on biomass type

This section describes results in detail. The fuels are divided into three categories: mixed biomass, sawmill residue and recycled wood.

8.1.1 Mixed biomass

There are currently two types of mixed biomass delivered to Caledonian. **Figure 38** presents the results as moisture average comparison. Average sampling moisture is shown on X-axis and average of the X-ray moisture measurement on Y-axis.

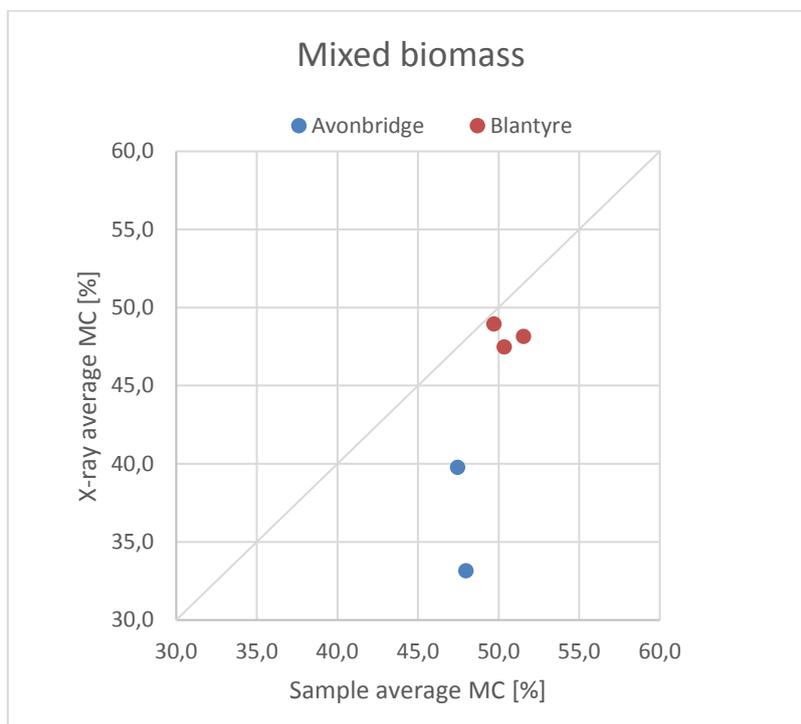


Figure 38. Average moisture comparison between sampling and X-ray measurement for mixed biomass.

The moisture averages for Blantyre are rather close to each other, X-ray giving slightly lower moisture contents. The maximum error is still below 3 percentage points. Moisture averages between measurement and samples vary significantly for Avonbridge, difference being from 8 to 14 percentage points. Each X-ray measurement gave a lower average moisture than samples.

Figure 4039 (Avonbridge) and **Figure 40** (Blantyre) present one measurement of each source. X-axis presents the number of a sample that corresponds the measurement point. Y-axis presents the moisture content in percentages.

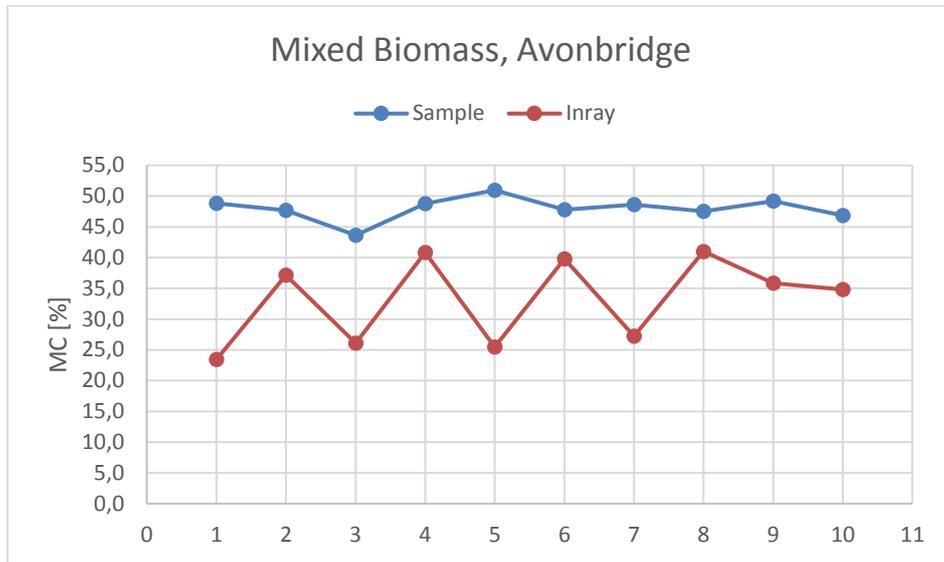


Figure 39. Moisture comparison between measurement and sample taken on corresponding time for Mixed Biomass from source Avonbridge.

The results for Avonbridge between measurement points have clear differences, x-ray measuring categorically too low. The difference in moistures between the two varies from 7 to 25 percentage points.

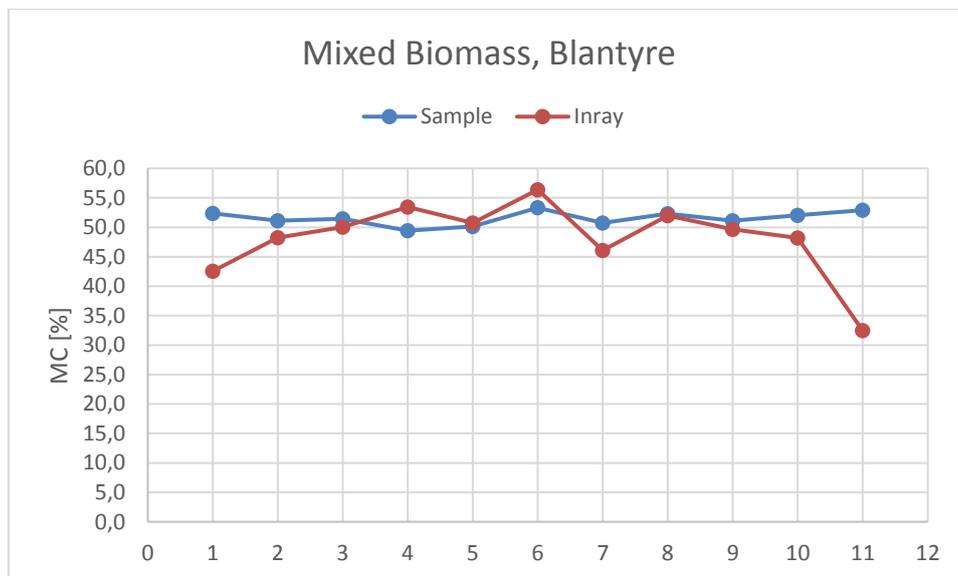


Figure 40. Moisture comparison between measurement and sample taken on corresponding time for Mixed Biomass from source Blantyre.

For Blantyre the results are very similar in measurement points 2-10, max error being 5 percentage points and on min. error less than 1 percentage point. The moistures however recede between measurement point 10 and 11. It is likely that the load is ending, the fuel bed on conveyor becomes thin, and distorts the measurement. X-ray moisture then appears lower than actual moisture. This phenomenon will be discussed further in section 8.2.

8.1.2 Sawmill Residue

There is currently six sources from which Caledonian CHP plant receives sawmill residues. Five of those were tested during the testing trial. The missing type is by visual inspection very similar to the fuel from source Lockerbie thus, the results can be extended. The load specific moisture average comparison between samples and X-ray measurement moistures is presented in **Figure 41**.

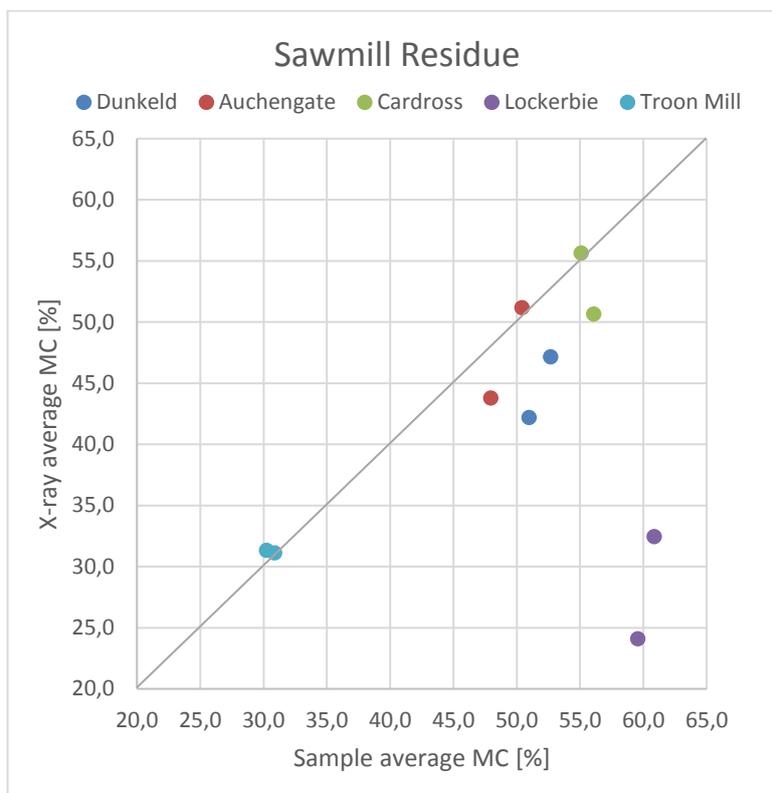


Figure 41. Average moisture comparison between sampling and X-ray measurement for Sawmill Residue.

Three out of five sawmill residue types were measured with a rather good average moisture accuracy with X-ray. The difference in average load moisture ranges from 0 to 5 percentage points. X-ray tends to give rather lower than higher average moistures.

Two sources, Lockerbie and Dunkeld, had unreliable moisture results from X-ray measurement. Lockerbie is measured as significantly drier by X-ray than by sampling average. While X-ray gives load moisture averages of 32 % and 24 %, the corresponding actual sample moisture averages are 61 % and 60 %. The deliveries measured from Dunkeld included two types of wood chips: thin chips from debarking and thicker chips. These were not mixed with each other but were in different parts of a load. The load moisture averages measured with X-ray were 47 % and 42 % while the corresponding sampling averages are 53 % and 51 %.

Figure 42 presents a load measurement of Dunkeld. In measurement points 1-3 and 9-12 biomass had a low density (thin chips), and in measurement points in between there was chips with higher density. The dry densities from samples were <80 , and >120 kg/m^3 . In comparison to individual samples the measurement error is up to 30 percentage points at the start and end of load but the in the middle comparable results only differ 1-6 percentage points.

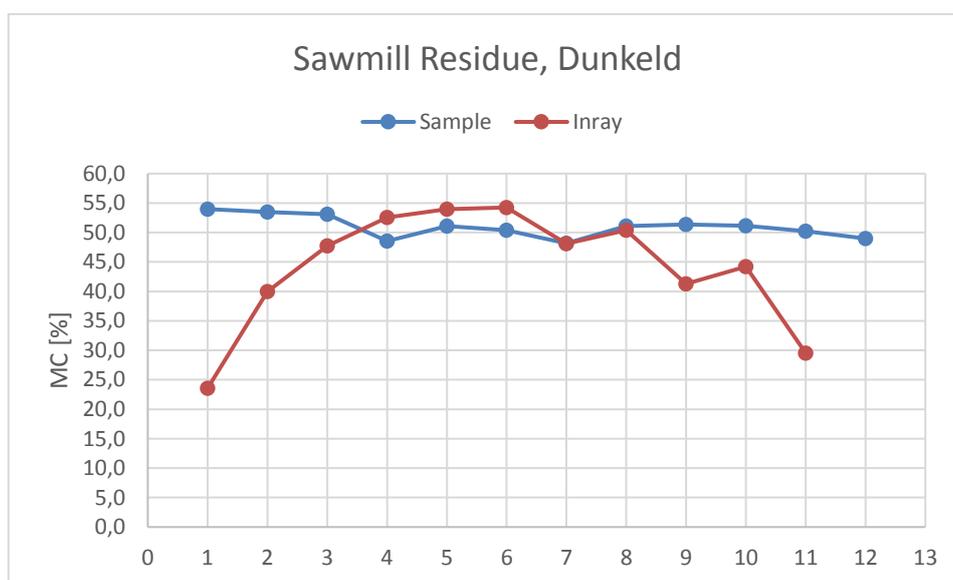


Figure 42. Moisture comparison between measurement and sample taken on corresponding time for Sawmill Residue from source Dunkeld.

Figure 43 compares a Lockerbie load X-ray measured moistures to individual samples. The X-ray is constantly lower, the difference to actual sample moistures varying from 26 to 44 percentage points. Lockerbie has a low dry density of < 80 kg/m^3 . Another issue effecting and lowering the results may be thin fuel bed. The results also include X-ray moistures of 17 %, current X-ray minimum limit, and that by empirical experience has occurred with either very low moisture biomass or with extremely thin fuel bed thickness.

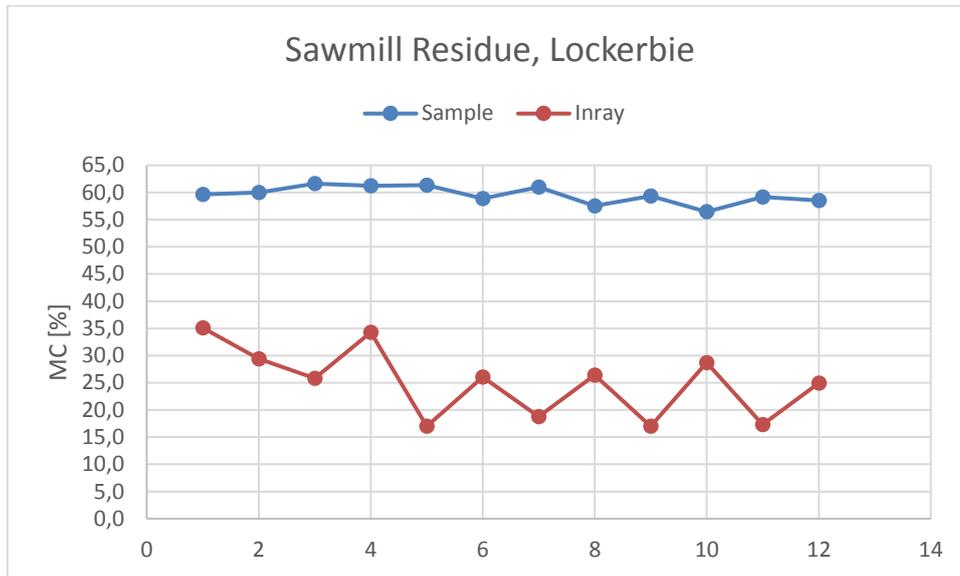


Figure 43. Moisture comparison between measurement and sample taken on corresponding time for Sawmill Residue from source Lockerbie.

Figure 44 presents one load of sawmill residue referred to as Troon Mill. There is barely any difference in moisture averages but some differentiation can be seen between individual measurement points, X-ray moisture differing 7 percentage points at most and 0 at lowest.

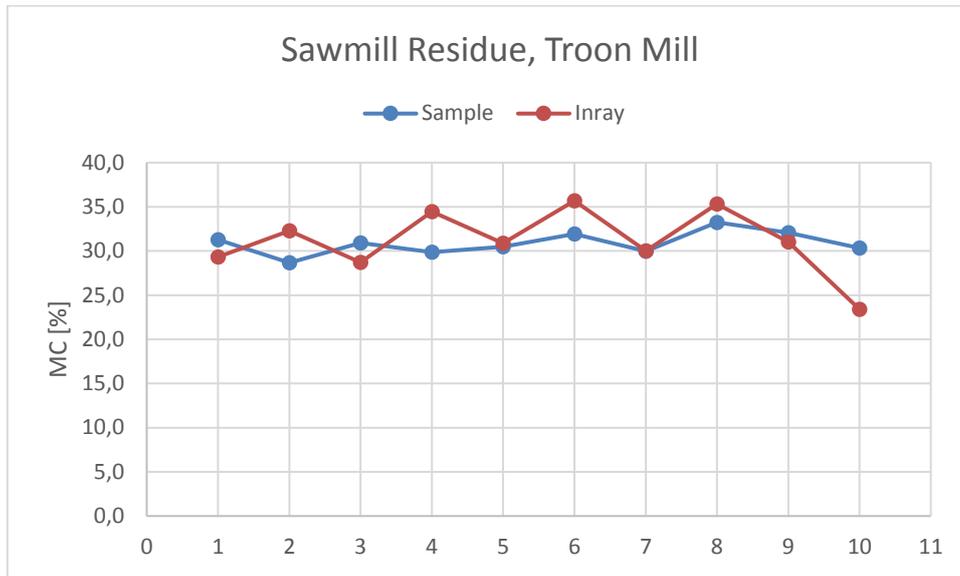


Figure 44. Moisture comparison between measurement and sample taken on corresponding time for Sawmill Residue from source Troon Mill.

Moisture comparison for one Auchengate load is shown in **Figure 45**. There is very little difference between the two measurements. Out of 10 measurement points there were two that have difference of 5-6 percentage points, and the error is otherwise less than 4 percentage points. Altogether three measurements of Auchengate were conducted during the trial. One had X-ray moistures continuously lower than actual moistures were. See Appendix 1

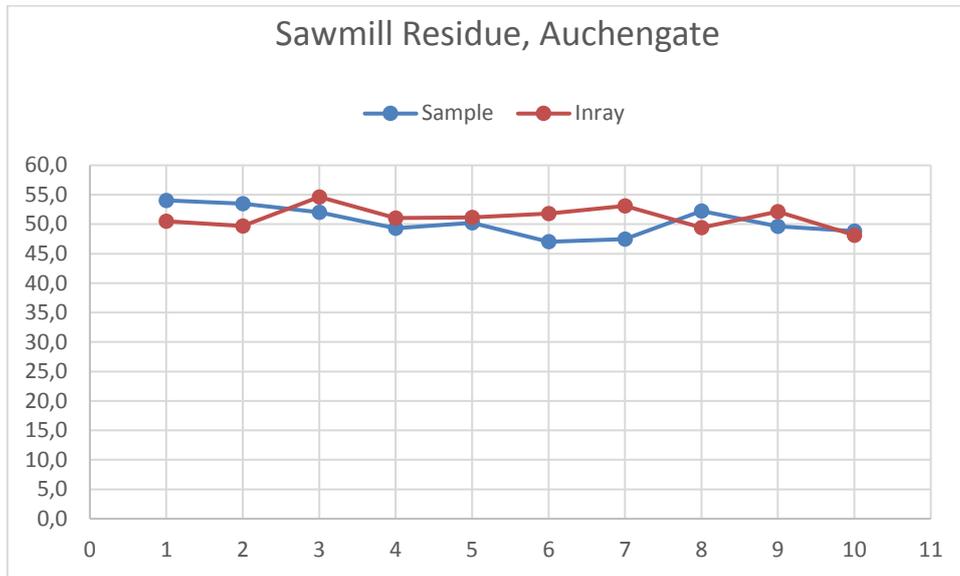


Figure 45. Moisture comparison between measurement and sample taken on corresponding time for sawmill residue from source Auchengate.

Cardross is the only sawmill residue source including significant amounts of bark. A measurement of a Cardross load is presented in **Figure 46**. The fuel bed thickness is comparatively low when X-ray moistures drop to 38 % increasing the difference to sample moisture to 16 percentage points. The other measurement of the same fuel type had barely any difference between the moisture results obtained by sampling and X-ray.

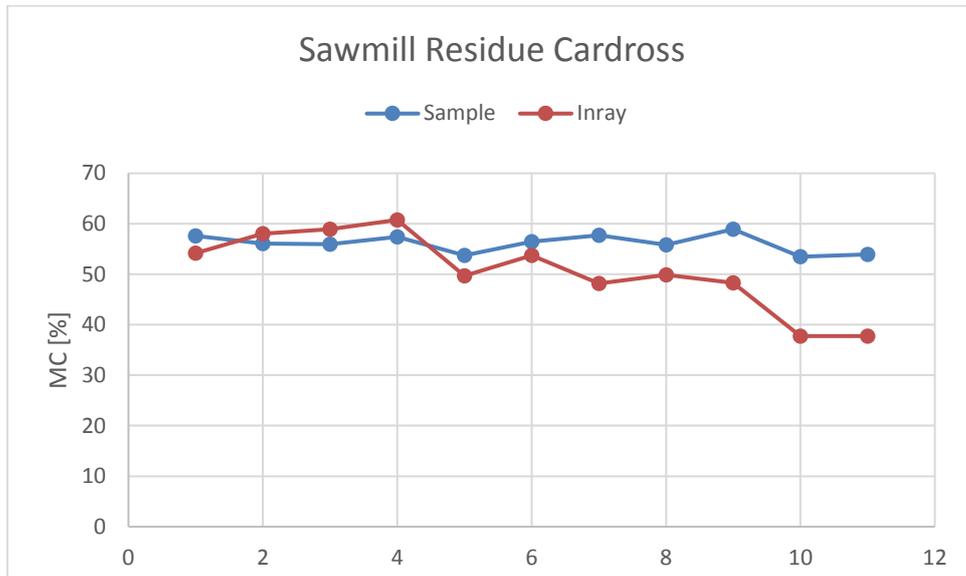


Figure 46. Moisture comparison between measurement and sample taken on corresponding time for Sawmill Residue from source Cardross.

8.1.3 Recycled Wood

Recycled wood is the driest of biomasses measured. Moisture average comparison is presented in **Figure 47**. Three out of four studied loads had a load moisture average difference between measurement and sampling of < 1 percentage point. One fuel which was very dry with a moisture content of 16 %, was measured with X-ray to have a moisture average of 23 %.

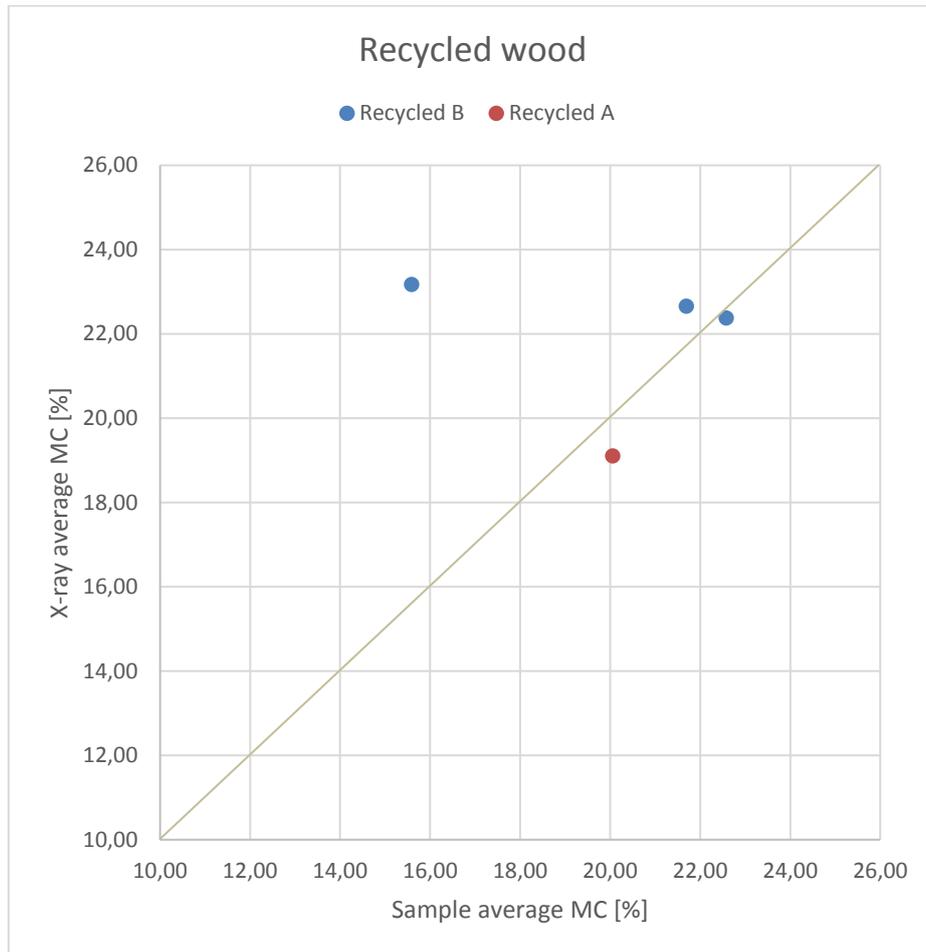


Figure 47. Average moisture comparison between sampling and X-ray measurement for Recycled Wood.

Two recycled wood B loads measurements with 12 measurement points each are presented in **Figure 48** and **Figure 49**. The former from a source called Mt Vernon has a max difference between corresponding measurement points of 5 percentage points. The error is in both direction thus moisture averages are similar. The very dry waste wood from source Mossley proved difficult to measure with X-ray. The percentage point difference ranged between 2 and 14, X-ray giving constantly higher moistures.

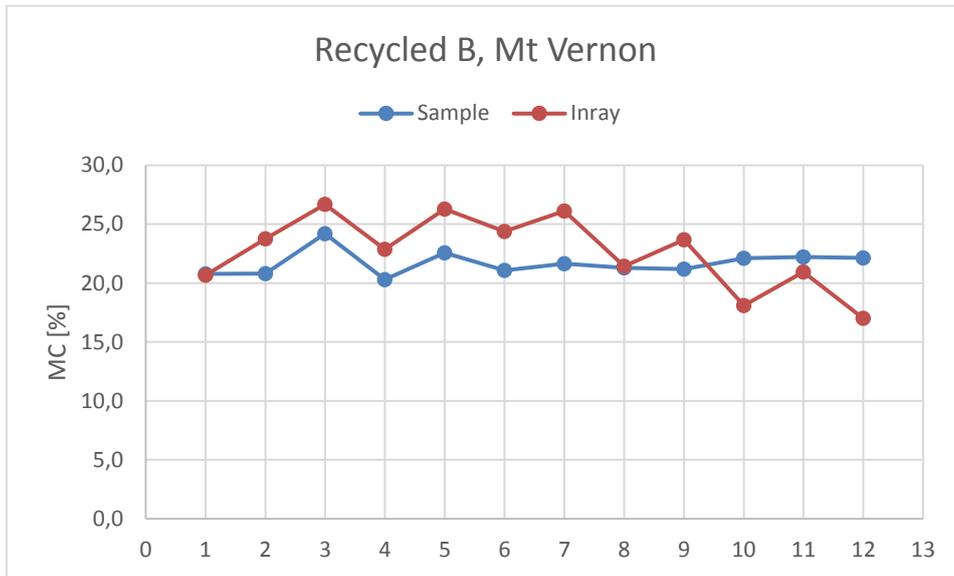


Figure 48. Moisture comparison between measurement and sample taken on corresponding time for Recycled Wood B from source Mt Vernon.

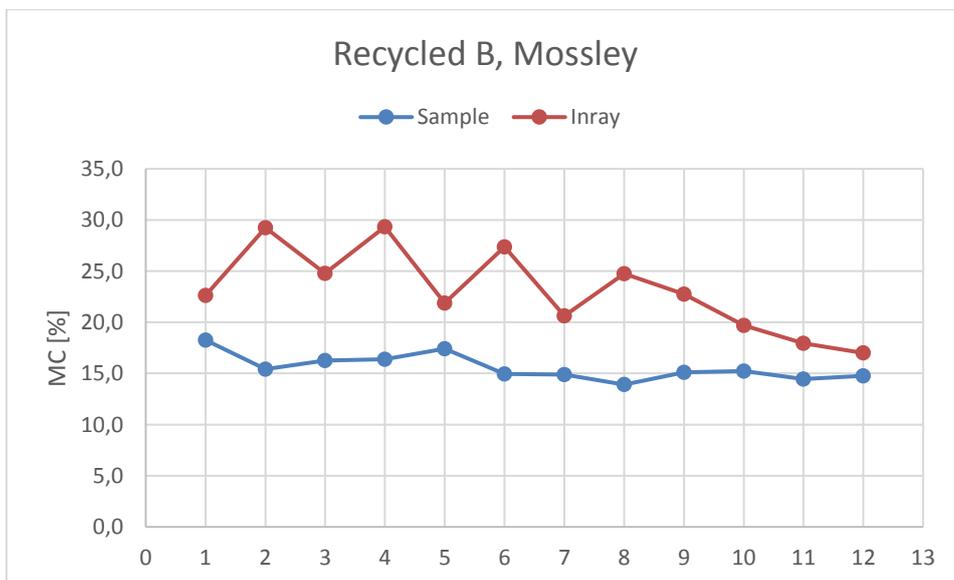


Figure 49. Moisture comparison between measurement and sample taken on corresponding time for Recycled Wood B from source Mossley.

8.2 Relationship between biomass thickness on conveyor and X-ray measured moisture

During testing phase in June 2017, it came visible that fuel bed thickness on conveyor had an effect on the X-ray moisture results. Flat layer or short gaps absent of biomass tend to constantly cause moistures that are too low compared to the actual moistures. On contrary piles of biomass on conveyor tend to cause higher moistures in X-ray measurement data. This is presented for wet fuels in **Figure 50** and **51**. The corresponding correlation for dry fuels is shown in **Figure 52** and **53**. Biomass central height is an average from a certain width from a time of ~30 seconds. Data of fuel bed thickness for each measurement conducted during trial 2.-22.6., and can be found in Appendix 1.

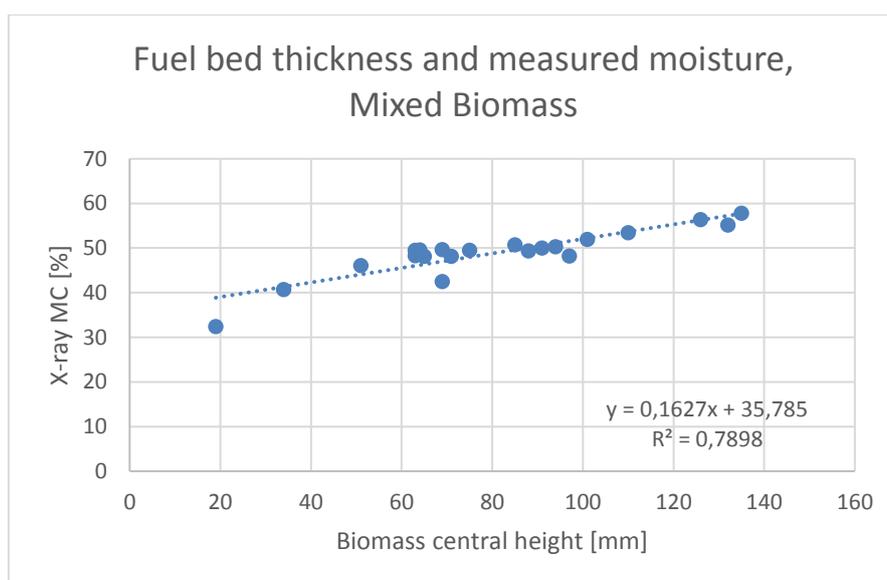


Figure 50. Moisture content plotted as a function of average fuel thickness on conveyor for Mixed Biomass.

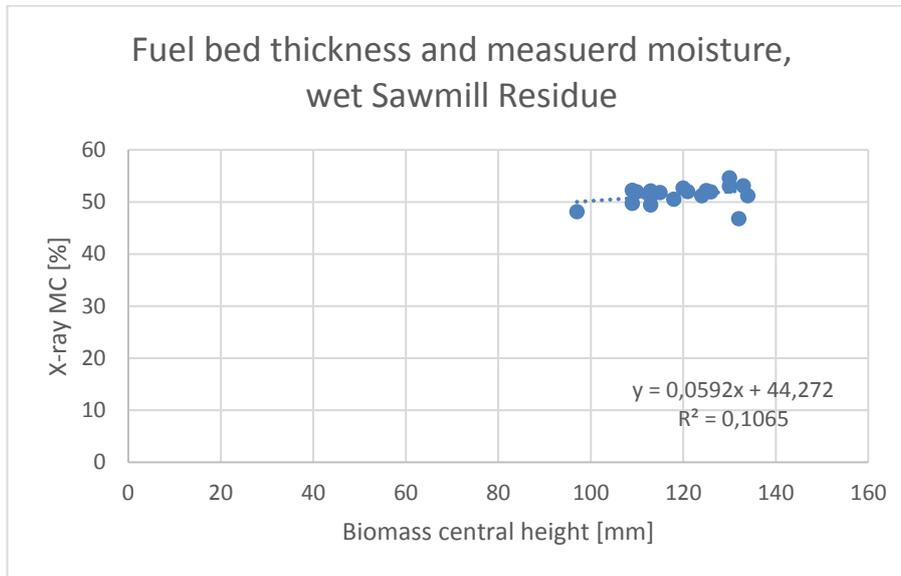


Figure 51. Moisture content plotted as a function of average fuel thickness on conveyor for wet Sawmill Residue.

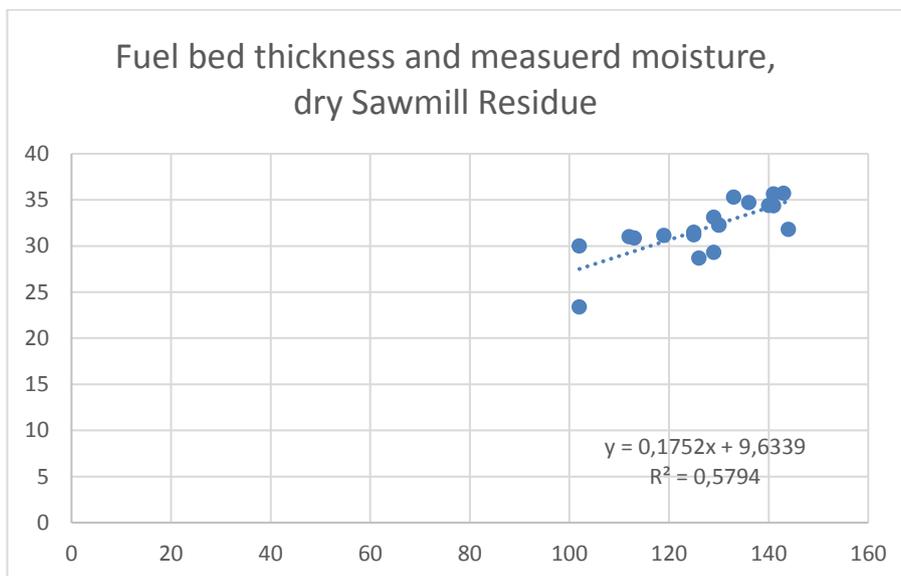


Figure 52. Moisture content plotted as a function of average fuel thickness on conveyor for dry Sawmill Residue.

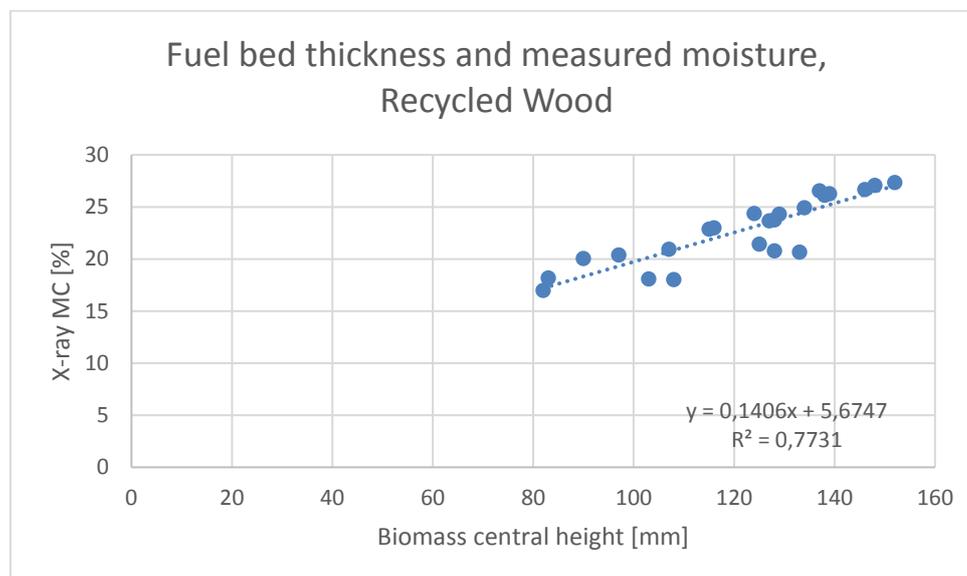


Figure 53 Moisture content plotted as a function of average fuel thickness on conveyor for Recycled Wood B.

Figures suggest there is some kind of dependence between X-ray moisture and fuel bed thickness on conveyor. R^2 values suggest the regression lines approximate the real data points quite well with a few exceptions. For most measurements R^2 is 0.6-0.9 thus the correlation is rather clear. The fitted model suggests that changes in fuel layer height can predict most of the changes in measured moisture. It seems in general that the higher the fuel top the higher the moisture measured with X-ray. The R^2 analysis does not show causality so it could be that wet fuel piles up on conveyor and moistures should be higher. The variation in load specific sample moistures is rather small so this suggest that the linear regression is actually caused by fuel bed thickness variation. The R^2 values for each load measurement are presented in **Table 7**.

Table 7. R² values for loads based on fuel layer thickness on conveyor and X-ray measured moisture.

Fuel type	Source	R ² (load 1)	R ² (load 2)	R ² (load 3)
Mixed	Avonbridge	0.579	0.869	
Biomass	Blantyre	0.596	0.935	
Sawmill	Auchengate	0.874	0.919	0.107
Residue	Cardross	0.845	0.680	
	Dunkeld	0.650	0.003	
	Lockerbie	0.676	0.848	
	Troon Mill	0.921	0.579	
Recycled B	Mossley	0.842		
	Mt vernon	0.773	0.641	
Recycled A	E&K pallets	0.498		

8.3 Generally about results

There are few considerations that can be made based on measurement trial:

- Load measurement moisture averages whether X-ray measured or based on samples, are generally quite close to each other. This is presented in **Table 8**. There were fuel types that are continuously measured incorrectly with X-ray with errors from 8 to 35 percentage points.

Table 8. Testing trial load moisture averages compared.

	Sample average MC [%]	X-ray average MC [%]	Differen percentace points	Difference %
Avonbridge 1	48.0	33.2	-14.8	-30.9
Avonbridge 2	47.4	39.8	-7.7	-16.1
Blantyre 1	50.4	47.5	-2.9	-5.7
Blantyre 2	49.7	48.9	-0.8	-1.5
Blantyre 3	51.5	48.2	-3.4	-6.6
Auchengate 1	51.3	43.8	-7.6	-14.7
Auchengate 2	50.4	51.2	0.8	1.5
Auchengate 3	48.0	43.8	-4.2	-8.7
Cardross 1	56.1	50.6	-5.4	-9.7
Cardross 2	55.1	55.6	0.5	1.0
Dunkeld 1	52.7	47.2	-5.5	-10.5
Dunkeld 2	51.0	42.2	-8.8	-17.2
Lockerbie 1	60.8	32.4	-28.4	-46.7
Lockerbie 2	59.6	24.1	-35.5	-59.5
Troon Mill 1	30.3	31.3	1.1	3.6
Troon Mill 2	30.9	31.1	0.2	0.8

- Fuel bed thickness on conveyor seems to distort X-ray moisture results by distorting individual data points. The higher the fuel top on conveyor, the higher the measured moisture. X-ray measured load averages are closer to load sampling averages than individual samples. The distortion is in both directions.
 - o A thin biomass layer on the conveyor is particularly clear at the end and start of a load
 - o Some wetter fuels especially mixed biomass and some sawmill residues tend to form piles on conveyor.
- Biomass with low dry densities, those by estimation below 90 kg/m³, tend to be measured as too low in moisture by the X-ray measurement.
- In current state, the X-ray has a set limit of 17 % as the lowest moisture that can be measured. This is too high for some loads of recycled wood that in a dry season can have a moisture content of 15 %. The current limit is due to earlier calibration in Finland, where only biomass with moistures from 20 % up has been tested.

- A summary of results by biomass category is shown in **Table 9**. Wetter fuels: Mixed Biomass or Sawmill Residues have X-ray measured moisture averages that are either acceptable or too low. Dry recycled wood is measured with X-ray to have an acceptable error or as too high in moisture.

Table 9. Summary of moisture results from testing trial 2.-22.6.2017 arranged by fuel type.

Fuel type	Testing trial results (X-ray compared to sample)
Mixed Biomass	OK or too low
Sawmill Residue	OK or too low
Recycled wood	OK or too high

9 EVALUATION OF CURRENT SAMPLING PROCEDURE

This chapter evaluates the current moisture determination practices in Caledonian. The accuracy of drivers' or operators' samples taken from the back of a truck is evaluated in three ways: comparing sample moistures to additional samples taken from the same truck, going through fuel data from years 2014- 2016 and comparing it to energy balance based results, and with comparison to Daily Mixed Biomass samples moistures. Daily Mixed Biomass samples refer to samples taken from the fuel mix entering boiler silos.

9.1 Empirical evidence

This section compares drivers' or operators' sample moisture to the load sampling moisture averages from the same truck. All results are from testing trial 2.-22.6.2017. The truck driver or operator takes the sample from the back of the truck. The sample is put to a resealable plastic bag that is during weekdays prepared for analyzation on the preceding day. During testing trial the share of samples taken by operators, compared to samples taken by drivers on average, may have been over presented. Comparison between additional trial sampling average and corresponding drivers' or operators' sample moisture is shown in **Figure 54**. RMPMS MC in the figure refers to the drivers' or operators' sample.

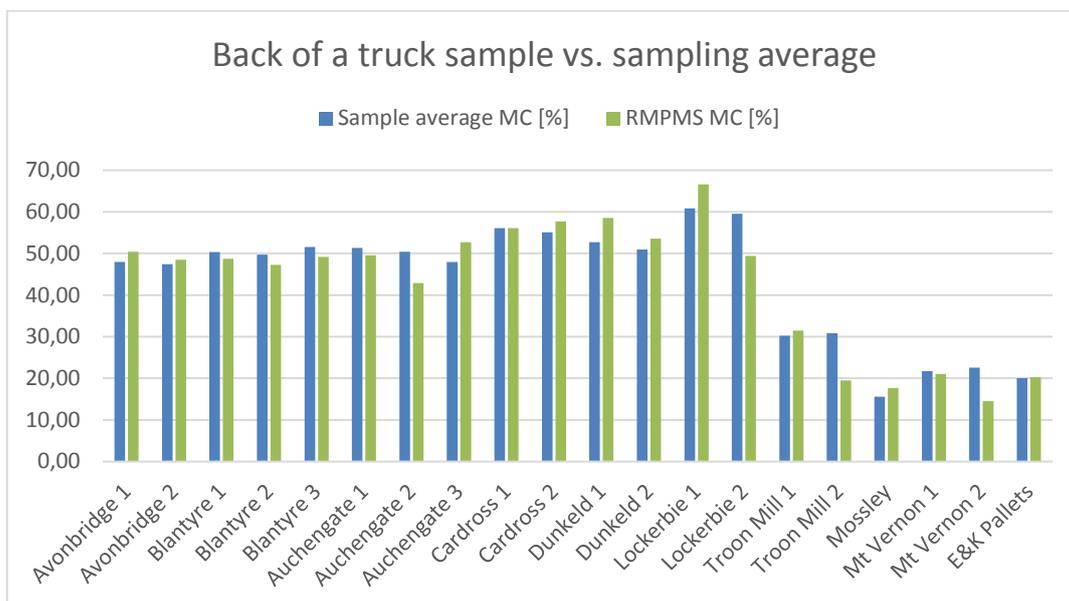


Figure 54. Moisture averages from trial sampling compared to general sample moistures.

The results suggest that the sampling moisture averages are close to those obtained from drivers' or operators' samples. Excluding moisture results "Lockerbie 2", "Troon Mill 2", "Auchengate 3" and "Mt Vernon 2" the average error is 1.24 percentage points, and with the results likely defect for handling reasons, 0.86 percentage points. The errors are in both directions. The results are presented as numeric values in Table 10.

Table 10. Sample moisture comparison between trial samples and drivers' or operators' sample.

	Sampling average MC [%]	Drivers' or operators' sample MC [%]	Difference, percentage points	Difference [%]
Avonbridge 1	47.97	50.43	2.46	5.12
Avonbridge 2	47.45	48.53	1.08	2.28
Blantyre 1	50.35	48.73	-1.62	-3.22
Blantyre 2	49.70	47.28	-2.42	-4.88
Blantyre 3	51.54	49.18	-2.36	-4.57
Auchengate 1	51.34	49.54	-1.80	-3.51
Auchengate 2	50.42	42.90	-7.52	-14.92
Auchengate 3	47.95	52.73	4.78	9.97
Cardross 1	56.09	56.12	0.03	0.05
Cardross 2	55.09	57.71	2.62	4.76
Dunkeld 1	52.69	58.58	5.89	11.19
Dunkeld 2	50.97	53.57	2.60	5.11
Lockerbie 1	60.85	66.60	5.75	9.46
Lockerbie 2	59.56	49.40	-10.16	-17.06
Troon Mill 1	30.25	31.47	1.22	4.02
Troon Mill 2	30.87	19.52	-11.35	-36.78
Mossley	15.59	17.69	2.10	13.48
Mt Vernon 1	21.69	21.06	-0.63	-2.92
Mt Vernon 2	22.58	14.52	-8.06	-35.69
E&K Pallets	20.06	20.28	0.22	1.09

9.2 Energy balance

To get an estimate of the actual energy in the fuel combusted, boiler balance can be calculated. Boiler energy balance can be calculated based on flows on system boundaries. A schematic of these flows is presented in **Figure 55**. A more detailed view of the calculations and assumption can be found in Appendix 3. Energy balance calculations are based on X Steam tables (Holmgren, M.).

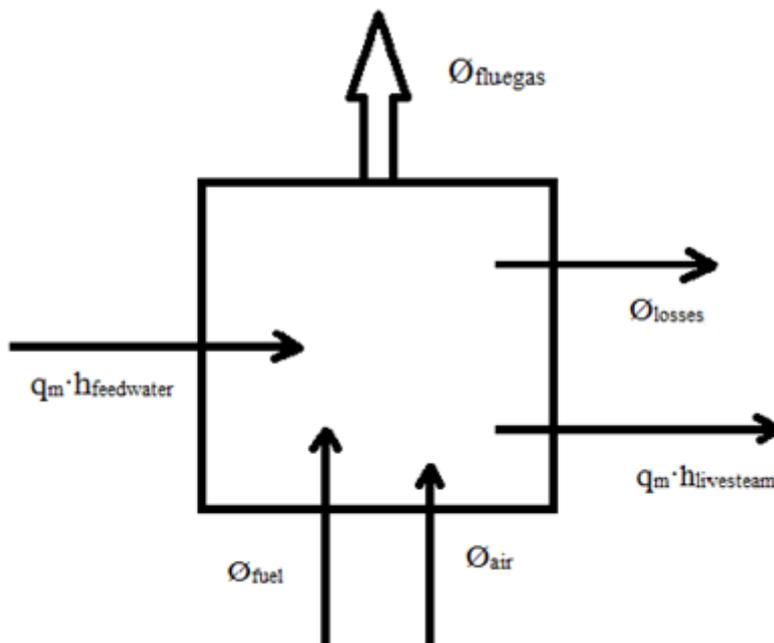


Figure 55. Boiler balance with energy flows.

Fuel energy content is calculated using ultimate analysis based on Caledonian data with equation 1. Dry basis effective heating value is calculated with equation 4 using the data from ultimate analysis. Moistures from drivers' or operators' samples are used in order to calculate lower heating value with equation 5. The fuel energy content based on deliveries also include an evaluation of site derived biomass: sludge, bark and chips.

Table 11 presents the annual fuel energy need based on energy balance that is compared to energy contained in fuel based on moistures and ultimate analysis, and actual deliveries including an evaluation of site derived biomass.

Table 11. Annual biomass need based on energy balance and actual deliveries in 2014-2016.

Year	Ø_{fuel} , Energy balance [TJ/a]	Ø_{fuel} , Actual biomass deliveries [TJ/a]	Difference [TJ/a]	Difference [%]
2016	3004.64	2935.96	-68.68	-2.34%
2015	2891.14	2854.55	-36.59	-1.28%
2014	3080.47	3011.89	-68.58	-2.28%

Based on energy balance the moistures obtained from drivers' or operators' samples are annually, on average, close to actual fuel moistures.

9.2.1 Sources of error

There are several sources of error in the boiler balance calculation. The most significant is volume flow measurements and particularly flue gas volume flow, which has had both issues with Pitot tube but also with data handling. The assumption of all biomass deliveries being combusted not taking into account stock and evaluation of site derived biomass may cause error but that should not be significant.

9.3 Fuel mix weighted average net calorific heating value

Once in an hour (or three hours) a sample of the fuel flow entering the boiler silos is taken. This fuel mix includes the received ready chipped biomass, crushed fuelwood and site derived biomass. This large sample is then mixed and one sample of it is sent to a third-party laboratory for analyzation on weekly basis. In addition, moisture is checked daily by oven drying on site.

Fuel feed to boiler is measured with weight scales. There are three weight scales currently employed at Caledonian Paper CHP plant. One for biomass from A-framed silo, one for site derived biomass and one for the mix of these two. The annual fuel energy feed to boiler is based on the last weighing and net calorific heating value of the fuel.

Table 12 presents a comparison between fuel energy content based on actual deliveries and counted heating value (same as presented in 9.2) including an evaluation of site derived biomass and:

- 1) Daily Mixed Biomass sampling weighted average NCV and weight scale measured fuel tonnages. This means that annual fuel energy to boiler is calculated by using NCV that is effected by Daily Mixed Biomass samples' moistures, and biomass tonnages to boiler based on weight scale measurements.

- 2) Daily Mixed Biomass sampling weighted average NCV and deliveries plus site derived biomass. This means that annual fuel energy to boiler is calculated by using NCV that is effected by Daily Mixed Biomass samples' moistures, and tonnages of actual deliveries weighed in the main gate and an evaluation of the site derived biomass.

Table 12 .Comparison of fuel mix energy content based 1) weight scale, 2) annual deliveries and weighted NCV, to actual annual deliveries where moisture is based on drivers' or operators' samples.

Year	1) Ø_fuel, weight scale, mixed biomass NCV [TJ/a]	2) Ø_fuel, deliveries, mixed biomass NCV [TJ/a]	1) Difference to actual deliveries [%]	2) Difference to actual deliveries [%]
2016	2462.47	2515.35	-16.13%	-14.33%
2015	2462.73	2480.70	-13.73%	-13.10%
2014	2544.07	2545.18	-15.53%	-15.50%

There is a clear difference for both 1) and 2) in comparison to energy content of actual deliveries including site derived biomass, and where LHV is based on ultimate analysis and moistures from drivers' or operators' samples. **Table 12** suggest that on average the last weight scale gives rather reliable readings, and that on average the NCV is lower than LHV calculated for this thesis. The assumption is that this is due to difference in moistures.

9.4 Fuel mix weighted average moisture

Fuel mix weighted average moisture was compared to the weighted average moisture of actual deliveries based on drivers' or operators' samples, fuelwood and site derived biomass. This is presented in **Table 13**. "MC weighted average DMBS" refers to the annual weighted moisture average of biomass, sampled prior to boiler silos, based Daily Mixed Biomass samples.

Table 13. Annual moisture averages based on Daily Mixed Biomass sample and load samples including evaluation of site derived biomass.

Year	MC weighted average DMBS [%]	MC weighted average, drivers' or operators' sample[%]	Difference, percentage points	Difference [%]
2016	51.71	46.10	-5.61	-12.16
2015	49.78	45.78	-4.00	-8.73
2014	50.67	44.69	-5.98	-13.38

As can be seen there is a clear difference between weighted averages, Daily Mixed Biomass reading constantly higher approximately 5 percentage points.

9.5 Sampling accuracy

According to empirical evidence from June 2017 the current back of truck sampling procedure gives acceptable results – the operators' and drivers' samples have moistures close to the truck load averages consisting of 9-12 samples. The boiler energy balance based annual fuel energy need is similar to the biomass energy content that is based on fuel moistures from drivers' or operators' samples and delivered fuel tonnages. The Daily Mixed Biomass samples points to a opposite direction. Annually Daily Mixed Biomass has a moisture content average, approximately 5 percentage points higher than weighted moisture average of individual load samples including an evaluation of site derived biomass. These results are presented in **Table 14** that summarizes the different approaches.

Table 14. Summary of current sampling procedure accuracy. Is the current sampling procedure reliable?

Means of comparison	Yes	No
Empirical evidence (excess sampling)	x	
Energy Balance	x	
Daily Mixed Biomass samples		x

Data combined suggest that there might not be significant difference between the actual fuel moisture and that based on drivers' or operators' samples. The Daily Mixed Biomass data suggest the opposite.

10 SUGGESTIONS FOR FURTHER ACTIONS

This chapter includes suggestions for further actions on the X-ray measurement and its use. Some reflection is also done on the use of second X-ray measurement unit installed in May 2017 by boiler silos. Reasoning about accuracy and improvement suggestion regarding current sampling procedure are given: for the truck specific sample and the Daily Mixed Biomass sample.

10.1 X-ray moisture measurement in fuel receiving

The X-ray unit requires additional fine tuning. At least two new calibrations are needed: low density, thin chips type sawmill residue (Lockerbie, most likely A&J Scott) and for the other mixed biomass (Avonbridge) that tends to have similar thin wood chips with first mentioned. Both fuels are currently measured with X-ray as significantly drier than they actually are.

Further attention on particle size is required. Recycled wood varies greatly in particle size from dust to clear pieces with a diameter of several centimeters. This in theory has an effect on the X-ray measurement that is closely aligned with density variation. Waste wood during dry seasons may have moistures below 17 %, which is the currently set limit for the X-ray measurement. If the aim is to measure lower moistures than 17 % this issue should be addressed. However generally the moisture of waste wood is not the main concern but foreign contents are.

Sampling was conducted between February and April 2017 and during testing trial in June 2017. There was variation in April in results for Mixed Biomass and Recycled Wood, X-ray giving constantly higher moistures. There is a risk that some mixing may have occurred in April but that does not explain the entire variation. Compared to February and March the biomass received in April was drier. I would recommend to follow if this phenomenon reoccurs.

There are loads that have changing fuel type inside, this holds for some sources of sawmill residue. This means that the load that starts and ends e.g. with saw dust, consists in the middle of larger particle size chips. If both fuel types require separate calibration, some type of fuel type identification is required in order to measure moistures correctly.

There remains need for fine tuning and further calibration. **Table 15** summarizes the test results and development areas.

Table 15. X-ray measurement results and suggestions for further actions.

Fuel type	Testing trial results (X-ray to samples)	Development areas
Mixed Biomass	OK or too low	<ul style="list-style-type: none"> - Separation between types in measurement - Variation in results April 2017
Sawmill Residue	OK or too low	<ul style="list-style-type: none"> - New calibrations for low density fuels - Attention to quality variation inside a delivery
Waste Wood	OK or too high	<ul style="list-style-type: none"> - Attention to particle size - 17 % lowest limit - Large variation in results April 2017

Fuel bed thickness on conveyor needs to be addressed. For this there are two possible approaches: either the fuel on conveyor is evened out or the variation is compensated by the equipment.

10.1.1 Use

During tuning phase and trial, it became obvious that with current fuel receiving set up and delivery timings load specific measurements are very difficult if not impossible. More than one load in the fuel pit introduces risk of mixing. If deliveries remain non-scheduled

from Caledonian perspective and receiving design is not altered, there are in practice two options to operate the equipment: the selective measurement presented in 6.2.4 or data gathering with the measurement which would be based on that each delivery is registered and the Inray Fuel system would do automatic fuel type identification. Most likely measurements would be stopped during crusher operation (or unlikely if possible crush excluded from moisture measurement). With lots of moisture data that to some extent could be linked to specific deliveries, loads with constantly higher moistures than reported with traditional samples may be spotted. The moisture data may also be used to fuel energy content estimation.

The foreign content measurement addressing rocks and metals should be followed and utilized. Metals in waste wood and rocks in general, by experience, seem not to be a major problem in Caledonian. Detection of plastics, glue and paint with X-ray should be investigated further, in case any such data could be obtained.

Lastly even with suggestions above the vital question remains – if X-ray measurement is unsuitable for load specific on-line measurement what can it be used for.

10.2 X-ray moisture measurement by boiler silos

A more robust and even regulation of bed temperature can be achieved by installing an on-line moisture measurement that is combined with feedback connections forwards and backwards in a suitable position by boiler fuel feed (Lestander et al. 2008).

The second X-ray moisture measurement unit is installed by the two boiler silos in Caledonian. The boiler silos can supply the boiler on full effect with fuel of approximately 1.5 hours. The connections after proper calibration of the unit with boiler operation should be further studied. Due to the fact there is the time gap between measurement and fuel feed to the boiler the findings by Lestander et al. cannot straightly be applied. Still connections between fuel moisture and boiler operation should be further studied: how the fuel moisture effects the operation, can the fuel feed be adjusted based on moisture

data and can the boiler deterioration caused by moisture (higher flue gas velocities) and foreign objects be limited.

The measurement could be used as the mean to determine the fuel moisture entering the boiler. However, depending on requirements (e.g. ROCs) additional sampling would likely be required to detect foreign matter. Currently the daily mixed biomass sample is taken every hour, reducing the sampling frequency to once every three hours causes condensation by experience, thus reducing sampling frequency might be problematic.

10.3 Current sampling procedure

Based on testing trial results presented in 9.1 there is no significant difference between drivers' or operators' sample taken from back of a truck and load average moisture. Looking at the annual 2016 moisture data based on drivers' or operators' samples, there is clearly moistures too low to be accurate but if compared to boiler energy balance this does not affect the annual fuel energy. Energy balances 2014-2016 suggest that based on fuel energy content, drivers' or operators' sample moistures are close to actual moistures on average. Thus, on average the current sampling procedure seems give acceptable results.

Some improvements could be considered to the current sampling. The drivers and operator place the biomass to a A4 sized resealable plastic bags that is used several times. If the bags are left open either outside or inside soaking of moisture and drying are a risk. Some CHP plants in Finland put samples into buckets with a lock. This is an option also for Caledonian, the biomass would hold well the original moisture in a sealed bucket. A more frequent change of plastic bags may also offer a solution.

Daily Mixed Biomass sample moisture average is 5 percentage points higher annually than weighted moisture average of individual truck specific samples including an evaluation of site derived biomass. With the results from energy balance and empirical evidence it is likely that for one reason or another Daily Mixed Biomass gives on average too high moistures. This does not however mean that samples from back of a truck

sampled by drivers or operators give accurate moistures – there still may be error. I would recommend investigating further if there is moisture ingress to the Daily Mixed Biomass sample, where it occurs, if the suspected error is due to sampling or handling or what causes the suspected error.

11 SUMMARY

The use of renewables and biomass combustion have increased and are likely to continue to do so with EUs ambitious efforts to curb climate change. Fuel costs make up approximately half of all operating costs for a plant combusting biomass thus, paying for actual energy content is vital. Moisture measurement of a load combined with foreign content analysis is a good tool for fuel pricing on energy content base. An on-line quality measurement is a rapid measurement that gives instant data on fuel properties that can be used for pricing and fuel sorting and possibly rejection of low quality biomass if the handling design allows it. Besides payment knowledge of fuel moisture and foreign content may help boiler operation and slow down boiler degradation by e.g. controlling fuel moisture content and in that way limiting flue gas flow and velocity. Monitoring of foreign contents may help reduce ash management costs and prolong life of boiler parts. Measurement of fuel stream entering boiler can be combined with back and forward feedback from boiler data and exploited for boiler operation by bed temperature regulation.

There are many non-destructive testing options for moisture (and foreign content) determination, some of them on-line, and utilizing different technologies. The best suitable application should be chosen based on need, boundaries set by the fuel receiving and handling design or other requirement set by e.g. the environment like occurrence of snow.

Even with increased supply of measurement options, for most old power plants the traditional oven-drying remains the most widely applied method regardless of its limited sample size, representativeness issues and labor intensiveness. The gravimetric method is however very precise and reliable if sample representativeness is excluded. The NDT measurements have better representativeness ability of a load, give rapid results and may be used for foreign content detection. Their limitation is calibration, meaning that often the equipment is calibrated for certain fuel types and conditions, surrounding conditions may affect the measurement as may snow or changes in fuel composition.

This Master's Thesis focused on verification of an X-ray moisture measurement of biomass in UPM Caledonian Paper CHP plants' fuel receiving. In general, the X-ray measured average moistures are quite close to actual average moistures according to testing trial results. There are some fuel types, at least one sawmill residue and mixed biomass that need new calibrations. There is a correlation between fuel bed thickness on conveyor and X-ray measured moistures – the thicker the biomass layer, the higher the moisture. This issue needs to be addressed even if the average moistures are acceptable. The biggest bottle neck is not the moisture measurement itself but its suitability to fuel receiving design. As currently used load specific measurement is practically impossible thus the measurement cannot be used as a base for fuel price. Some options to utilizing the measurement with and without alterations to fuel receiving were given in sections 6.2 and 10.1.1.

Additional calibration and fine tuning of the X-ray equipment in Caledonian are needed. A clear vision of how to utilize the measurement and how to exploit the data obtained, if load specification is impossible, is required.

REFERENCES

Alakangas, E. et al. 2015. Classification of used wood to biomass fuel or solid recycled fuel and cascading use in Finland. Book of Proceeding Bioenergy. P. 79-86.

Alakangas, E. et al. 2015b. Quality guidelines for wood fuels in Finland. VTT-M-04712-15.

Alakangas, E. 2016. Properties of solid and liquid biofuels. Lecture notes. Available: https://mycourses.aalto.fi/pluginfile.php/182706/mod_folder/content/0/Lecture%203a_Alakangas-190116.pdf?forcedownload=1.

Alakangas, E et al. 2016. Suomessa käytettyjen polttoaineiden ominaisuuksia. VTT Tehcnology 258. Teknologian tutkimuskeskus VTT Oy.

Alipour, Y. 2013. High temperature corrosion in a biomass-fired power boiler. Licentiate Thesis in Corrosion Science. KTH Royal Institute of Technology.

Alipour, Y. et al. 2014. Effect of temperature on corrosion of furnace walls in a waste wood fired boiler. Materials at High Temperatures, 2015, VOL 32.

American Society for Nondestructive testing. 2016. Introduction to Nondestructive testing. [Referenced to: 24.1.2017] Available: <https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT>

Aurell, J. et al. 2005. Minskad dioxinbildning med hjälp av additiv vid sameldning av skogsbränsle och returbränsle. Värmeforsk. Miljö- och förbränningsteknik 928.

Barale, P. et al. 2002. The Use of a Permanent Magnet for Water Content Measurements of Wood Chips. IEEE Transactions On Applied Superconductivity, Vol. 12, No. 1, March 2002.

Basu, P. 2006. Combustion and Gasification in Fluidized Beds. Taylor & Frances Group, LLC.

BMH Technology. 2017. Biomass Fuel Handling Process Overview. [Referenced to: 17.7.2017] Available: <http://www.bmh.fi/entire-solutions/biomass-fuel-handling>

BioNormII. Review for online measurement possibilities of chemical parameters for process control of industrial solid biofuel production. Pre-normative research on solid biofuels for improved European standards. Project no. 038644.

Braynt, L. et al. (ed). 1985. Nondestructive testing handbook. Second edition. Volume 3, Radiography and radiation testing. American Society for nondestructive testing.

Chilcott, T. et al. 2010. Characterizing Moisture Content and Gradients in Pinus radiata Soft Wood Using Electrical Impedance Spectroscopy. *Drying Technology*, 29:1, 1-9.

Chunjiang, Y. et al. 2011. Experimental research on agglomeration in straw-fired fluidized beds. *Applied Energy*. Volume 88, Issue 12, December 2011, p.4534-4543

Ciolkosz. 2010. Characteristics of Biomass as a heating fuel. Renewable and alternative energy fact sheet. The Pennsylvania State University 2010.

Coda, B. et al. 2001. Behavior of Chlorine and Enrichment of Risky Elements in Bubbling Fluidized Bed Combustion of Biomass and Waste Assisted by Additives. *Energy & Fuels* 2001, 15, 680-690.

Corredor, C. et al. 2011. Comparison of near infrared and microwave resonance sensors for at-line moisture determination in powders and tablets. *Analytica Chimica Acta* 696 (2011) 84-93.

Defra. 2012. Wood waste: A short review of recent research. July 2012. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/82571/consult-wood-waste-researchreview-20120731.pdf

Enestam, S. et al. 2011a. Occurrence of Zinc and Lead in Aerosols and Deposits in the Fluidized-Bed Combustion of Recovered Waste Wood. Part 1: Samples from Boilers. *Energy & Fuels* 2011, 25, p. 1396–1404

Enestam, S. et al. 2011b. Occurrence of Zinc and Lead in Aerosols and Deposits in the Fluidized-Bed Combustion of Recovered Waste Wood. Part 2: Thermodynamic Considerations. *Energy & Fuels* 2011, 25, p. 1970–1977.

European Commission. 2008. Directive 2008/98/EC of the European Parliament and of The Council of 19 November 2008 on Waste and Repealing Certain Directives.

European Commission. 2016. Proposal for a Directive of the European Parliament and the Council on the Promotion of the Use of Energy from Renewable Sources (recast). European Commission. COM(2016) 767 final.

European Commission. 2017. Renewable energy: Bioenergy. Research & Innovation, Energy. [Referenced to: 14.7.2017] Available: http://ec.europa.eu/research/energy/index.cfm?pg=area&areaname=renewable_bio

Eurostat. 2017. Energy from renewable sources. [Referenced to: 14.7.2017] Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources#Primary_production_of_energy_from_renewable_sources

Grammelis, P. et al. 2011. Fluidized Bed Combustion of Solid Biomass for Electricity and/or Heat Generation. *Green Energy and Technology* 2011, Vol.28.

Hakkila, P. 2004. Puuenergian teknologia ohjelma 1991-2003. Teknologiaohjelmaraportti 5/2004, Loppuraportti. Tekes.

Holmgren, M. X Steam tables. Excel macros, IF-97 Steam tables. Version 2.6. [Referenced to: 14.7.2017] Available: www.x-eng.com.

Huang et al. 2009. Effects of metal catalysts on CO₂ gasification reactivity of biomass char. *Biotechnology Advances*. Volume 27, Issue 5, September-October 2009, p. 568-572.

Huhtinen, M. et al. 1994. Höyrykattilatekniikka. Edita.

Hultnäs, M. et al. 2012. Determination of moisture content in wood chips of Scots pine and Norway Spruce using Mantex Desktop Scanner based on dual energy X-ray absorptiometry. *J Wood Sci* (2012) 58, p. 309-314.

Hupa, M. et al. 2016. Biomass combustion technology development – It is all about chemical details. *Proceedings of the Combustion Institute* 000 (2016) 1-22

Jenkins, B. et al. 1998. Combustion properties of biomass. *Fuel Processing Technology* 54 (1998) 17–46.

Järvinen, T. 2013. Nopea ja tarkka biopolttoaineiden kosteuden määrittäminen käyttäen magneettisen resonanssin mittaukseen perustuvaa laitetta. *VTT TECHNOLOGY* 90.

Kassman, H. 2012. Strategies to Reduce Gaseous KCl and Chlorine in Deposits during Combustion of Biomass in Fluidised Bed Boilers. Thesis for the degree of doctor of philosophy. Chalmers University of Technology.

Kim, CK et al. 2015. Dual-energy X-ray absorptiometry with digital radiograph for evaluating moisture content of green wood. *Wood Sci Technol* (2015) 49, p- 713-723.

Korpilahti, A and Melkas, T. 2010. Kosteuden online-mittausmetsätähdehakkeesta. *Metsätehon raportti* 213.

Kullenberg, R. et al. 2010. Dual-Energy X-Ray Absorptiometry Analysis for the Determination of Moisture Content in Biomass. *Journal of Biobased Materials and Bioenergy*. Vol. 4, p. 363-366, 2010.

Kumar, M. et al. 2015. Fire side erosion–corrosion protection of boiler tubes by nanostructured coatings. *Materials and Corrosion* 2015, 66, No. 7.

Lavric, E. et al. 2003. Dioxin levels in wood combustion—a review. *Biomass and Bioenergy* 26 (2004) 115 – 145.

Lestander et al. 2008. On-line NIR-fukthaltsmätning för styrning av panna i värmekraftverk. In Swedish, Värmeforsk, Skogsindustriella programmet, Rapportnummer 1059.

Lindberg, J. et al. 2012. Best Available Techniques (BAT) in solid biomass fuel processing, handling, storage and production of pellets from biomass. Norden.

Mcgowan, T. et al. 2010. Biomass and Alternate Fuel Systems: An Engineering and Economic Guide. John Wiley & Sons.

Metso. 2014. Metso's biomass moisture analyzer wins esteemed iF design award. [Referenced to: 3.3.2017] Available: <http://www.metso.com/news/2014/3/metsos-biomass-moisture-analyzer-wins-esteemed-if-design-award/>

Montes, A. 2016. Study of bed materials agglomeration in a heated bubbling fluidized bed (BFB) using silica sand as the bed material and KOH to simulate molten ash. Power Technology 291 (2016), p. 178-185.

Moradian et al. 2016. Thermodynamic equilibrium prediction of bed agglomeration tendency. Article. Fuel Processing Technology 154 (2016), p. 82-90.

Ofgem. 2013. Renewables Obligation: template methodology for measuring fossil derived contamination within waste wood. Available: [templatemethodology-contaminationofwastewood20131112-pdf](#)

Ofgem. 2015. Renewables Obligation: Guidance for suppliers. Available: https://www.ofgem.gov.uk/sites/default/files/docs/ro_supplier_guidance_december_2015_finaldocx.pdf

Ofgem. 2016. Renewables Obligation: Sustainability Criteria, Guidance. Ofgem e-serve. Available: https://www.ofgem.gov.uk/system/files/docs/2016/03/ofgem_ro_sustainability_criteria_guidance_march_16.pdf

NL Agency 2013. Competition in wood waste: inventory of policies and markets, NL Agency, Ministry of Economic Affairs. Available: <http://english.rvo.nl/sites/default/files/2013/12/Competition%20in%20wood%20waste%20June%202013.pdf>

Nyström, J. 2006. Rapid measurements of the moisture content of biofuel. Department of Public Technology, Mälardalen University. Mälardalen University Press Dissertations, No.24.

Raiko, R. et al. 2002. Poltto ja palaminen, toinen täydennetty painos. International Flame Research Foundation - Suomen kansallinen osasto.

Samuelsson, R. et al. 2006. Comparison of different methods for determination of moisture content in biomass. Biomass and Bioenergy. Volume 30, Issue 11, November 2006, p. 929-934.

Salvola, S. 2014. Suitability of a portable XRF analyzer for recovered waste wood and fly ash quality control. Master of Science Thesis. Tampere University of Technology.

Sheng, S and Azevedo, J. 2004. Estimating the higher heating value of biomass fuels from basic analysis data. Biomass and Bioenergy 28 (2005) 499-507.

Silmu, R. 2014. Improved quality follow-up of forest fuels.

Silvennoinen, J. et al. 2013. High Temperature Corrosion Controlling by On-line Fuel and Process Atmosphere Management Solution. Metso. Available: <http://pennwell.sds06.websds.net/2013/vienna/pge/papers/T5S1O3-paper.pdf>

Tanaka, T. et al. 2012. A new method for nondestructive evaluation of solid wood moisture content based on dual-energy X-ray absorptiometry. Wood Sci Technol (2013) 47. p. 1213-1229.

Torgrip, R. et al. 2017. Rapid X-ray based determination of moisture-, ash content and heating value of three biofuel assortments. Biomass and Energy 98 (2017). p. 161-171.

Tynjälä, T. 2009. Teknillinen termodynamiikka, luentomoniste osa 2. Lappeenranta University of Technology.

UPM. 2014. UPM Caledonian General Presentation Nov 14. Slides.

Vakkilainen E. 2010. Höyrykattilatekniikka, luentomoniste 2010, Lappeenranta University of Technology.. P. 10-1 - 10-29.

Vakkilainen, E. et al. 2012. Sähkön tuotantokustannusvertailu. Tutkimusraportti 27. Lappeenrannan teknillinen yliopisto.

Van Eyk, P. et al. 2005. Control of Agglomeration and Defluidization during Fluidized-Bed Combustion of South Australian Low-Rank Coals. Energy Fuels 2012, 26, 118–129.

Van Loo, S. et al. 2008. The Handbook of Biomass Combustion and Co-firing. Earthscan.

Wang, B. 1995. Erosion-corrosion of coatings by biomass-fired boiler fly ash. Wear 188 (1995) 40-48

The Waste and Resources Action Programme. 2012. Waste Incineration Directive. EfW Development Guidance. Available:
http://www.wrap.org.uk/sites/files/wrap/8_O_And_EFW_Guidance_WID.pdf

APPENDIX

Appendix 1: Moisture measurement data from testing trial 2.-22.6.2017

Time	Inray Id	Fuel Type	Supplier	Moisture [%]	Xray Moisture [%]	Central Height [mm]
02/06/17 8:55	101176	Recycled Wood B	Mossley	18,26	22,62	113
02/06/17 8:56	101176	Recycled Wood B	Mossley	15,42	29,25	135
02/06/17 8:57	101176	Recycled Wood B	Mossley	16,27	24,77	103
02/06/17 8:58	101176	Recycled Wood B	Mossley	16,38	29,33	136
02/06/17 8:59	101176	Recycled Wood B	Mossley	17,42	21,89	107
02/06/17 9:00	101176	Recycled Wood B	Mossley	14,94	27,38	119
02/06/17 9:01	101176	Recycled Wood B	Mossley	14,89	20,64	95
02/06/17 9:02	101176	Recycled Wood B	Mossley	13,91	24,76	103
02/06/17 9:03	101176	Recycled Wood B	Mossley	15,11	22,77	98
02/06/17 9:04	101176	Recycled Wood B	Mossley	15,23	19,69	79
02/06/17 9:05	101176	Recycled Wood B	Mossley	14,45	17,95	59
02/06/17 9:06	101176	Recycled Wood B	Mossley	14,78	17	29
02/06/17 15:07	101178	Mixed Biomass	Avonbridge	48,8	23,43	14
02/06/17 15:08	101178	Mixed Biomass	Avonbridge	47,65	37,12	61
02/06/17 15:09	101178	Mixed Biomass	Avonbridge	43,63	26,07	25
02/06/17 15:10	101178	Mixed Biomass	Avonbridge	48,75	40,83	93
02/06/17 15:11	101178	Mixed Biomass	Avonbridge	50,95	25,46	18
02/06/17 15:12	101178	Mixed Biomass	Avonbridge	47,8	39,81	79
02/06/17 15:13	101178	Mixed Biomass	Avonbridge	48,61	27,21	32
02/06/17 15:14	101178	Mixed Biomass	Avonbridge	47,54	41	87
02/06/17 15:15	101178	Mixed Biomass	Avonbridge	49,17	35,86	61
02/06/17 15:16	101178	Mixed Biomass	Avonbridge	46,83	34,78	53
02/06/17 17:04	101179	Sawmill Residue	Auchengate	50,92	47,51	98
02/06/17 17:05	101179	Sawmill Residue	Auchengate	51,89	48,64	101
02/06/17 17:06	101179	Sawmill Residue	Auchengate	49,88	49	93
02/06/17 17:07	101179	Sawmill Residue	Auchengate	50,48	45,26	116
02/06/17 17:08	101179	Sawmill Residue	Auchengate	50,69	47,63	97
02/06/17 17:09	101179	Sawmill Residue	Auchengate	52,8	47,76	108
02/06/17 17:10	101179	Sawmill Residue	Auchengate	54,08	47,18	84
02/06/17 17:11	101179	Sawmill Residue	Auchengate	54,77	48,83	107
02/06/17 17:12	101179	Sawmill Residue	Auchengate	52,87	43,62	70
02/06/17 17:13	101179	Sawmill Residue	Auchengate	52,37	43,65	78
02/06/17 17:14	101179	Sawmill Residue	Auchengate	50,6	28,39	26

02/06/17 17:15	101179	Sawmill Residue	Auchengate	44,78	27,84	35
05/06/17 10:09	101180	Mixed Biomass	Blantyre	46,56	52,67	86
05/06/17 10:10	101180	Mixed Biomass	Blantyre	48,71	56,68	137
05/06/17 10:11	101180	Mixed Biomass	Blantyre	51,2	52,49	99
05/06/17 10:12	101180	Mixed Biomass	Blantyre	48,15	55,95	121
05/06/17 10:13	101180	Mixed Biomass	Blantyre	51,53	53,02	113
05/06/17 10:14	101180	Mixed Biomass	Blantyre	53,07	48,94	117
05/06/17 10:15	101180	Mixed Biomass	Blantyre	50,95	52,84	143
05/06/17 10:16	101180	Mixed Biomass	Blantyre	50,91	47,59	98
05/06/17 10:17	101180	Mixed Biomass	Blantyre	51,2	45,46	95
05/06/17 10:18	101180	Mixed Biomass	Blantyre	49,04	33,51	73
05/06/17 10:19	101180	Mixed Biomass	Blantyre	50,36	36,93	42
05/06/17 10:20	101180	Mixed Biomass	Blantyre	52,54	33,73	22
05/06/17 10:34	101181	Recycled Wood B	Mt Vernon	20,77	20,67	133
05/06/17 10:35	101181	Recycled Wood B	Mt Vernon	20,8	23,76	128
05/06/17 10:36	101181	Recycled Wood B	Mt Vernon	24,2	26,68	146
05/06/17 10:37	101181	Recycled Wood B	Mt Vernon	20,3	22,87	115
05/06/17 10:38	101181	Recycled Wood B	Mt Vernon	22,57	26,28	139
05/06/17 10:39	101181	Recycled Wood B	Mt Vernon	21,09	24,38	124
05/06/17 10:40	101181	Recycled Wood B	Mt Vernon	21,64	26,12	138
05/06/17 10:41	101181	Recycled Wood B	Mt Vernon	21,29	21,43	125
05/06/17 10:42	101181	Recycled Wood B	Mt Vernon	21,2	23,68	127
05/06/17 10:43	101181	Recycled Wood B	Mt Vernon	22,1	18,09	103
05/06/17 10:44	101181	Recycled Wood B	Mt Vernon	22,21	20,94	107
05/06/17 10:45	101181	Recycled Wood B	Mt Vernon	22,14	17	82
05/06/17 13:32	101182	Sawmill Residue	Dunkeld	56,69	46,08	87
05/06/17 13:33	101182	Sawmill Residue	Dunkeld	55,09	34,83	43
05/06/17 13:34	101182	Sawmill Residue	Dunkeld	52,97	48,75	104
05/06/17 13:35	101182	Sawmill Residue	Dunkeld	50,99	36,24	39
05/06/17 13:36	101182	Sawmill Residue	Dunkeld	54,21	53,77	129
05/06/17 13:37	101182	Sawmill Residue	Dunkeld	51,74	46,2	111
05/06/17 13:38	101182	Sawmill Residue	Dunkeld	51,63	54,27	131
05/06/17 13:39	101182	Sawmill Residue	Dunkeld	53,71	51,18	98
05/06/17 13:40	101182	Sawmill Residue	Dunkeld	52,24	52,28	122
05/06/17 13:41	101182	Sawmill Residue	Dunkeld	52,16	48,58	80
05/06/17 13:42	101182	Sawmill Residue	Dunkeld	50,64	46,86	82
05/06/17 13:42	101182	Sawmill Residue	Dunkeld	50,16	46,86	82
05/06/17 16:22	101183	Mixed Biomass	Blantyre	50,99	60,11	130
05/06/17 16:23	101183	Mixed Biomass	Blantyre	51,04	58,79	123
05/06/17 16:24	101183	Mixed Biomass	Blantyre	49,61	56,04	120

05/06/17 16:25	101183	Mixed Biomass	Blantyre	49,87	56,34	114
05/06/17 16:26	101183	Mixed Biomass	Blantyre	50,43	53	101
05/06/17 16:28	101183	Mixed Biomass	Blantyre	49,75	36,77	22
05/06/17 16:29	101183	Mixed Biomass	Blantyre	48,59	48,06	58
05/06/17 16:30	101183	Mixed Biomass	Blantyre	48,96	28,68	16
05/06/17 16:31	101183	Mixed Biomass	Blantyre	48,09	42,72	31
06/06/17 14:50	101185	Sawmill Residue	Troon Mill	32,55	35,95	131
06/06/17 14:51	101185	Sawmill Residue	Troon Mill	31,67	38,52	150
06/06/17 14:52	101185	Sawmill Residue	Troon Mill	30,37	33,4	119
06/06/17 14:53	101185	Sawmill Residue	Troon Mill	31,42	36,59	139
06/06/17 14:54	101185	Sawmill Residue	Troon Mill	30,64	29,94	115
06/06/17 14:55	101185	Sawmill Residue	Troon Mill	28,38	35,8	132
06/06/17 14:56	101185	Sawmill Residue	Troon Mill	30,94	27,59	99
06/06/17 14:57	101185	Sawmill Residue	Troon Mill	29,81	33,58	118
06/06/17 14:58	101185	Sawmill Residue	Troon Mill	30,07	30,78	103
06/06/17 14:59	101185	Sawmill Residue	Troon Mill	28,79	27,45	79
06/06/17 15:00	101185	Sawmill Residue	Troon Mill	30,74	26,47	70
06/06/17 15:01	101185	Sawmill Residue	Troon Mill	27,65	20	51
06/06/17 15:15	101186	Sawmill Residue	Auchengate	49,38	47,36	95
06/06/17 15:16	101186	Sawmill Residue	Auchengate	52,04	50,96	105
06/06/17 15:17	101186	Sawmill Residue	Auchengate	50,58	47,78	102
06/06/17 15:18	101186	Sawmill Residue	Auchengate	46,79	54,39	116
06/06/17 15:19	101186	Sawmill Residue	Auchengate	49,85	47,12	103
06/06/17 15:20	101186	Sawmill Residue	Auchengate	50,02	49,11	106
06/06/17 15:21	101186	Sawmill Residue	Auchengate	49,51	45,56	95
06/06/17 15:22	101186	Sawmill Residue	Auchengate	47,3	43,66	69
06/06/17 15:23	101186	Sawmill Residue	Auchengate	44,87	40,58	50
06/06/17 15:24	101186	Sawmill Residue	Auchengate	42,41	25,71	17
06/06/17 15:25	101186	Sawmill Residue	Auchengate	44,71	29,38	29
06/06/17 16:19	101189	Sawmill Residue	Cardross	57,58	54,17	91
06/06/17 16:20	101189	Sawmill Residue	Cardross	56,09	58,04	115
06/06/17 16:21	101189	Sawmill Residue	Cardross	55,92	58,89	115
06/06/17 16:22	101189	Sawmill Residue	Cardross	57,38	60,77	117
06/06/17 16:23	101189	Sawmill Residue	Cardross	53,74	49,66	73
06/06/17 16:24	101189	Sawmill Residue	Cardross	56,43	53,72	104
06/06/17 16:25	101189	Sawmill Residue	Cardross	57,74	48,19	57
06/06/17 16:26	101189	Sawmill Residue	Cardross	55,83	49,88	72
06/06/17 16:27	101189	Sawmill Residue	Cardross	58,92	48,32	49
06/06/17 16:28	101189	Sawmill Residue	Cardross	53,93	37,75	27
06/06/17 16:28	101189	Sawmill Residue	Cardross	53,47	37,75	27

07/06/17 15:10	101191	Sawmill Residue	Cardross	57,07	59,12	107
07/06/17 15:11	101191	Sawmill Residue	Cardross	55,99	55,16	73
07/06/17 15:12	101191	Sawmill Residue	Cardross	53,15	58,89	114
07/06/17 15:13	101191	Sawmill Residue	Cardross	55,16	49,8	54
07/06/17 15:14	101191	Sawmill Residue	Cardross	55,18	57,27	104
07/06/17 15:15	101191	Sawmill Residue	Cardross	55,9	54,7	94
07/06/17 15:16	101191	Sawmill Residue	Cardross	55,11	56,75	124
07/06/17 15:17	101191	Sawmill Residue	Cardross	54,2	53,62	81
07/06/17 15:18	101191	Sawmill Residue	Cardross	54,06	56,82	113
07/06/17 15:19	101191	Sawmill Residue	Cardross	55,44	55,38	87
07/06/17 15:20	101191	Sawmill Residue	Cardross	53,82	55,42	86
07/06/17 15:21	101191	Sawmill Residue	Cardross	56	54,68	81
09/06/17 17:50	101195	Sawmill Residue	Lockerbie	61,36	33,22	78
09/06/17 17:51	101195	Sawmill Residue	Lockerbie	60,13	33,1	92
09/06/17 17:52	101195	Sawmill Residue	Lockerbie	59,94	34,65	85
09/06/17 17:53	101195	Sawmill Residue	Lockerbie	62,08	33,32	87
09/06/17 17:54	101195	Sawmill Residue	Lockerbie	60,79	32,92	75
09/06/17 17:55	101195	Sawmill Residue	Lockerbie	60,25	31,17	80
09/06/17 17:56	101195	Sawmill Residue	Lockerbie	60,43	26,35	37
09/06/17 17:57	101195	Sawmill Residue	Lockerbie	60,67	36,95	109
09/06/17 17:58	101195	Sawmill Residue	Lockerbie	61,85	29,75	58
09/06/17 17:59	101195	Sawmill Residue	Lockerbie	62,6	36,52	113
09/06/17 18:00	101195	Sawmill Residue	Lockerbie	59,31	26,28	41
09/06/17 18:01	101195	Sawmill Residue	Lockerbie	60,75	35,1	96
12/06/17 8:48	101197	Sawmill Residue	Lockerbie	59,63	29,4	101
12/06/17 8:49	101197	Sawmill Residue	Lockerbie	60,02	25,81	76
12/06/17 8:50	101197	Sawmill Residue	Lockerbie	61,62	34,29	117
12/06/17 8:51	101197	Sawmill Residue	Lockerbie	61,25	17	24
12/06/17 8:52	101197	Sawmill Residue	Lockerbie	61,33	26,03	64
12/06/17 8:53	101197	Sawmill Residue	Lockerbie	58,87	18,78	30
12/06/17 8:54	101197	Sawmill Residue	Lockerbie	61	26,41	51
12/06/17 8:55	101197	Sawmill Residue	Lockerbie	57,55	17	27
12/06/17 8:56	101197	Sawmill Residue	Lockerbie	59,34	28,68	86
12/06/17 8:57	101197	Sawmill Residue	Lockerbie	56,45	17,28	29
12/06/17 8:58	101197	Sawmill Residue	Lockerbie	59,17	24,97	91
12/06/17 8:59	101197	Sawmill Residue	Lockerbie	58,5	23,56	67
12/06/17 9:12	101198	Recycled Wood B	Mt Vernon	21,74	29,54	138
12/06/17 9:12	101198	Recycled Wood B	Mt Vernon	21,74	29,54	138
12/06/17 9:13	101198	Recycled Wood B	Mt Vernon	22,19	19,34	69
12/06/17 9:14	101198	Recycled Wood B	Mt Vernon	22,72	27,9	134

12/06/17 9:15	101198	Recycled Wood B	Mt Vernon	22,62	18,25	65
12/06/17 9:16	101198	Recycled Wood B	Mt Vernon	21,56	23,49	135
12/06/17 9:17	101198	Recycled Wood B	Mt Vernon	22,45	19,56	78
12/06/17 9:18	101198	Recycled Wood B	Mt Vernon	23,5	22,44	141
12/06/17 9:19	101198	Recycled Wood B	Mt Vernon	24,87	22,31	106
12/06/17 9:20	101198	Recycled Wood B	Mt Vernon	21,98	20,67	122
12/06/17 9:20	101198	Recycled Wood B	Mt Vernon	23,16	20,67	122
12/06/17 9:21	101198	Recycled Wood B	Mt Vernon	21,44	20,2	91
12/06/17 9:22	101198	Recycled Wood B	Mt Vernon	23,54	17	66
12/06/17 9:34	101199	Sawmill Residue	Troon Mill	31,26	29,33	129
12/06/17 9:35	101199	Sawmill Residue	Troon Mill	28,67	32,3	130
12/06/17 9:36	101199	Sawmill Residue	Troon Mill	30,91	28,72	126
12/06/17 9:37	101199	Sawmill Residue	Troon Mill	29,88	34,44	140
12/06/17 9:38	101199	Sawmill Residue	Troon Mill	30,48	30,88	113
12/06/17 9:39	101199	Sawmill Residue	Troon Mill	31,91	35,68	141
12/06/17 9:40	101199	Sawmill Residue	Troon Mill	29,96	30,02	102
12/06/17 9:41	101199	Sawmill Residue	Troon Mill	33,24	35,33	133
12/06/17 9:42	101199	Sawmill Residue	Troon Mill	32,08	31,02	112
12/06/17 9:43	101199	Sawmill Residue	Troon Mill	30,35	23,4	102
12/06/17 10:41	101201	Mixed Biomass	Blantyre	52,36	42,54	69
12/06/17 10:42	101201	Mixed Biomass	Blantyre	51,13	48,24	97
12/06/17 10:43	101201	Mixed Biomass	Blantyre	51,46	50,01	91
12/06/17 10:44	101201	Mixed Biomass	Blantyre	49,42	53,44	110
12/06/17 10:45	101201	Mixed Biomass	Blantyre	50,13	50,74	85
12/06/17 10:46	101201	Mixed Biomass	Blantyre	53,31	56,37	126
12/06/17 10:47	101201	Mixed Biomass	Blantyre	50,72	46,08	51
12/06/17 10:48	101201	Mixed Biomass	Blantyre	52,3	51,98	101
12/06/17 10:49	101201	Mixed Biomass	Blantyre	51,12	49,65	69
12/06/17 10:50	101201	Mixed Biomass	Blantyre	52,05	48,16	71
12/06/17 10:51	101201	Mixed Biomass	Blantyre	52,91	32,46	19
12/06/17 17:03	101202	Sawmill Residue	Auchengate	54,04	50,53	118
12/06/17 17:04	101202	Sawmill Residue	Auchengate	53,5	49,71	109
12/06/17 17:05	101202	Sawmill Residue	Auchengate	52	54,63	130
12/06/17 17:06	101202	Sawmill Residue	Auchengate	49,33	51,07	113
12/06/17 17:07	101202	Sawmill Residue	Auchengate	50,21	51,18	134
12/06/17 17:08	101202	Sawmill Residue	Auchengate	47,01	51,82	115
12/06/17 17:09	101202	Sawmill Residue	Auchengate	47,46	53,1	133
12/06/17 17:10	101202	Sawmill Residue	Auchengate	52,22	49,43	113
12/06/17 17:11	101202	Sawmill Residue	Auchengate	49,61	52,11	113
12/06/17 17:12	101202	Sawmill Residue	Auchengate	48,83	48,14	97

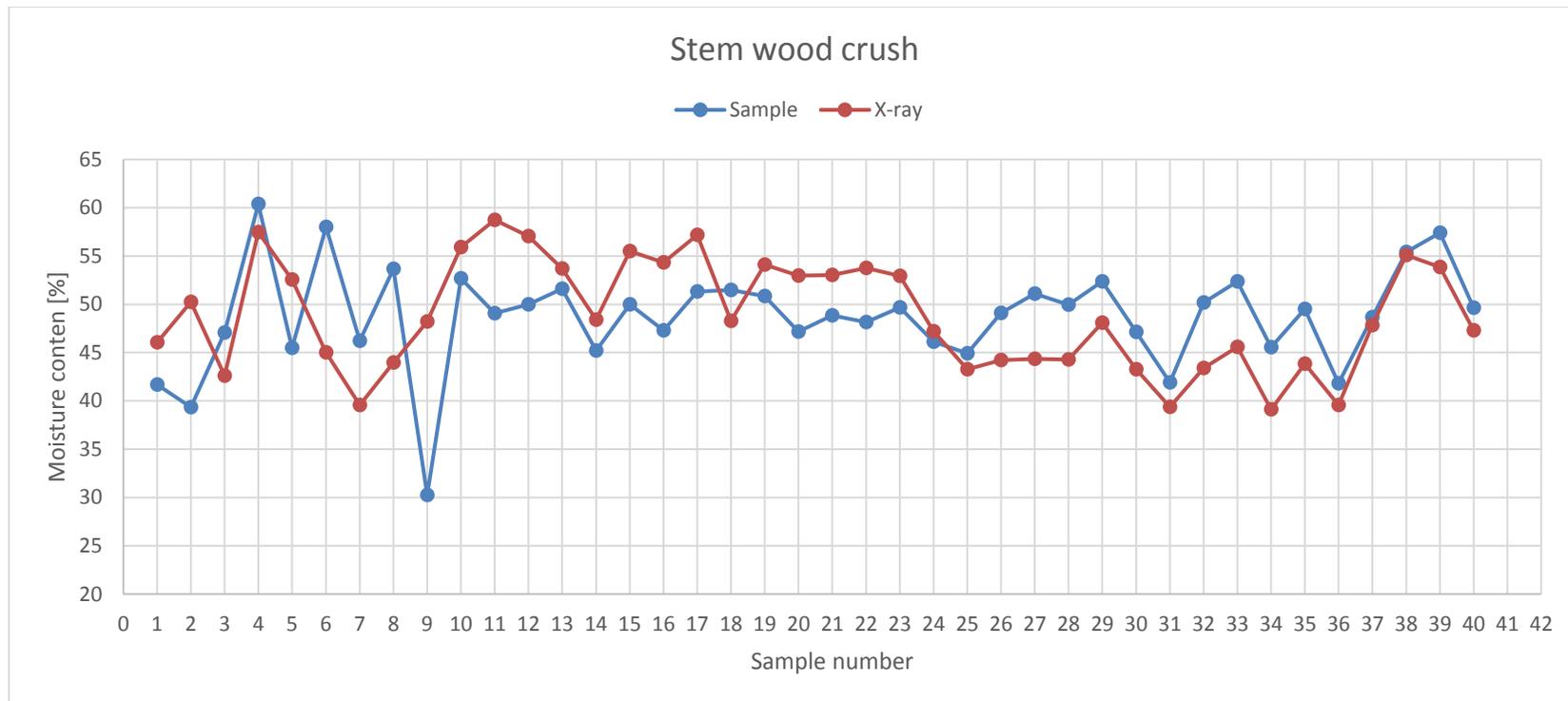
20/06/17 14:23	101205	Recycled Wood A	EK Pallets	19,97	17	85
20/06/17 14:24	101205	Recycled Wood A	EK Pallets	18,5	19,26	133
20/06/17 14:25	101205	Recycled Wood A	EK Pallets	18,92	19,01	101
20/06/17 14:26	101205	Recycled Wood A	EK Pallets	18,65	20,15	132
20/06/17 14:27	101205	Recycled Wood A	EK Pallets	19,04	20,05	115
20/06/17 14:28	101205	Recycled Wood A	EK Pallets	20,81	22,07	127
20/06/17 14:29	101205	Recycled Wood A	EK Pallets	20,03	21,2	122
20/06/17 14:30	101205	Recycled Wood A	EK Pallets	20,51	19,23	107
20/06/17 14:31	101205	Recycled Wood A	EK Pallets	20,34	20,34	113
20/06/17 14:32	101205	Recycled Wood A	EK Pallets	21,28	17	73
20/06/17 14:32	101205	Recycled Wood A	EK Pallets	20,96	17	73
20/06/17 14:32	101205	Recycled Wood A	EK Pallets	21,72	17	73
20/06/17 15:42	101206	Sawmill Residue	Dunkeld	53,98	20,9	137
20/06/17 15:43	101206	Sawmill Residue	Dunkeld	53,46	23,57	108
20/06/17 15:44	101206	Sawmill Residue	Dunkeld	53,1	40	97
20/06/17 15:45	101206	Sawmill Residue	Dunkeld	48,57	47,73	103
20/06/17 15:46	101206	Sawmill Residue	Dunkeld	51,1	52,56	129
20/06/17 15:47	101206	Sawmill Residue	Dunkeld	50,38	53,96	115
20/06/17 15:48	101206	Sawmill Residue	Dunkeld	48,17	54,25	134
20/06/17 15:49	101206	Sawmill Residue	Dunkeld	51,1	48,09	97
20/06/17 15:50	101206	Sawmill Residue	Dunkeld	51,35	50,39	113
20/06/17 15:51	101206	Sawmill Residue	Dunkeld	51,15	41,29	67
20/06/17 15:52	101206	Sawmill Residue	Dunkeld	50,24	44,23	79
20/06/17 15:53	101206	Sawmill Residue	Dunkeld	49	29,5	31
22/06/17 11:32	101225	Mixed Biomass	Avonbridge	44,08	43,25	126
22/06/17 11:33	101225	Mixed Biomass	Avonbridge	44,3	34,55	78
22/06/17 11:34	101225	Mixed Biomass	Avonbridge	47,56	44,03	122
22/06/17 11:35	101225	Mixed Biomass	Avonbridge	49,59	35,27	64
22/06/17 11:36	101225	Mixed Biomass	Avonbridge	44,04	43,83	125
22/06/17 11:37	101225	Mixed Biomass	Avonbridge	49,49	36,32	81
22/06/17 11:38	101225	Mixed Biomass	Avonbridge	46,49	43,68	126
22/06/17 11:39	101225	Mixed Biomass	Avonbridge	49,22	35,09	64
22/06/17 11:40	101225	Mixed Biomass	Avonbridge	49,26	37,61	78
22/06/17 11:41	101225	Mixed Biomass	Avonbridge	49,3	42,19	98
22/06/17 11:42	101225	Mixed Biomass	Avonbridge	48,86	36,89	65
22/06/17 11:43	101225	Mixed Biomass	Avonbridge	47,19	44,74	131

Appendix 2: Moisture measurement data of fuelwood (stem wood crush) from 23.4.2017.

Time	Moisture [%]	Xray Moisture [%]	Inray Id	Fuel Type
2017-04-23 13:18:00	41,68	46,06	101122	Fuelwood crush
2017-04-23 13:19:00	39,35	50,25	101122	Fuelwood crush
2017-04-23 13:20:00	47,08	42,62	101122	Fuelwood crush
2017-04-23 13:21:00	60,37	57,46	101122	Fuelwood crush
2017-04-23 13:22:00	45,5	52,55	101122	Fuelwood crush
2017-04-23 13:23:00	58	45,01	101122	Fuelwood crush
2017-04-23 13:24:00	46,23	39,55	101122	Fuelwood crush
2017-04-23 13:25:00	53,65	43,97	101122	Fuelwood crush
2017-04-23 13:26:00	30,24	48,2	101122	Fuelwood crush
2017-04-23 13:27:00	52,67	55,92	101122	Fuelwood crush
2017-04-23 13:28:00	49,07	58,74	101122	Fuelwood crush
2017-04-23 13:30:00	49,98	57,07	101122	Fuelwood crush
2017-04-23 13:42:00	51,62	53,71	101123	Fuelwood crush
2017-04-23 13:44:00	45,19	48,39	101123	Fuelwood crush
2017-04-23 13:45:00	49,98	55,49	101123	Fuelwood crush
2017-04-23 13:47:00	47,31	54,32	101123	Fuelwood crush
2017-04-23 13:48:00	51,31	57,18	101123	Fuelwood crush
2017-04-23 13:50:00	51,48	48,28	101123	Fuelwood crush
2017-04-23 13:51:00	50,85	54,12	101123	Fuelwood crush
2017-04-23 13:52:00	47,17	52,96	101123	Fuelwood crush

2017-04-23 13:53:00	48,84	53,03	101123	Fuelwood crush
2017-04-23 13:54:00	48,16	53,75	101123	Fuelwood crush
2017-04-23 13:55:00	49,67	52,94	101123	Fuelwood crush
2017-04-23 13:56:00	46,13	47,2	101123	Fuelwood crush
2017-04-23 14:10:00	44,93	43,28	101124	Fuelwood crush
2017-04-23 14:11:00	49,09	44,23	101124	Fuelwood crush
2017-04-23 14:12:00	51,11	44,34	101124	Fuelwood crush
2017-04-23 14:13:00	49,97	44,3	101124	Fuelwood crush
2017-04-23 14:14:00	52,38	48,09	101124	Fuelwood crush
2017-04-23 14:15:00	47,13	43,27	101124	Fuelwood crush
2017-04-23 14:16:00	41,9	39,37	101124	Fuelwood crush
2017-04-23 14:17:00	50,19	43,39	101124	Fuelwood crush
2017-04-23 14:18:00	52,37	45,6	101124	Fuelwood crush
2017-04-23 14:19:00	45,54	39,11	101124	Fuelwood crush
2017-04-23 14:20:00	49,5	43,83	101124	Fuelwood crush
2017-04-23 14:21:00	41,83	39,57	101124	Fuelwood crush
2017-04-23 14:29:00	48,66	47,82	101125	Fuelwood crush
2017-04-23 14:30:00	55,42	55,08	101125	Fuelwood crush
2017-04-23 14:31:00	57,41	53,84	101125	Fuelwood crush
2017-04-23 14:32:00	49,64	47,3	101125	Fuelwood crush

Stem wood crush (fuelwood) moisture measurement points compared to individual samples taken on corresponding times of the measurement. Measurements were conducted 23.4.2017 and figure is based on data from Appendix 2 table.



Appendix 3: Boiler energy balance calculation.

With good accuracy mechanical or equivalent power can be excluded and the system is assumed to be in a stationary state (Tynjälä, 2009). Based on that and on the Figure 55, equation a can be formed for energy balance.

$$\dot{\phi}_{\text{fuel}} + \dot{\phi}_{\text{air}} = \dot{\phi}_{\text{fluegas}} + \dot{\phi}_{\text{cooling}} + \dot{\phi}_{\text{losses}} \quad (\text{a})$$

where,

$\dot{\phi}_{\text{fuel}}$ is energy in fuel feed to the boiler

$\dot{\phi}_{\text{air}}$ all air flows to boiler combined

$\dot{\phi}_{\text{fluegas}}$ is the sensible heat in flue gases including water

$\dot{\phi}_{\text{cooling}}$ is the heat transferred to water

$\dot{\phi}_{\text{losses}}$ includes all losses and blowout

Water-steam side

Water-steam side consists of feed water that is preheated with flue gases in economizer prior to entering steam drum. The heat transferred to the water can be written as Eq. b.

$$\dot{\phi}_{\text{cooling}} = \dot{q}_m \cdot (h(p, T)_{\text{livesteam}} - h(p, T)_{\text{feedwater}}) \quad (\text{b})$$

where,

\dot{q}_m is the mass flow of water or steam

$h(p, T)_{\text{livesteam}}$ is enthalpy of livesteam

$h(p, T)_{\text{feedwater}}$ in enthalpy of feedwater

Blowdown is used to keep the boiler water clean of contaminants. The heat lost from power generation can be obtained from Eq. c. In calculation blowdown is included in losses.

$$\dot{\phi}_{\text{blowdown}} = \dot{q}_{m,\text{blowdown}} \cdot h(p, T)_{\text{blowdown}} \quad (\text{c})$$

Flue gas side

Flue gas side consists of feed air and flue gas flow. This is depicted in equations d and e.

$$\dot{Q}_{\text{air}} = \dot{q}_{\text{m,air}} \cdot h(p, T)_{\text{air}} \quad (\text{d})$$

$$\dot{Q}_{\text{fluegas}} = \dot{q}_{\text{v,fluegas}} \cdot h(p, T)_{\text{v,fluegas}} \quad (\text{e})$$