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Energy efficient storage of biomass at Vattenfall heat and power plants

Anders Eriksson

SLU, Institutionen för energi och teknik
Swedish University of Agricultural Sciences
Department of Energy and Technology

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SLU, Swedish University of Agricultural Sciences
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Anders Eriksson

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Supervisor: Raziyeh Khodayari, Vattenfall Research and Development
Assistant supervisor: Mattias Moëll, Vattenfall Research and Development
Assistant examiner: Raida Jirjis, Department of Energy and Technology, SLU
Examiner: Tord Johansson, Department of Energy and Technology, SLU
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Abstract

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Storage of biomass is often associated with problems such as heat development, dry matter losses and reduction of fuel quality. The rise in temperature can potentially cause a risk of self-ignition in the fuel storage. Moreover, emissions from storage piles can cause health problems in the surrounding. The dry matter losses and reduction of fuel quality can have economical effects. The aim of this thesis project is to develop guidelines on how to store large amount of biomass at Vattenfalls heat and power plants in an optimal way. Storage trials at Idbäckens CHP were done in order to study the effect of storage on fuel quality, dry matter losses and temperature development. Two storage trials were performed over six weeks with waste wood chips and stem wood chips stored in about 4.5 m high outdoor piles. A trial over four days in which waste wood chips was placed on a heated surface was evaluated. A study to test the possibility of using waste heat to dry waste wood chips was performed.

Small but not negligible dry matter losses were observed in both of the piles of stored material. The largest weekly losses were found during the first week of storage and a declining behavior could thereafter be seen. The accumulated losses during six weeks of storage were 2.0 % and 1.7 % respectively, for waste wood and stem wood. Storage during six weeks of waste wood and newly chipped stem wood did not cause any major deterioration of the fuel quality as such, beside the substance losses.

No drying effect could be seen in the heated surface trial. The surface became warm, about 50°C, but it was not sufficient to dry the chips. The conclusion is that it is not possible to dry large amount of chips on a heated surface with the design used here and during four days.

The overall conclusion is that in order to minimize the dry matter losses the material should be handled according to the LIFO (last in first out) principle. Whenever possible, try to purchase fuel that has been stored for a while since the more easily degraded compounds has already been degraded through microbial activity. There is a possibility that the largest losses has already occurred. Furthermore, try also to comminute the material (reduce the particle size) at the plant and as close in time to combustion as possible.

Sammanfattning

Med anledning av debatten kring den globala uppvärmningen har efterfrågan på förnybara bränslen, till exempel biobränslen, blivit allt större. Beträffande biobränslen i Sverige är efterfrågan störst under den kallaste delen av året medans produktionen sker året runt. Det uppstår således ett behov att lagra bränsle mellan säsonger och det behövs dessutom korttidslagring hos användaren då leveranser ”just in time” är omöjlig. Lagring av biomassa är dock ofta förknippat med problem såsom värmeutveckling, substansförluster, försämrad bränslekvalité och en potentiellt hälsovådlig närmiljö. Genom temperaturstegringen kan risken för brand i det lagrade materialet öka. Problemen uppkommer som en del i en kopplad kedja av olika processer där biologiska och kemiska nedbrytningsprocesser är av stor vikt.

Målet med det här examensarbetet är att utveckla riktlinjer för hur Vattenfall ska lagra biomassa på deras värme- och kraftvärmeverk på ett så energieffektivt sätt om möjligt. Fokus ska också ligga på att undvika bränder i lagrat bränsle samt att säkra en hälsosam arbetsmiljö på anläggningarna.

För att studera de processer som sker i lagrat material samt hur de påverkar bränslekvaliteten utfördes två olika lagringsförsök under vardera sex veckor med RT-flis (returträflis) och stamvedsflis på Vattenfalls anläggning Idbäcken i Nyköping. Ytterligare ett försök undersökte möjligheten till en energieffektivare användning av överskottsvärme genom ett försök till förtorkning av bränslet. En litteraturstudie över tidigare utförda lagringsförsök och teoretiska beskrivningar av förloppen som sker i lagrat biobränsle utfördes också.

Temperaturen i stacken med RT-flis var måttligt men den låg hela tiden betydligt över den rådande utomhustemperaturen i alla delar av flisstacken. Den högsta temperaturen som nåddes under lagringstiden var 30 °C. De ackumulerade substansförlusterna var störst under de första lagringsveckorna och nådde efter sex veckor 2,0 %. Någon slutsats angående förändring i bränslekvalitet var svår att påvisa då materialet var för inhomogent.

I stacken med stamvedsflis steg temperaturen till som mest 17 °C under lagringstiden. Även här var temperaturen i flisstacken under hela försöket över utomhustemperaturen. Något lägre substansförlusterna noterades i stacken med stamvedsflis jämför med RT-flis, men de uppvisade samma mönster med störst förluster de första lagringsveckorna. Efter sex veckors lagring hade 1,7 % torrsubstans försvunnit. En marginell höjning av askhalten under lagringstiden kunde noteras vilket kan förklaras av att biomassa bryts ned medans askan inte gör det. Värmevärdet och fukthalten visade även de endaste på marginella förändringar under lagringsperioden.

Sammanfattningsvis kan man utifrån försöken säga att korttidslagring av stamvedsflis och RT-flis, med liknande egenskaper och under liknande förutsättningar, inte resulterar i någon nämnvärd försämring i bränslekvalité förutom substansförlusterna. Vill man undvika stora substansförluster kan nyinkommet bränsle prioriteras vid eldning framför bränsle som lagrats längre på anläggningen eftersom det nyinkomna kan ha en högre nedbrytningstakt. Försök vidare att köpa bränsle som tidigare lagrats hos leverantören vilket gör att de mest lättnedbrytbara komponenterna redan kan vara nedbrutna. Då kan de största bränsleförlusterna redan ha inträffat och bränslet kan därigenom vara mer lättlagrat. Försök också att finfördela bränslet så sent i tid som möjligt eftersom nedbrytningsprocesserna ofta startar då material sönderdelas.

Effekten av substansförluster är att anläggningarna måste köpa mer bränsle. Det resulterar vidare i ekonomiska konsekvenser av i storleksordningen 14 000 till 25 000 SEK per vecka. Spannet mellan dem beror på olika bränslepris, mängd lagrat bränsle samt förlusttakt hos materialet. De ekonomiska förlusterna basers på förlusttakten från lagringsförsöken på anläggningen vilka genomfördes i mindre skala än det verkliga bränslelagret. Förlusterna skulle därför kunna vara ännu större flislager av den storleken som finns på anläggningen.

I försöket att effektivare använda överskottsvärme genom att förtorka bränslet byggdes en värmeyta där en stack av RT-flis lagrades. Försöket varade i fyra dagar och under den tiden kunde ingen nämnvärd skillnad i fukthalt observeras i den eller gentemot en likadan referensstack. Ytan blev förvisso varm och nådde som högst omkring 50 °C men temperaturstegringen upp i stacken var låg.

Resultaten beträffande bränslekvalitet (askhalt, fukthalt och värmevärde) för RT-flis är osäkra. Det beror till stor del på att RT-fliset var så inhomogent vilket gör det svårt att ta representativa prover, innan och efter lagring, av materialet för analys. Resultaten från lagringsförsöken är annars väl korrelerade med resultat från tidigare utförda studier. Dock måste stor försiktighet iakttas då extrapolering av data görs då många faktorer så som till exempel stackens storlek och form, egenskaper hos det lagrade materialet och omgivningsfaktorer tillsammans påverkar resultatet.

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1 Abbreviations

%DM – Percentage of dry matter weight
AC - Ash content
BFB - Bubbling fluid bed
CEC - Change in energy content
CFB Circulating fluid bed
CHP - Combine heat and power
DM - Dry matter
DML - Dry matter losses
DW – Dry weight
FIFO - First in first out
GW - Green weight
GWh – Giga watt hour – 10^9 Wh
LIFO – Last in first out
MC - Moisture content
MJ - Mega Joule
MWh – Mega Watt hour - 10^6 Wh
PEH - Polyethen with high density
SMHI - Swedish meteorological and hydrological institute
W_{gross} - Gross heating value, also calorific value
W_{net} - Net heating value, effective heating value

2 Introduction

2.1 Description of the problem

In response to global warming Vattenfall has put up a target of reducing their CO2 emissions from energy production by 50 % by 2030. Today Vattenfall is using biomass as input in their energy production. One possible way to reduce the CO2 emissions, and thereby reach the target, is to increase the share of bio based fuel.

Vattenfalls heat and power plants must store fuel at the plants. Storage of biomass is however often associated with problems such as heat development, dry matter losses and reduction of fuel quality. The rise in temperature can potentially cause a risk of self-ignition in the fuel storage. Moreover, emission from storage piles can cause health problems in the surrounding. The dry matter losses and reduction of fuel quality can have economical effects. The biomass could give less energy when combusted compared to the energy content at the time of purchase.

2.2 Aim

The aim of this thesis project is to develop guidelines on how to store large amount of biomass at Vattenfall heat and power plants in an optimal way. It should be done with a focus on minimizing the dry matter losses and thereby the energy losses as well. The guidelines should also deal with potential self-ignition and health impacts from emissions during storage.

2.3 Boundaries

The trials were limited to study only wood chip in outdoor piles. Two different kinds of field trials were performed at Idbäckens combined heat and power CHP-plant, in Nyköping, Sweden but the result can be applied to other plants as well. The fuel quality changes is limited to only considering processes at the plant.

3 Background and theory

3.1 Biofuels and its use

There is a number of different bio based fuels and they have different characteristics and origins. One common thing about them is that they originally come from organic and biological material. The driving force is the sun through the photosynthesis. Biofuels based on origin can according to Ringman (1996) for examples be divided into peat, reed, straw, wood fuel, recycled paper, phalaris arundinacea and black liquor. Wood fuel can further be divided into fuel from short rotation forestry, forest fuel and recycled wood fuel (Ringman, 1996).

Forest fuels can then furthermore be divided into more sub sections with various raw materials as input. It could be logging residues, wood with non industrial application, by-products and waste from the industry (Ringman, 1996).

Recycled wood has also different types of raw material. For example packing, recycled building material, mould wood, wastage from construction and reconstruction work (Ringman, 1996).

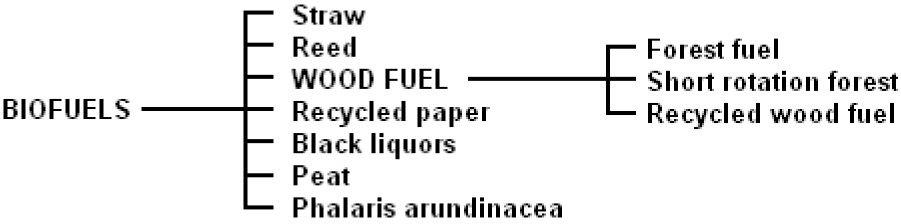

Figure 3.1, Biofuels and subcategories (Ringman, 1996).

The biofuel is generally used in the forest industry, heating plants, for electricity production, and heating of housing. It is also used by the transport sector to some extent. The bio based supply in the Swedish energy system has been doubled in the last 25 years. The total bio energy supply in 2009 was 127 TWh. The industry used 51 TWh. The housing and service sector used 13 TWh and the transport sector used 4.6 TWh. In 2008 39.4 TWh was used to district heating and 13.3 TWh for electricity production (Anon, 2010).

In 2009, Vattenfall Heat Sweden produced 4 055 GWh heat and 312 GWh electricity in their larger heat and power plants in Visby, Vänersborg, Motala, Nyköping, Drefviken, Uppsala, Ludvika, Kalix, Haparanda, Överkalix and Övertårneå. They used

71 % renewable fuels in their production and 46 % of them where pure biofuels. Totally, that implies a quite large amount of biofuels being handled each year. Figure 3.2 shows the fuel mix in the Vattenfall heat and power plants in Sweden 2009 (Vattenfalls homepage A, 2010).

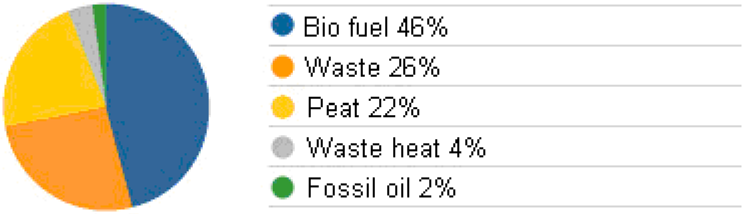

Figure 3.2, Vattenfall heat Sweden's fuel mix 2009 for their heat and power production (Vattenfall A, 2010).

3.2 Properties of biomass

All woody biomasses roughly have about the same major components but in different proportions. However, there are some differences between fuels mainly related to age of the tree and which part of the tree that is studied. The main component in all woody biomass is carbohydrates (cellulose and hemicelluloses) and lignin. Besides these components the material also contains extractives. A cellulose molecule is made up by about 10 000 glucose units. The hemicellulose has besides the glucose also other sugar units such as xylose, galactose, mannose and arabinose. The lignin is made up by many phenolpropane units and gives the material its mechanical strength due to its gluing effect to the cellulose. The extractives include among others terpene, phenol and different types of fats. The cellulose represents about 40 % of the dry weight, hemicellulose about 30 %, lignin about 20-30 % and the extractives 2-4 %. The distribution of these components varies between different tree species and also within the tree. The heating value also varies between these components. Cellulose for example has an energy content around 17-18 MJ/kg DM, hemicellulose around 16-17 MJ/kg DM, lignin around 25-26 MJ/kg DM and the extractives around 33-38 MJ/kg DM (Strömberg, 2005).

All woody material consists of water, burnable substance and ash. Basically dry material has about 52 % carbon, about 42 % oxygen, 6 % hydrogen and a few percent of minerals such as calcium, potassium, magnesium and silicon, as can be seen in figure 3.3.

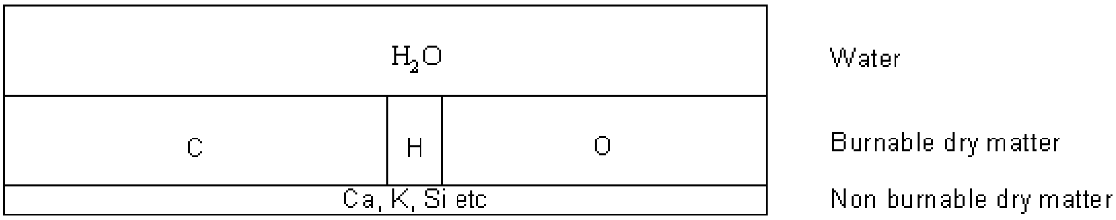

Figure 3.3, Biomass composition (Bioenergihandboken 2010).

3.3 Fuel quality

The main purpose of burning biomass is often to generate heat and sometimes also electric power. Therefore the amount of energy that can be produced per unit fuel is interesting but the environmental impacts when combusting are also relevant. Basically, the fuels carbon, hydrogen and oxygen are reacting with the oxygen in the air and thereby forming carbon dioxide and water. The bound energy in the cellulose, hemicellulose, lignin and extractives is thereby released in an exothermal reaction (Strömberg, 2005).

There are both controllable and non controllable factors concerning the fuel quality. As uncontrollable parameters dry density, chemical composition, calorimetric heating value and natural ash content of the fuels can be mentioned. There are also factors that can be affected during the handling and storing. Moisture content, net heating value, distribution of fines, microbial activity and impurities are example of controllable parameters (Lehtikangas, 1998).

The heating value is all chemical energy that is bound in the material and is thereby determined by its chemical composition. There are two ways of express heating values, calorific or gross heating value and net or effective heating value. The calorific heating value is the amount of energy liberated during complete combustion in an oxygen filled bomb calorimeter where all vapor condensates to water at a certain temperature. The net heating value is the amount of energy generated without condensation of the vapor. The value is calculated from the calorific value but the energy to vaporize the water is subtracted (Hakkila, 1989).

The moisture content is the ratio of water content in relation to the total weight. It affects indirectly the dry matter losses through microbial activity which could also create health problems and potential self-ignition. The moisture content is also the major parameter that affects the net heating value, as can be seen in figure 3.4. Much energy is consumed during the vaporization of water. Some of that could be regained if there is “flue gas condensation” at the plant. Usually dry fuel is preferable, but the optimum varies depending on the furnaces. The moisture content in stored comminuted wood fuel is affected by weather conditions, particle size and storage method. High moisture content fuel can create problems with freezing in the material which causes feeding and handling problems (Strömberg, 2005).

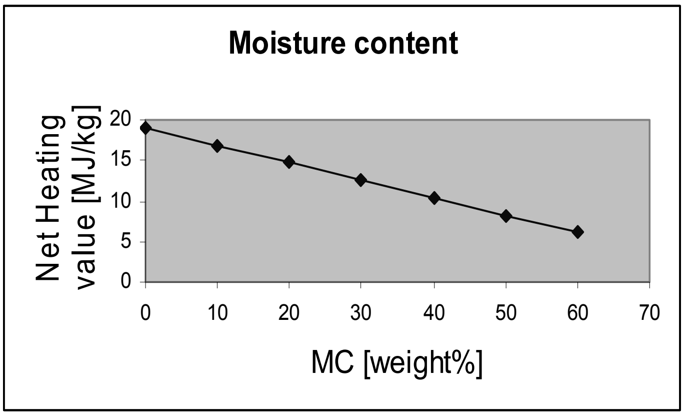

Figure 3.4, Net heating value [MJ/kg wet wt.] as a function of moisture content for biomass (Hakkila, 1989).

The ash content is usually expressed in relation to total dry mass. The ash is from an energy point of view unwanted material since it is incombustible. High ash content reduces the heating value since it does not contribute to any heat production. The ash can moreover contribute to higher cost for transport, handling, landfilling, sintering problems and more mechanical wear in transport mechanism and grates. Fine fractions of wood chips often have a higher ash content (Stridsberg, 1983). There are two types of ash; a natural ash content derived from the minerals that the tree has incorporated during its lifetime and ash that is derived from impurities during for example handling. The natural ash content varies between different tree species and parts but it is usually around 0.5 % for stem wood and up to five % for needles and leaves (Jirjis and Thelander, 1990). The ash content can sometimes be very high due to improper handling. For example can stones and sand from the storage yard, dust from the roads and minerals from the logging area contribute to higher ash content. Some fuels such as waste wood can above that have a large amount of impurities not related to handling (Thörnqvist, 1984).

The comminuting processes such as chipping and crushing result in particles with varying sizes. A large amount of small particles or fines in a material can cause problems in the fuel feeding process and can affect fuel quality (Jirjis, 2005a).

3.4 Storage of biomass

The production of biomass takes place all over the year. The main demand for biofuel in Sweden is, however, mostly concentrated in the cold winter season. It thereby creates a demand for long term storage of biofuels (Bjorheden et al., 2002).

There is also a need for short term storage of biomass at site. Since a heating plant handles large quantities of fuel, delivery just in time is almost impossible. The plant need to have a buffer storage of fuel at site in order to be less vulnerable for fluctuations and delays in the delivery chain. The heat demand also fluctuates which creates a need for a fuel buffer to secure the heat production at all times (Thörnqvist and Jirjis, 1990; Jirjis, 2003).

The fuel can be stored at the heating plant in many different ways depending on the type of fuel and the local conditions. They could be stored uncomminuted or comminuted. They can be stored outdoors or inside in barns, silos or container (Jirjis, 2009).

Wood powder and pellets can be stored in silos. Peat can be stored in containers. Large scale wood chip storage is in almost all cases stored outdoors in piles. There are other storages methods such as in piles under roofs or tarpaulins or in barns. These methods are for technical and economical reasons not used for large quantities (Jirjis, 2009).

3.5 Storage related problems

There are a number of problems related to storage of wood chips in piles. Fuel quality, risk of self-ignition and health issues are some of these problems.

It is a well known fact that when organic matters are stored in piles a heat can develop. The heat development inside the storage can be explained by biological, physical and chemical processes. Wood chips are organic matter and thereby affected by these processes (Jirjis and Thelander, 1990; Thörnqvist, 1985a).

The heat generation processes are respiration of living tree cells, metabolism of microorganism, chemical oxidation and pyrolysis. Presence of water also influences the heat generation through moisture adsorption and hydrolyses processes (Blomqvist and Persson, 2003).

Schloesinger and Lauper, cited by Thörnqvist (1985b), came up with early ideas and explanations of the phenomenon. Schloesinger already in 1884 has reported that it is the chemical and microbial oxidation processes that cause heat development in piles of organic matters. Laupper (1927) developed the theory and came up with the idea that it is living parenchyma cells that initiates the process before the oxidation processes starts. Others e.g. Assarsson (1969) and Springer et al. (1971), cited by Thörnqvist (1987), reference to the respiration of living parenchyma cells as a starter for the heat development. The process starts when the material is chipped. The reason is that the parenchyma cells have buffer storage of nutrients in form of starch and fat that is being released during the comminution. These nutrients are degraded and water and carbon dioxide is thereby produced. The oxygen concentration inside the wood is too low when stored in uncomminuted form and there will be no respiration process by the cells. The heat development can also get started just before the storage phase is initiated by the comminution of the material. It is then pure mechanical friction that starts the heating of the wood chips. Allen (1968) and Niggemann (1969), cited by Thörnqvist (1987), also brought up an alternative heating mechanism. They claimed that the phenomenon also could relate to the moisture equalization inside the storage.

When the temperature starts to rise new processes are initiated. The biological processes that is of interest is both bacteria and fungi development. The parameter that generally set the limits to the biological processes is the access to oxygen, nutrients, heat and the moisture content. Many bacteria can however develop and grow without oxygen. Also pH-value is affecting the microbial growth (Jirjis, 2009).

If the environment is right, bacteria and fungi start to degrade the fuel. They basically consume the fuel and produce heat, carbon dioxide and water. The heat can be accumulated if the pile is large or compacted. Most of the heat is produced in the center of the pile where the cooling from the outside is lowest. Heat is transported mainly from the inner to the cooler outer parts where the saturated hot air will condensate. This will cause moisture redistribution where the inner parts are drier and a wetter layer near the outside of the pile is formed. The microbial processes can take place at temperatures up to about 60 °C but rapidly decline at higher temperature (Lehtikangas, 1998).

The most important fungi are mold fungi, wood-decaying fungi and blue stain fungi. Basically, they consume the organic matter and oxygen through aerobic degradation and thereby decompose the fuel and cause a buildup of heat, water and carbon dioxide. Wood-decaying fungi are of most importance in the degrading process and thereby a major factor behind dry matter losses. The fungi degrade preferably cellulose and hemi cellulose but in some extent also lignin. The other fungi such as molds are more important in a health perspective. The optimal temperature range for fungal growth varies between species but in general, temperatures around 20 to 40 °C are acceptable. They can however survive temperatures down to a couple of degrees below freezing and up to about 50 °C. The access of nitrogen can be a limiting factor for some fungi especially if there is low content of green parts. Wood-decaying fungi can however get its carbohydrate from the wood itself through degradation of mainly cellulose and hemicellulose. Wood-decaying and stain fungi needs access to free water and can thereby not develop at moisture contents below the fiber saturation point, which is approximately at 23 %. Mold fungi can tolerate almost all moisture contents (Henningsson, et al., 1989; Randall).

The bacteria development also causes dry matter losses since they can degrade cellulose but they are of most interest in a working environment and health perspective. The ones of most interest concerning storage of wood chips are actinomycetes. Bacteria can tolerate a wider temperature range than the fungi. Some of them can tolerate temperatures up to 75 °C but the variation between species is large (Schmidt, 2006).

The chemical processes slowly takes over as the dominating heat producing mechanism starting with temperature above 40 °C and at a temperature of 50 °C it is the most important one. All organic matters do to some extent react with oxygen in the air in an exothermal reaction. The specific surface area is important for that reaction (Blomqvist and Persson, 2003).

A potential spontaneous ignition process can be explained in several steps. First the biological activity raises the temperature to levels where the chemical oxidation can take over. If the heat dissipation is low a rapid increase in temperature can occur. This thermal runaway can initiate self-sustaining pyrolysis. If the pyrolysis front reaches the exterior of the pile a flaming combustion can occur (Blomqvist and Persson, 2003).

However, if the material is stored in an uncomminuted form it usually does not develop any heat. This can be explained by the fact that the friction heat is not added to the material, the specific area for the microbes to attack is much smaller and that the parenchyma cells has to little oxygen for their respiration (Thörnqvist, 1987).

Fuel quality issues

The heating value expressed in MJ/kg, can be higher after storage since microbial organism consumes primarily low energy components such as cellulose and hemicellulose. The percentage of more high energy carriers such as lignin and extractives becomes thereby larger. However the total amount of stored material has less energy due to dry matter losses. This has mainly economical effect to the company, which buys fuel with a specific energy and a certain weight and gets, after storage, a lower net energy content (Schmidt, 2006).

The ash content often becomes relatively higher after storage due to the dry matter losses. It is a logical result since the inorganic ash does not decompose but some of the fuel does. Ash content can also increase due to non proper handling of the fuel during storage (Thörnqvist, 1985a).

The heat development can also have positive consequences for the fuel quality. Heat causes a drying in the centre while moist is migrating to the outer parts. If the condition is right there could be a lower moisture content in the fuel and thereby a higher net heating value. This is of great importance if the plants don't have flue gas condensation since moisture content affecting the net heating value to a great extent. The heat can also create a moisture content fluctuation in different parts of the pile with a dry centre and a wetter outer part. From a combustion technical point of view those variations are unfavourable and can moreover, create a frozen outer layer in winter time. That phenomenon is described in figure 3.5 and is called the chimney effect (Hogland and Marques, 1999).

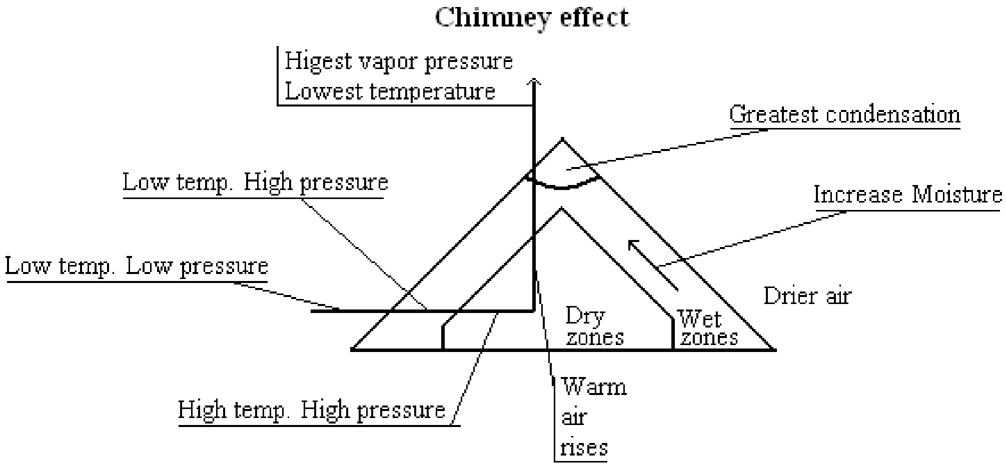

Figure 3.5, The chimney effect in a wood chips pile, modified from McGowan 2009.

Health and safety

The growth of microorganisms in a pile of wood chips can create health problem locally. The microfungi are a major cause of these health hazards. Examples of concentrations of about 10^{12} spore/kg dry weight of chipped logging residues has been found in previous studies (Jirjis, 1989). A common concentration in normal outside air is around 10^1 to 10^3 per m^3 air. The problems often arise when the spores become airborne during fuel handling. Some measurements indicate a 100 to 1000 time's higher concentration in air next to the fuel feeding inlet. Dry material more easily becomes airborne and thereby a larger potential sources of allergenic reactions due to a larger mobility (Lehtikangas, 1998). Lung diseases such as farmer's lung and wood trimmer's disease can be initiated by inhaling air in contact with infected wood chips. The correct name of both the diseases is allergic alveolit and is cause by airborne fungal particles such as spores and hyphae (Thörnqvist and Lundstöm, 1983).

Organic dust or bio-aerosols can cause a variety of diseases and at a biofuel plant it is mainly respiration associated ones that matters. Examples of them are asthma, chronic obstructive pulmonary diseases, hypersensitivity pneumonitis and organic dust toxic syndrome (Nordic innovation centre, 2008).

Allergic alveolit (type III-allergy) is a hypersensitivity reaction in the lungs with is caused by inhalation of fungi or actinomycetes spores. It is also known as extrinsic allergic alveolit or hypersensitivity pneumonits (Sköld, 2010). There are an acute, sub acute and a chronic form of the disease. The symptoms are shivering, high temperature, headache and muscle pain that occur a couple of hours after exposure. Most people infected by the acute form are recovered in a couple of days but can be sick when exposed again (Thörnqvist and Lundstöm, 1983). The sub acute or the chronic form takes more time to be both infected and recovered from. A regular expose of 15 to 30 minutes a day can be enough to develop these forms. Protective masks can help to avoid the problem (Lehtikangas, 1998).

The numbers of spores that become airborne depends on a number of factors including:

- The amount of spores in the material and the material handling
- The moisture content in the material. A dry fuel will cause more airborne spores
- The weather since a dry sunny day will release more spores and make them airborne for longer times compared to a rainy day

The bark and needles contains terpenes and isoprenes which are volatile hydrocarbons. These can cause irritation to skin, tissues and mucosa. However, this is a rare health hazard when handling stored wood chips outdoors (Lehtikangas, 1998).

It is important to minimize the microbial growth in order to minimize the health hazards by for example:

- Practice fuel storage systems according to FIFO, first in first out, instead of LIFO, last in first out.
- Try to store material as short time as possible at the plant

Another important thing to do is to always wear protective masks when exposed to infected material. It is important for the machine drivers to be careful when being outside the machine. A protective mask is recommended when handling infected fuel outside the wheel loader (Nordic innovation centre, 2008). The rules of the use of masks are described by the national working environment authority.

Risk for self ignition

The microbial activity can raise the temperature to about 60°C. A chain of chemical reactions can then further accelerates the temperature development and potentially cause a spontaneous combustion or self ignition (Jirjis, 1995). The self ignition process is a balance between the heat production and the heat dissipation (Nordic innovation centre, 2008). The exact temperature for a self ignition does not exist and it is affected by the type of material, access to oxygen and impacts from catalysts. The self ignition requires a certain oxygen level (Thörnqvist, 1985a).

A common thing about many self ignited piles is that they are quite heterogeneous concerning material, moisture content and the degree of compacting. They have often been built up under a couple of month (Bjorheden et al., 2002). The fire often starts in the areas between different fuel sorts or areas with different degrees of compacting (Thörnqvist, 1987).

The main reason for the ignition is that the material has different permeability. Heat can be accumulated in more compacted regions inside. Heat then slowly transfers to the outer parts and eventually at some occasion reaches a less compact part where the oxygen concentration is higher and self ignition can potentially occur (Hogland and Marques, 1999).

Recommended actions after an ignition (Lehtikangas, 1998):

- Try to cut out the area outside the ignition place and separate it from the rest of the fuel
- Be careful when ventilate or dig in the fire area, with for example a wheel loader, since it also introduce more oxygen
- Water can prevent firing at surface

How to overcome storage related problems

There are solutions to the problems discussed above but the implementation of those deals with economical, environmental and technical issues. The solutions mainly aim for a reduction of one or more of the growth requirements that the microbes have e.g. oxygen, heat, nutrients, moisture and pH-value. This could mean no or limited microbial activity will take place. That implies that no heat development will take place which further more implies that problem such as dry matter losses, a non-healthy working environment and potential self-ignition will be controllable (Thörnqvist, 1985b).

Most of the biological activity can be stopped if the oxygen is removed or kept at very low concentrations since most of the activities are aerobic ones. But it is hard to reach that low concentrations since many microorganisms needs only a few percent of oxygen. To some extent air and thereby oxygen can be removed by compacting the pile, but it is difficult to reduce the oxygen level sufficient to prevent microbial activity. The compaction is therefore often a bad idée since it also prevent the air circulation and thereby the cooling. One way is to store the material in an inert gas, for example nitrogen. One problem is that it requires a closed storage and in the case of large outdoor piles it could be complicated (Thörnqvist, 1985b).

The access of nutrients in the stored material affects the microbial development. Green parts in the storage such as needles and leaves acts as an easy nutrient supply. A good practice is to make sure that most of these parts have fallen out during previous storage in uncomminuted from (Thörnqvist, 1985b).

The development and accumulation of heat in the stack is of high importance. If it can be prohibited some of the problems, for example self-ignition, can be avoided. The heat conducting ability of the stack is interesting and it is affected by degree of compacting, particle size, moisture content and raw density. An unpacked stack with low raw density, low moisture content and with large particle size can more easily be ventilated and thereby continuously cooled down (Thörnqvist, 1985b). Small particle sizes implies large specific area were the microbes can attack (Wihersaari, 2005). The pile size is also important in this discussion and especially the pile height since a small pile more easily can be ventilated and cooled by the surrounding. The relative surface area in relation to stored volume is higher. The size and height also impact the degree of compacting (Thörnqvist, 1985b).

Some metals can act as catalysts to the heat development processes (Thörnqvist, 1987). Some of the problems could be avoided by removing them, if possible. If the pH-value in the pile is at a level where no microbial activity can take place there will be no heat development. A very low pH-value can be achieved chemically (Thörnqvist, 1985b). Another way to prevent the microbes to attack the material is to use some kind of fungicides such as Cuzul or Mitrol 48 (Thörnqvist, 1983; Thörnqvist, 1987). When dealing with chemicals, environmental and legislative issues must be considered (Springer, 1979).

The microbial activity will be low or absent if the moisture content is below the fiber saturation point which is about 23 %. That further more implies no or limited dry matter losses. An alternative way of eliminating the microbial activity is to raise the moisture content to above 70 % but that is no good solution from a fuel quality perspective (Thörnqvist, 1985b).

3.6 Drying of wood chips

Drying of fuel using waste heat is interesting due to the rise of fuel and electricity prices. That is encouraging a larger electricity exchange in the production and also a more economic use of the fuel (Berntsson, et al., 2010).

There are different reasons for drying the wood chips by using waste heat. If there is a heat surplus a drying process could act as a heat sink when the electricity production is profitable but the heat demand is low (Berntsson, et al., 2010). A dry fuel will reduce the risk of fungi attack during storage and thereby the risk of large dry matter losses as well. A dry fuel will furthermore reduce the risk of freezing in the material and also facilitate the fuel transport, both internal and external (Kipping and Schneider, 1988). Drying of fuel can give a more even moisture content and thereby a more steady heat output and a potential higher combustion efficiency (Kipping and Schneider, 1988; Suurs, 2002) A dry fuel will also have a higher net heating value which is of large importance for plants without a flue gas condenser (Johansson et al., 2004).

Water in wood can exist in both free and bound form. The free water is in the inner lumen and the bound or hygroscopic water in the cell walls. Water can also be produced by the microbial activity during the degradation of the material. Water occurs as vapor in the moisture migration process which takes place in stored chip piles. The point where no free water is left in the wood, but maximum bound water is retained is called fiber saturation point and usually occurs at around 20 to 25 % moisture content (Thörnqvist, 1982).

Wood chips can be dried passively by the ambient air or through microbial activity and chemical oxidation processes. The drying with ambient air depends on the moisture content of the chips and its surface area, the air movements, the relative humidity and the temperature (Gustafsson, 1988). There are some risks with passive drying by microbial activity such as dry matter losses during drying, an unhealthy working environment and potential risk of self ignition (Lehtikangas, 1998).

An alternative to the passive drying mentioned above is to dry the chips in a more active way by adding external energy. The microbial activity can be stopped and thereby the problems concerning health, self ignition and dry matter losses. However drying is probably the separation process that consumes the most energy, due to mainly the high enthalpy of vaporization needed. Economy is an important factor concerning drying of wood chips. (Wimmerstedt, 1999)

The mechanism of drying is the same independently of the method used. The drying is a function of different transport mechanism in the pile. Generally there are three types of heat transfer mechanism: Conduction, convection and radiation. The total heat transfer is often a combination of the three. Convection and conduction is dominant in the case of heat transfer in a pile of wood chips. If there is a temperature difference there will be a heat flow from the high to the low temperature as long there are a difference. Heat transport trough conduction occurs mainly in solid material when high energy particle gives kinetic energy to particles nearby. However, heat transport can also occur in fluent and gaseous medium. Heat transport by convection is always a process in fluids where warm particles rise due to lower density and creates a heat flow (Alvarez, 2006).

The heat development and transport in stored chip pile is coupled to other mechanisms such as oxygen and water transport. When the temperature rises within the pile, gas flow will occur due to free convection. The gas diffusion and the mixture of gases, both occur in the pores within the chips and in the ones between them (Erntsson and Rasmuson, 1993).

This water vapor diffusion will help to transport heat and in the same time blocking the oxygen transport. Water in gas phase has the ability to carry a large amount of heat. The heat and moisture can be moved and released through condensation in colder parts or to the surroundings (Erntsson and Rasmuson, 1993).

There can be only a little drying in a pile if the air flow through it is small. The outer layer can, as mentioned earlier, passively dry by the diffusion process. The moisture content of chips at hygroscopic equilibrium with the surrounding air is a function of relative humidity and temperature (Gustafsson, 1988). The inner part can dry if there is microbial activity inside. However, the only known reliable way to dry wood chips is to surround all drying chips with moving unsaturated air (Kipping and Schneider, 1988). Drying today is often done by moving air, hot air, smoke gases or water vapor in drum dryers, cascade dryers, band dryers, steam dryer or smoke gas dryers (Wimmerstedt and Linde, 1998).

As unsaturated air moves through the pile it will reduce the sensible heat and pick up moisture from particles until it is fully saturated. A drying front with particles in equilibrium with the incoming air will be formed due to this process. This front will over time be moving in the same direction as the air flow. The pile and the material will be in equilibrium with the incoming drying air when the entire drying front has passed through (Kipping and Schneider, 1988).

3.7 Results from other storage trials

The phenomenon of biological, chemical and physical processes in organic material is well known, and had been so for many years. Therefore similar experiments, as in this thesis, have been carried out earlier. Some of the relevant results for this thesis aim are listed below. The result from the trials deals with unventilated outdoor storage of wood chips in piles.

However, scaling and transformations of results from different trials can not be done uncritically. There are studies with different dry matter losses despite the same temperature. Microbial activity and chemical decomposition can probably alternately interact and counteract (Thörnqvist, 1985a). For example, when storing whole-tree chips in piles, Bergman and Nilsson (1979) presented material losses in the region of 1-2 % per month. Gislerud (1974 and 1978) and Gislerud and Grönlien (1978) presented however losses up to 4.8 % per month for the same material.

Large scale storage of chips

A study dealing with storage of chipped clear-cut residues in unventilated outdoor piles has been carried out in Sweden in 1990. The chips were from felling areas with at least 70 % spruce. The pile dimensions were 90 m long, 14 m wide and seven m high and it reached a maximum temperature of 75°C. One aim of the studies was to investigate whether the fuel storage should be handled as a first in first out (FIFO) or last in last out (LIFO) process. The result shows that the dry matter losses were largest in the first week and then declining during storage as the total energy content did. This indicates that this type of material and in this storage method should be handled as LIFO in order to decrease the total energy and dry matter losses. The result also shows that the initial moisture content is important for the dry matter losses. The material used to build sections stored for 4, 5, 6 and seven month had a high initial moisture content and the dry matter losses are also larger than previous ones. However, show the same decline over time behaviour was evident *(*Thörnqvist and Jirjis, 1990*)*.

Table 3.1, *A summary of the results from a wood chip (5300m^3) storage trial. Su - Summer, Au - Autumn, Wi - winter, MC – moisture content, Δ MC - change in moisture content during storage, DML – dry matter loss, Max Temp – The maximum temperature registered, (Thörnqvist and Jirjis , 1990)*

Material	Season	Time [month]	Initial MC [%]	Δ MC [+ - %]	DML [%]	DML [%/month]
Wood chip	Su	0.25	38.8	-0.4	3.6	14.4
Wood chip	Su	0.5	42.9	- 3.5	4.5	9.0
Wood chip	Su	0.75	40.3	- 7.8	5.2	6.9
Wood chip	Su	1	32.8	- 2.9	3.6	3.6
Wood chip	Su	1.5	38.8	- 8.2	6.0	4.0
Wood chip	Su	2	35.7	- 3.7	5.6	2.8
Wood chip	Su	2.5	40.1	- 5.9	5.9	2.4
Wood chip	Su	3	38.2	-10.5	4.6	1.5
Wood chip	Su/Au	4	49.7	- 12.4	11.8	3.0
Wood chip	Su/Au	5	50.6	- 12.1	12.2	2.4
Wood chip	Su/Au	6	45.9	- 11.4	11.9	2.0
Wood chip	Su/Au/Wi	7	48.8	- 8.7	11.3	1.6

Small scale storage of wood chips

This study includes storage of comminuted birch in small piles, 15 m long, eight m wide and three m high, and was performed in Norway. The maximum temperature reached was 35 °C and 45 °C respectively for the piles with large and small chip. Two types of wood chip sizes were tested. The dry matter losses were in the same region for the two different sizes. There was however a significant difference between the two materials at a 95 % level after six months (Gjölsjö, 1994).

Table 3.2, *A summary of the results from a wood chip (400m^3) storage trial. Su - Summer, Au - Autumn, Wi - winter, MC – moisture content, Δ MC - change in moisture content during storage, DML – dry matter loss, Max Temp – The maximum temperature registered (*Gjölsjö, 1994*).*

Material	Season	Time [month]	Initial MC [%]	Δ MC [+ - %]	DML [%]	DML [%/month]
Large Chip	Su	1.8	39.9	- 4	2.6	1.4
Large Chip	Su/Au	4.0	39.9	- 3	8.5	2.1
Large Chip	Su/Au/Wi	6.0	39.9	- 10	8.7	1.5
Small Chips	Su	1.8	41.5	- 9	2.3	1.3
Small Chips	Su/Au	4.0	41.5	- 11	7.5	1.9
Small Chips	Su/Au/Wi	6.0	41.5	- 10	7.5	1.3

Winter storage of chips

This trial was carried out in the northern part of Sweden and investigated the storage of saw mill chips. The storage pile was 12 m long and six m high. The maximum reached temperature during storage was 10 °C. Marginal changes in average moisture content were noticed during storage. There were however a redistribution of moisture inside the pile where the top parts become wetter. The dry matter losses varied considerably between different sampling points. However, the trend of larger losses at the beginning of the storage period is still evident (*Jirjis and Lehtikangas, 1998*).

Table 3.3, *A summary of the results from a wood chips storage study. Su - Summer, Au - Autumn, Wi - winter, MC – moisture content, Δ MC - change in moisture content during storage, DML – dry matter loss, Max Temp – The maximum temperature registered, (Jirjis, and Lehtikangas.1998).*

Material	Season	Time [month]	Initial MC [%]	Δ MC [+ - %]	DML [%]	DML [%/month]
Wood chip	Wi	1	26	none	1.8	1.8
Wood chip	Wi	2	27	none	0.5	0.3
Wood chip	Wi-Sp	8	24	+ 3	2.0	0.2

Chips and chunks

Another study dealing with small scale storage of chunks and chips was reported. There were significant differences between the two assortments after storage. The chunks were less wet and had less dry matter and energy losses after storage compared to chips. This can be explained by the larger pieces with less exposed area in the chunk wood. The maximum temperature reached inside the piles were about 35 °C for both chunks and chip *(Mitchel, et al., 1987).*

Table 3.4, *A summary of the results from a wood chips and chunks storage study. Wi - winter, Sp – Spring, MC – moisture content, Δ MC - change in moisture content during storage, DML – dry matter loss, Max Temp – The maximum temperature registered, (Mitchel, et al., 1987)*

Material	Season	Time [month]	Initial MC [%]	Δ MC [+ - %]	DML [%]	DML [%/month]
Wood chips	Au/Wi	6	45	+ 14	23.0	3.8
Chunks	Au/Wi	6	44	+ 8.5	10.0	1.7

3.8 General storage recommendations

Based on knowledge from previous research there are some general storage recommendations to be aware of. These recommendations are valid for wood chip storage in unventilated outdoor piles.

The developed heat during storage can have positive effects due to the lower moisture content obtained. However, it also results in dry matter losses. How to get balance between these factors is a difficult task. It is theoretically possible to dry the fuel passively without significant losses if the temperature is above 55-60°C. Both the microbial activity and the chemical oxidation are low in that region. However, it is almost impossible to be in that temperature zone over time. Some parts of the pile will have losses. It is in the overall perspective often good to minimize the microbial activity (Lehtikangas, 1998).

In order to minimize the dry matter losses, it is preferable to store as dry material as possible (Thörnqvist, 1983). A seasoned stored material will often has less matter losses compared to fresh material (Bjorheden, et al., 2002). Concerning the dry matter losses, to be on the safe side, the moisture content should be below 20%. It can from a furnace efficiency perspective be good with some moisture in the fuel. That extra moisture can be achieved by mixing in more moist fuel before burning it. It is good to store different sorts of material and material with different moisture content separately. Heating and thereby microbial activity can start by heat migration and equalization processes inside the pile (Thörnqvist, 1987).

Many studies show that the rate of dry matter losses is larger in the first weeks and then decaying during storage (Thörnqvist and Jirjis, 1990; Jirjis and Lehtikangas, 1998; McGowan, et al., 2009). Therefore, it could be advantageous could be a good idea to consider storage according to last in first out (LIFO) principle due to that fact. You could in that case always avoid the first larger losses. The loss rate is often smaller if the material has been stored for a while and thereby more appropriate in an energy perspective to store than newer and fresher material. Even if the material has been stored at other locations before arriving to the plant it could however be efficient to practice the LIFO strategy. When the material arrives to the plant and is stacked new oxygen is introduced to the pile which might start the microbial activity and a new loss-cycle (Wihersaari, 2005).

It is also more energy efficient to store uncomminuted material than comminuted ones. It could be a good idea to try to comminute the material as late as possible in order to minimize the dry matter losses (Wihersaari, 2005).

If possible avoid metal pieces inside the piles since it can act as a catalyst to the self ignition process (Lehtikangas, 1998). Concerning waste wood, it is however difficult to avoid metal pieces inside since the fuel often has those impurities.

Try to build the piles in elongated strings with a width of double the height. When enlarging the pile try to make it longer and not wider and higher. In that way you can maximize the cooling effect from the surroundings (Lehtikangas, 1998). Larger piles often have larger losses (Bjorheden, et al., 2002).

4 Overview of the project

Both a literature survey over present knowledge and new storage trials at Vattenfall heat and power plant in Nyköping were done in order to develop guidelines in how to store biomass in an optimal way. Storage trial using different fuels in unventilated outdoor piles during six weeks should give a description of the processes inside a pile and the changes in fuel quality during storage. Both chips from waste wood and stem wood were studied.

A second trial was also done. Its aim was to investigate the feasibility to pre-dry or de-ice the fuel on a ground heated surface fed with district heating water. The change in moisture content is of primary interest. A ground heating surface could act as a heat sink when there is a heat surplus and thereby be beneficial for the fuel as well as the heating plant.

5 Material and method

5.1 Description of the site

The location of the storage trial was at Vattenfalls facility Idbäcken which is a combined heat and power plant (CHP) in Nyköping, Sweden. As fuel supply mostly wood chips is used and most of it is from waste wood. The installed capacity for the base load bubbling fluidised bed furnace is 60 MW heat and 35 MW electricity. The plant has also two boilers with circulating fluidised bed each with a capacity of 30 MW heat. Additionally they have flue gas condensation up to 15 MW. The spare capacity for backup and top load is five oil burners with a total capacity of 60 MW heat and one electric furnace of 12 MW heat (Vattenfalls B; Vattenfall C).

The fuel yard has a maximum capacity of 35 000 m^3 of fuel. The amount of stored fuel varies greatly, from almost noting up to the maximum capacity. A full storage of fuel will last for approximate 350 hours or two weeks during the heating season. It means that about 100 m^3 is used every hour. A procedure of fuel deliveries all day is necessary in order to maintain the stored fuel volume. The main fuel stored is wood chips from waste wood but other fuels are also stored such as stem wood chips and forest residues (Nordqvist, 2011).

5.2 Material

The study deals with two different types of biomasses. Both wood chips from recycled waste wood and from whole trees where included in the trials. Waste wood is the ordinary fuel at Idbäcken heat and power plant. Wood chips from whole trees or stem wood are also used in the plant. There are thereby two interesting fuels to study in the storage trials. Chips from imported stem wood could be an interesting fuel type for Vattenfall in the future.

Figure 5.1, The left picture: Waste wood chips for the six weeks storage trial. The middle picture: Stem wood chips for the six weeks storage trial. The right picture: Waste wood chips for the four days storage on ground heating surface trial.

According to the Swedish standard SS 187106 recycled waste wood, or only waste wood, is a tree biomass that has had a previous use. Recycled wood assortment can come from demolition of buildings, waste from construction work or packaging wood. It could also be material from pallets, furniture and concrete formwork. Waste wood fuel are recycled and used as a fuel. Waste wood or demolition wood are also common names. Waste wood are often contaminated. Chemically the impurities can be paint, impregnation and other surface treatments. These impurities contain for example lead, zinc, arsenic, cupper and chrome. In addition to the chemical impurities, there are some mechanical ones as well. It is mainly pieces of plastic, metals, small stones and gravel in various sizes. The mechanical and chemical impurities give high or sometimes very high ash content in comparison to other fuels, sometimes above 10 % (Ringman, 1996). The fuel also often contains a large share of fines. It is a cheaper fuel compared to upgraded wood fuels due to the heterogeneity and presence of impurities. There is however some deliveries with high quality as well (Strömberg, 2005).

The forest fuel comes mainly from forest residues, timber with non industrial use and residues from the industry. The Idbäcken CHP sometimes buys stem wood with non industrial use and comminute the material at site with a wood chipper. The fuel quality is often high with almost no impurities and low ash content (Strömberg, 2005). Stem wood is often easier to store then logging residues due to low nitrogen content and high lignin content (Bjorheden et al., 2002).

6 weeks storage

Waste wood were used in one of the piles stored for six weeks, area two in figure 5.3. There was a fuel with a lot of fines and a large proportion of impurities from improper handling and from the waste wood itself, as can be seen in figure 5.1. The size of the pile was 20*8*4.5 meters. That corresponds to an approximate fuel volume of 400 to 500 m^3.

Stem wood that was comminuted at site was used in one of the piles stored for six weeks trial, area one in figure 5.3. The material was comminuted at the plant just days before the trial. It was a mixture of spruce, pine, and some birch. The majority was soft wood but with some birch. It was a quite homogenous fuel concerning fraction distribution, as can be seen in figure 5.1. The size of the pile was 20*9*5 meters. That corresponds to an approximate fuel volume of 400 to 500 m^3.

4 days storage

Another delivery of waste wood was used in the four days storage on ground heated surface, area four in figure 5.3. The fraction of larger particles was higher, compared to the waste wood discusses above in the six weeks trial, while the amount of fines were lower, as can be seen figure 5.1.

Figure 5.2, Chipping of stem wood at Idbäcken CHP.

In order to study changes in fuel quality and dry mater losses over time in the wood chip storage, net plastic sample bags, as shown in figure 5.4, were used. In that way it is possible to study chips from the same area both before and after storage. The thought is to let the sealed chips be affected by the surroundings in the same way as all other chips in the storage. These bags where made of nylon with small holes in them. Each bag was labeled in order to be able to separate them afterwards. The holes in the bags were circular with a radius of one mm and the spacing between them where two mm. The size of the bag was 30*30 cm and had an approximate volume of five liters.

To measure the temperature development in the pile thermocouples of type K (chromel-alumel) and type T (copper-constantan) where placed in different locations in the pile, as can be seen in figure 5.6. More than 3 000 meters of cable were used. There was no specific reason to why two different thermocouples were used. Both are suitable to use in the actual temperature interval and had about the same sensitivity (41µV/°C respectively 43 µV/°C) Each thermocouple was drawn from the pile across a vehicle passage and into a room inside the nearest building where they were connected to PC-loggers 3100i from Intab. The cables were protected by a rubber cable tunnel across the vehicle passage, as can be seen in figure 5.4.

Tarpaulins were placed under the storage piles to make the ground as homogenous as possible since some parts of the pile were outside the asphalt area.

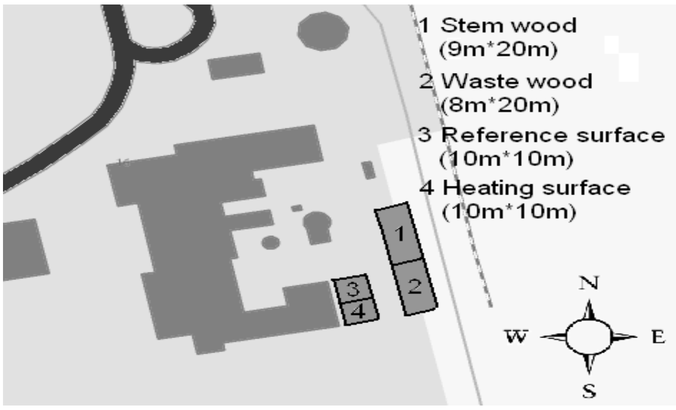

Figure 5.3, Area description showing the CHP-plant with the placement of the storage trial surfaces and the orientation.

Figure 5.4, The left picture: A thermocouple and a sample bag filled with chips. The right picture: The thermocouples and the rubber cable protector.

5.3 Experimental design of storage trial

In order to study the fuel quality changes over time two fuel stacks were built. One of them contained waste wood chips and the other chips from stem wood. Each of the fuel stacks had 28 measurement points in four different sections. Samples of fresh material and after 1, 2, 3 and 6 weeks of storage were taken for analyse.

Wood chips for initial values were sampled from these 28 different measure points in each stack. Then four unique weighted sample bags with wood chips inside were placed at every of the 28 measurement points. In each fuel stack 20 thermocouples were also placed in order to continuously be able to follow the temperature changes inside. In order to study changes in different heights in the stack it were build in layers as showed by figure 5.5 and figure 5.6. Layer one was one meter above ground, layer two was 2.5 meter above ground and layer three was 3.5 meters above ground.

Figure 5.5, The building of the second layer of the waste wood piles with sample bags at the sampling points.

One thermocouple was placed outside the stack to measure the ambient temperature. More ambient weather conditions such as wind speed, wind direction, precipitation and relative humidity was delivered by SMHI, Swedish meteorological and hydrological institute. The precipitation data was collected at Vrena and Oxelösund, approximately 30 km and 15 km respectively from Nyköping. The other weather data was collected in Strömfors, approximately 40 km from Nyköping.

In every test period or revision a specific cross section of the pile was demolished to expose the seven measurement points corresponding to that time (figure 5.6). After the collection of the sample bags, the demolished part of the stack was restored to its original shape, but without sample bag bags to maintain the original volume of the pile.

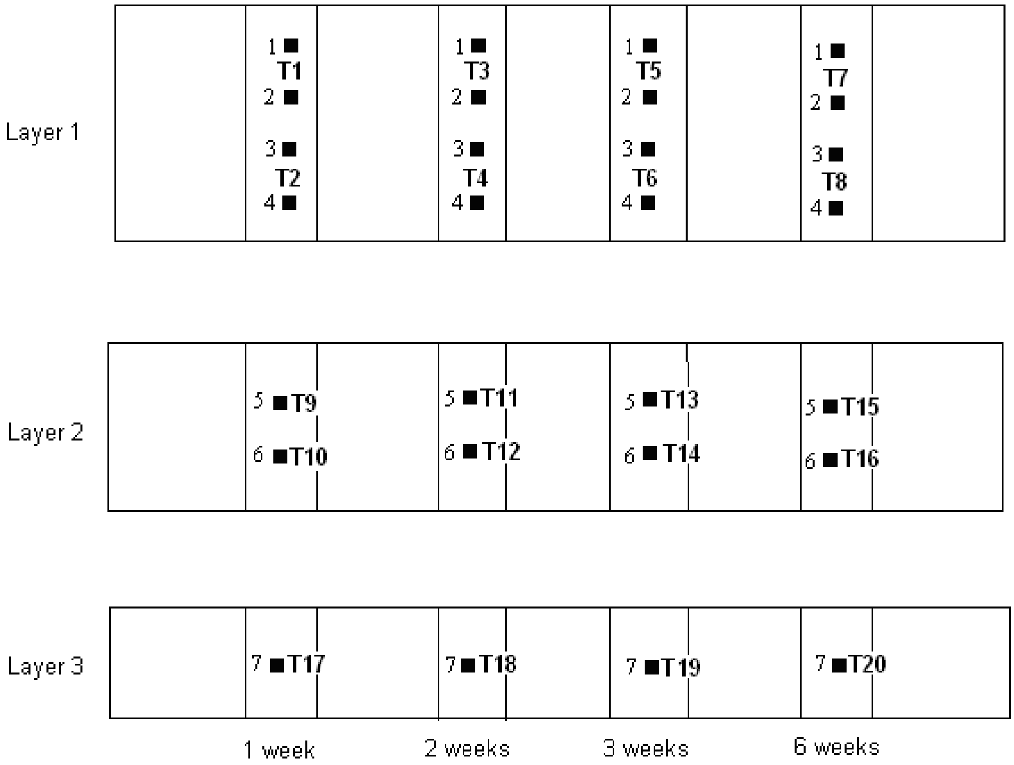

Figure 5.6, Overview of the measurement points (■) and the thermocouple (**T**) placement. The fuel stack is seen from above and layer 1, 2 and 3 was located approximately 1, 2.5 and 3.5 meters above ground respectively. Week one is located in the north side of the pile and week six in the south side.

5.3.1 Storage of waste wood chips

The time schedule for the waste wood pile is listed below. All samples were collected during the year of 2010.

Oct. 6-8	Building of waste wood stack
Oct. 14	Sampling of one week stored material
Oct. 21	Sampling of two week stored material
Oct. 28	Sampling of three week stored material
Nov. 23	Sampling of six week stored material

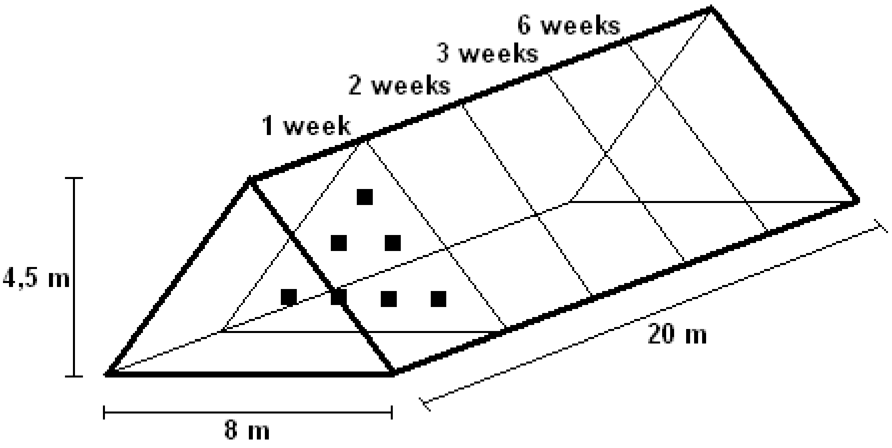

Figure 5.7, Simplified overview of the waste wood stack showing the position of sampling points for revision 1.

5.3.2 Storage of stem wood chips

The time schedule for the stem wood trial is listed below. All samples were collected during the year of 2010.

Oct. 27-29	Building of stem wood stack
Nov. 5	Sampling of one week stored material
Nov. 15	Sampling of two week stored material
Nov. 23	Sampling of three week stored material
Dec. 8	Sampling of six week stored material

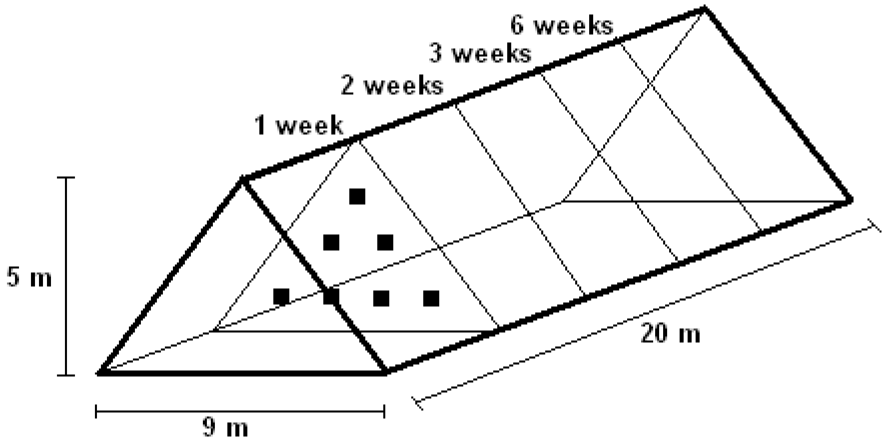

Figure 5.8, Simplified overview of the stem wood stack showing the position of sampling points for revision 1.

5.4 Laboratory analyses

The change in fuel quality was evaluated by the change in moisture content, ash content, heating value, dry matter losses and energy content.

Temperature

The temperature was measured in 20 locations at three different levels inside the pile (figure 5.6). The temperature was measured using thermocouples and logged every fifth minute during the trial. One thermocouple was placed outside the pile to measure the ambient temperature.

Moisture content

The moisture content was measured at the start of the trial and after 1, 2, 3 and 6 weeks storage. The moisture content was determined according to SS 187170. The sample was weighted and then dried in 105 ± 2°C until constant weight. The moisture content is the amount of water in relation to the green weight.

Chips from the 28 measuring points in the two fuel stacks was sampled and put in 28 paper bags. The initial moisture content was then analysed for each of the 28 measuring point.

Chips from every measuring point was sampled and put into four sample bags at each point. They were then placed in the pile. The sample bags were after storage collected and put directly into paper bags. The paper bags, with sample bags and chips inside, were then weighted and dried until constant weight. The moisture content was then calculated with equation (1) for the 28*4 sample bags.

$$MC = \frac{GW - DM}{GW} \times 100 \qquad (1)$$

MC: Moisture content [Percent in green weight basis]
DM: Dry matter weight [kg]
GW: Green weight [kg]

Ash content

The completely dry fuel, both the before samples and the after storage samples, was grinded into wood powder and then analysed according to SS 187171. One to two grams of dry wood powder was weighted and combusted in 550 °C. The remaining substance, the ash, was then weighted and the ash content was calculated as the ratio between ash and dry matter. Two ash contents was measured and calculated for each samples in order to verify the results.

The ash content was analysed for every of the 28 samples collected before storage. For the samples after storage, four sample bags from the same measurement point was put together to one merged sample and analysed in order to reduce the numbers of analysed samples. The ash content was calculated with equation (2).

$$AC = \frac{AW}{DW} \times 100 \qquad (2)$$

AC: Ash content [Percent ash in dry matter]
AW: Ash weight [kg]
DW: Dry matter weight [kg]

Heating value

The calorific or gross heating value was analyzed in a bomb calorimeter, Parr 6300, according to the Swedish standard SS 18 71 82. Pellets were pressed from the wood powder. They were then dried, weighted and combusted in an oxygen bomb and the increase in the surrounding water temperature were measured. The increase in water temperature together with the pellet weight can then be expressed as a specific heating value. Two heating values were measured for each sample in order to verify the results.

The calorific value was analysed for every 28 initial value and for all the 28 merged samples from after storage samples. The net or lower heating value for moist material was calculated for the same samples using equation (3) (Jirjis, 2005b).

$$Wnet = Wgross - \left(2.45 \times \frac{9}{100} \times H2\right) - \left(2.45 \times \frac{MC}{100 - MC}\right) \qquad (3)$$

Wnet: Net or lower heating value [MJ/kg DM]
Wgross: Calorific or gross heating value [MJ/kg DM]
2.45: Heat of evaporation for water at 20°C [MJ/kg]
9: Number of created parts of water from one unit hydrogen
H2: Percentage of hydrogen in forest fuel [wt%], Often approximated to 6wt% for biomass
MC: Moisture content [%]

Dry matter losses

Four sample net bags at each of the 28 measuring point was filled with wood chips, weighted and placed in the pile. The initial dry weight was calculated using the moisture content of a parallel sample. The sample bags were collected when the stack was demolished at the revision. Each sample bag was carefully placed directly in a paper bag and then weight and dried in 105 ± 2°C until they are completely dry and thereby at constant weight. The dry matter losses were calculated using equation (4) (Jirjis and Thörnqvist, 1990).

$$DML = \left(1 - \left(\frac{DW2}{DW1}\right)\right) \times 100 \tag{4}$$

DML: Dry matter losses [%DM]
DW1: Dry weight before storage [kg]
DW2: Dry weight after storage [kg]

Change in energy content

The change in energy content is affected by the dry matter losses and the change in net heating value. It is calculated by equation (5) (Thörnqvist and Jirjis, 1990).

$$CEC = \left(\left[\left(1 - \frac{DML}{100}\right) \times Wnet2\right] - Wnet1\right) \times \frac{100}{Wnet1} \tag{5}$$

CEC: Change in energy content in percentage compared to initial energy content [%]
DML: Dry matter losses [%]
Wnet1: Net heating value before storage [MJ/kg DM]
Wnet2: Net heating value after storage [MJ/kg DM]

5.5 Experimental design of heated surface trial

5.5.1 Heated surface trial

Since Idbäcken is a combined heat and power plant they can sometimes have a surplus of heat. It could be economical beneficial to produce electric power even when there is a lack of heat demand. The heat must in that case be dumped in a heat sink.

The task was to investigate whether it is useful for the facility to use a heated surface as a heat sink in order to pre-dry or de-ice the fuel before burning it. The idea was that the heat from the surface should heat the chips at the bottom and create a convective and conductive heat flow up in the pile. Moisture should then be transported with up moving air.

A heated surface with pipes filled with the return water imbedded in 30 cm deep layer of sand and covered with steel plates at a surface of 10*10 meters were built. The surface had two 10 m long PEH distribution pipes with a diameter of 110 mm at each side. Smaller ground heating pipes (25mm diameter and 2.3 thick) were mounted as an interconnection between the larger distribution pipes. 14 pieces (4*2meters) of three cm thick steel plates were used to cover the surface in order to get a hard surface. A stack of waste wood chips was built on top of the heated surface and another fuel stack was build next to it as a reference.

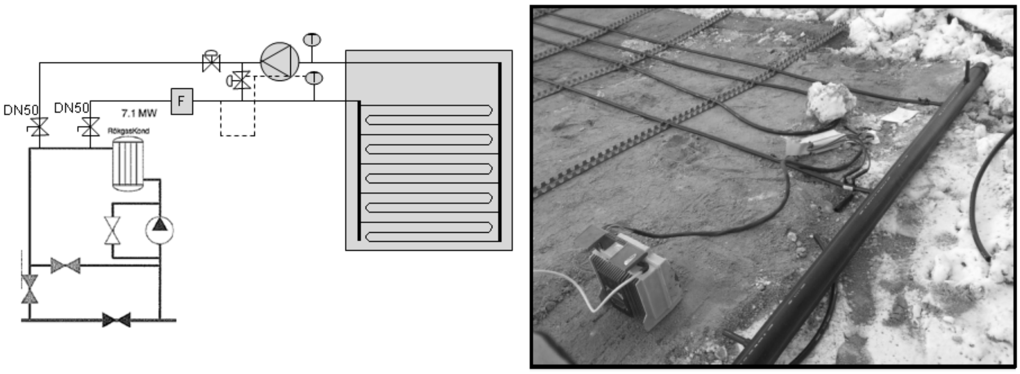

Figure 5.9, A principle drawing of the heated surface and a picture from the construction.

In the four days trial on the heating surface the drying processes is of interest. Since the trial only lasts for four days no change in ash content, fraction distribution, and heating value are expected. No large dry matter losses are expected and thereby not analysed either. The drying process by the heat from beneath is determined by analysing initial moisture content and moisture content after four days of storage and by the temperature changes inside the pile.

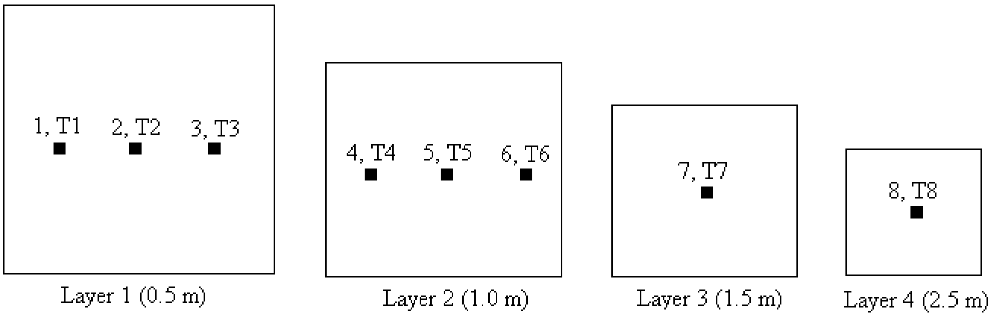

Figure 5.10, Placement of thermocouples and sample bags in the four day storage on heating surface trial. Three more thermocouples were placed, T0.1, T0.2 and T0.3, directly on the steel plates on the heating surface under T1, T2 and T3.

5.6 Analyses

Heating surface parameters

A flow measurement instrument was installed to be able to measure the water flow inside the pipes. The temperatures of the water flowing in and out were measured. Using these values it was possible to calculate the power that had left in the heat sink or surface. These measurement signals (4-20mA) were connected to an energy integrator and then logged in a PC-logger 3100i.

Temperature

The temperature was continuously measured and logged with the same equipment as in the six weeks trial. It was done in 12 locations in four different heights in the pile as shown in figure 5.10. The temperature was also measured in five places in the sand and the ambient temperature was also measured outside the pile.

Moisture content

The initial moisture content of the eight sampling points in the heated and the reference pile was determined. Two sample bags were filled and placed at each sampling point to be used for moisture content determination after storage. The moisture content was then determined as described earlier.

6 Results and discussion

6.1 Local weather conditions

The local weather, and especially the parameters that is of interest for the drying process such as wind speed, temperature, relative humidity and precipitation during the storage trial, are presented here. The fuel quality parameters can during storage be affected by the surroundings. The storage trial with waste wood was performed during the period October 8 to November 23 and between October 29 and December 8 for stem wood.

The ambient temperature can to some extent affect the behaviour and temperature development inside the pile due to larger cooling but the inner parts of the piles are not sensitive to the ambient temperature.

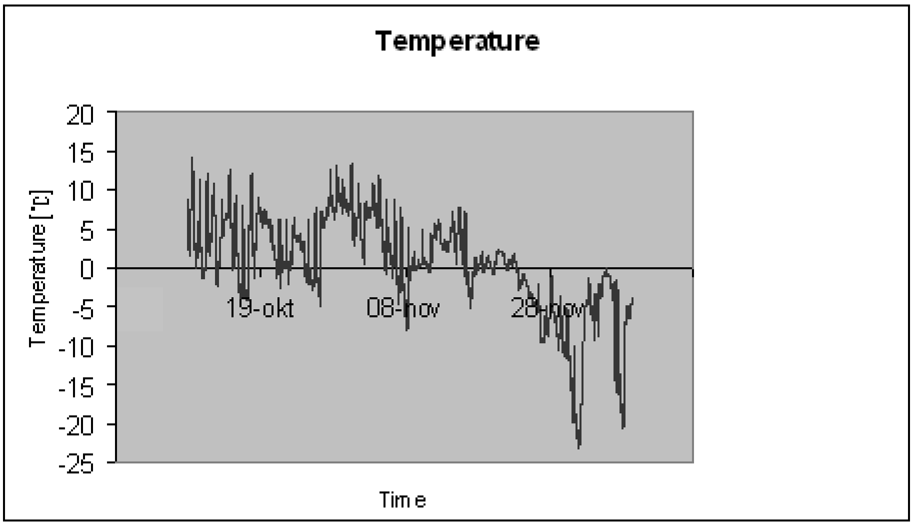

Figure 6.1, The temperature (°C) at Idbäckens CHP during the storage period.

The precipitation can affect the moisture content mainly in the most outer layer. There was large precipitation around the 10th of November and in the end of November (figure 6.2).

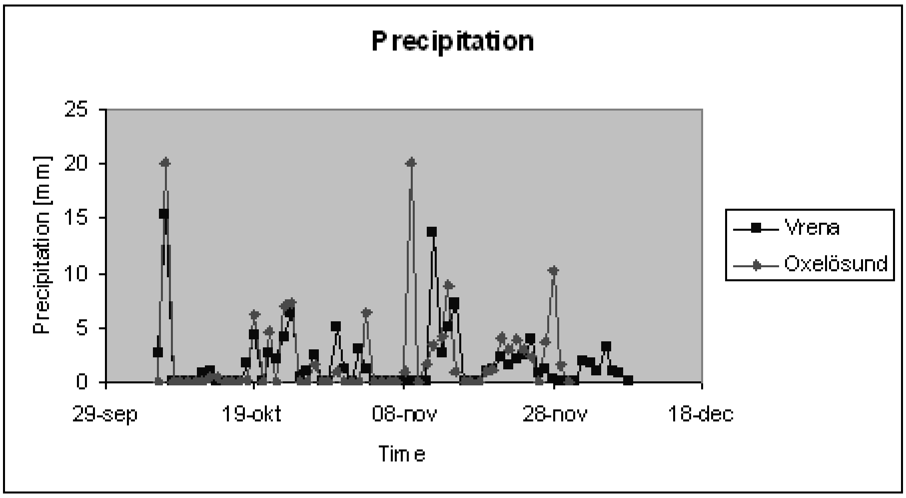

Figure 6.2, The daily precipitation in millimetres at the two nearest SMHI-measurement station (Swedish Meteorological and Hydrological Institute)

Wind can to some extent affect the pile. The wind was fairly even most of the storage time but with a period of stronger winds at the end of November.

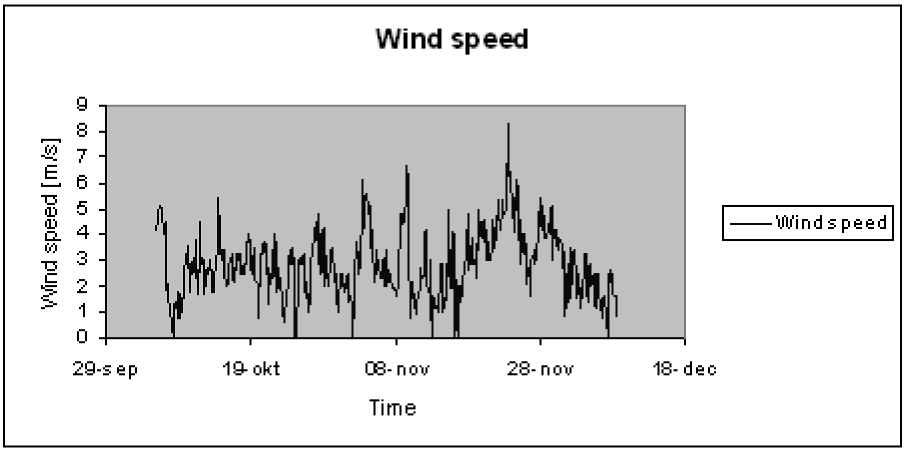

Figure 6.3, The mean wind speed is a plot of ten minutes mean value taken at eight different times per a day.

The wind speed values are accumulated wind speeds for a specific direction and for a specific measurement period. The wind can both help to ventilate the pile and to some extent dry the outer layer. The plot shows that the most frequent and strongest wind came from the north east. Pure eastern winds were rarest. The winds are however collected at the nearest SMHI-measurement station and not directly at the plant. The local winds might be somewhat different due for example wind shading from buildings.

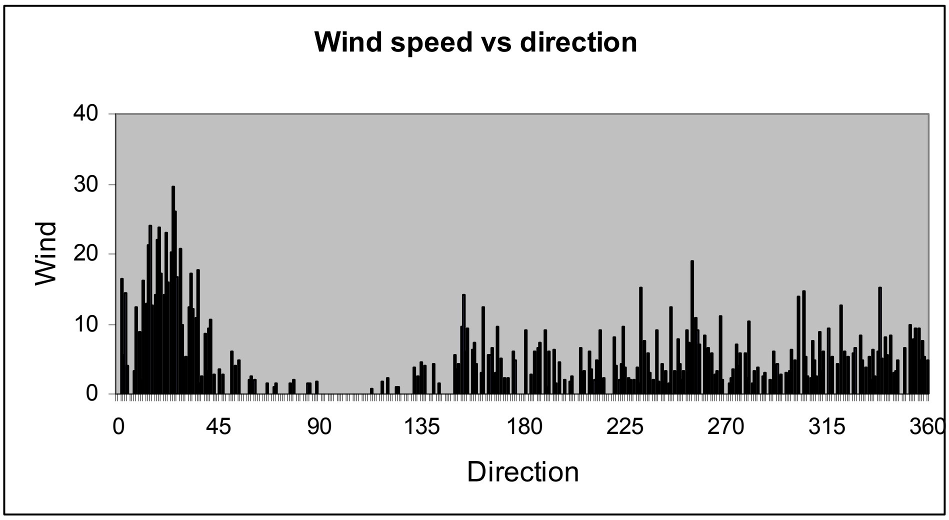

Figure 6.4, The plot of wind speed and wind direction is based on ten minutes mean value taken at eight times per day. 360° indicate northerly winds, 90° east wind, 180° southerly winds and 270° westerly winds.

The humidity can affect the drying process in the other layer by diffusion process. The moisture content of chips at hygroscopic equilibrium with the surrounding air is a function of relative humidity and temperature.

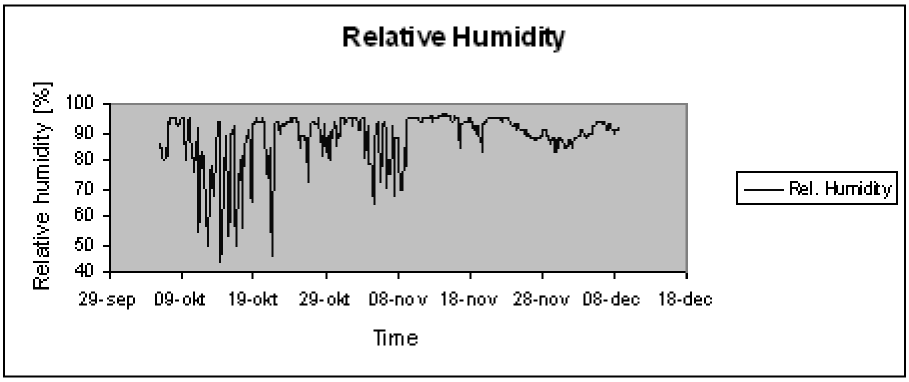

Figure 6.5, The relative humidity is a plot of ten minutes mean value taken at eight different times per a day.

6.2 Storage of waste wood chips

The general results for waste wood storage is presented in 6.2.1 to 6.2.7, se appendix 1, 2, 3 and 4 for more detailed results.

6.2.1 Temperature

The temperature development was generally moderate and varied in different parts of the pile. The temperature was slowly rising from 15 to about 25 °C during the first storage week for all measurement points except the one at the top of the pile (C17, se figure 6.6) which mostly followed the ambient temperature.

There were more temperature fluctuations in the section stored for two weeks. Point (C3) and (C11) reached the highest temperature, about 30 °C during the period. The temperature at the top (C18) followed the ambient temperature but started to rise at the end of the period, as did (C11).

The temperature varied between 15 and 25 °C for most of the points in the three weeks storage part. The top point also here followed the ambient temperature. The two points on the east side of the pile, (C5) and (13), fluctuated during the period.

After six weeks of storage unfortunate damage to some the of the thermo couples cable was recorded. The cable protection across the road did not sufficient protect all cables. The fluctuation trend was however the same as for the three weeks period between, 15 and 25 °C for the bottom and middle layer. The temperature in the top point followed the ambient temperature.

During the whole storage period, the temperature in the top roughly followed the ambient temperature. That can be explained by the more exposed location with more cooling effect. The general trend with an increase in temperature the first weeks can be related to the higher microbial activity with easy access to degradable material. Only mild pulsing and fluctuating behaviour was noticed which is common in smaller piles. Some dips in the temperature can be due to the opening of a nearby section in the pile.

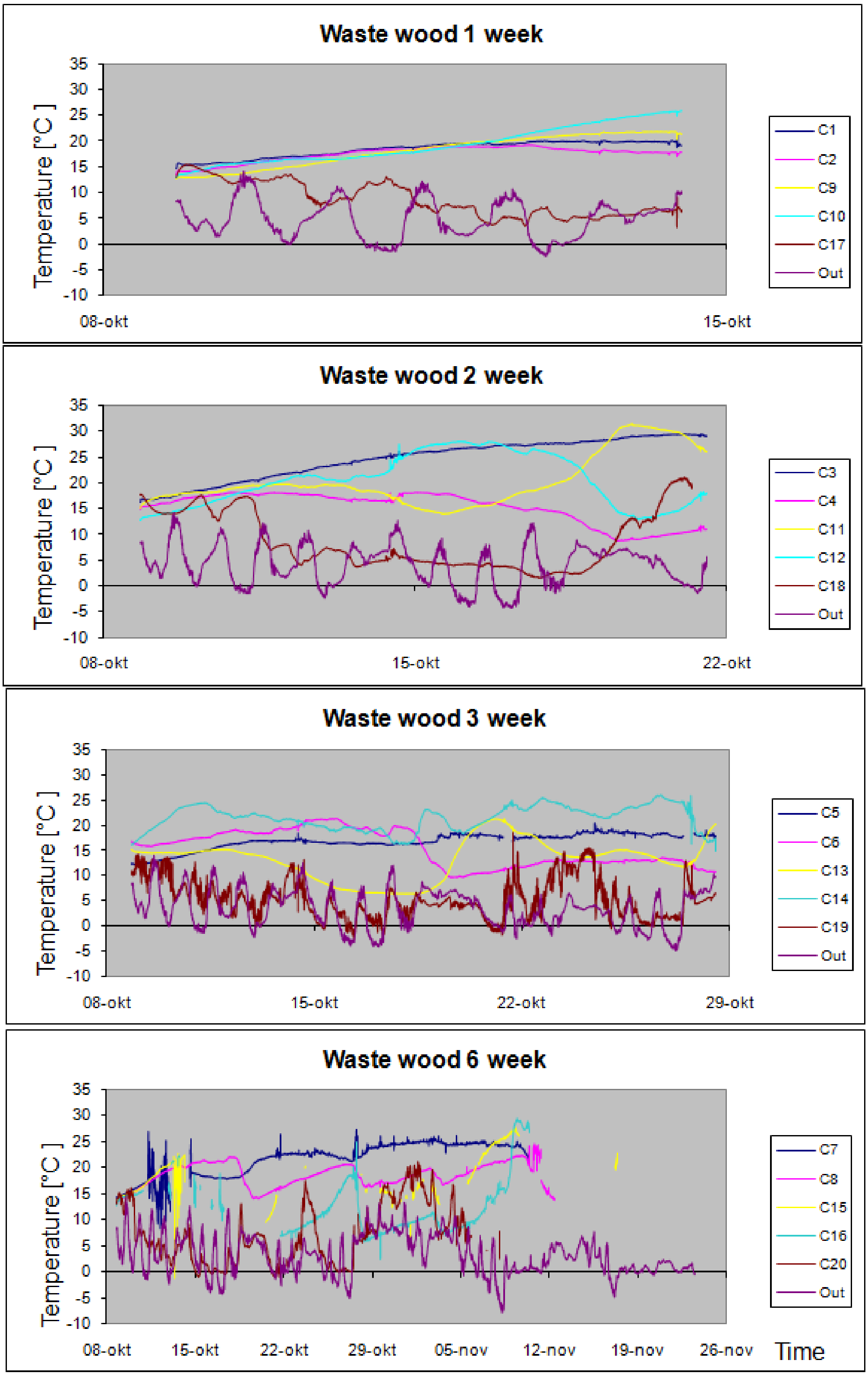

Figure 6.6, The temperature profile inside the different sections of the pile. The first two temperatures are from the bottom layer, the following two are from the middle layer and the fifth is from the top layer. The points Cx corresponds to Tx in figure 5.6.

6.2.2 Moisture content

There were small changes in the moisture content in each cross section during storage. The tendency was that the material became a bit drier during storage and especially the first weeks, but it could also be due to natural variations. The drying or change in moisture content was quite small based on a weighted average for each section, as can be seen in table 6.1.

Table 6.1, *Weighted average moisture content* (MC) in waste wood before and after storage with standard deviation (SD) and the change in moisture content during storage with a 95% confidence interval (95% CI).*

	MC Before (SD)	**MC After (SD)**	**Change in MC (95% CI)** **After - Before**
1 week	42.9 (4.9)	42.3 (5.7)	- 0.6 ± 0.2
2 week	43.4 (3.6)	41.9 (4.4)	-1.5 ± 0.5
3 week	42.6 (3.5)	40.4 (5.5)	- 2.2 ± 0.8
6 week	42.1 (2.8)	40.0 (6.1)	- 2.1 ± 0.8

* Before storage values are based on seven samples per section. After storage values are based on 28 (4*7) samples per section

The change in moisture content inside the pile was not even. The point from the top-layer (3.5 m above ground) had a significant increase in moisture content after three and six weeks of storage. It was evident that the points from the middle layer and the central zone of the bottom layer dried more, as can be seen in table 6.2. The higher temperatures in the middle of the pile did probably transfer the moisture to the upper parts of the pile. That is, most probably, the reason for the changes at specific points although the average for the whole crosses section was unchanged. Redistribution of moisture in heated chip piles is a well known behaviour. The precipitation could also partly explain the higher moisture content at the top after three and six weeks.

Table 6.2, *The initial moisture content* and the after storage data at each measuring point. Δ-value is the moisture content change at each point.*

Sample point	1	2	3	4	5	6	7
Initial	43.9%	47.3%	48.9%	47.2%	37.4%	38.3%	37.1%
1 week	42.9%	49.4%	46.0%	48.1%	37.0%	36.2%	36.6%
Δ	-1.0%	2.1%	-2.9%	0.9%	-0.4%	-2.1%	-0.5%
Initial	42.6%	46.2%	46.3%	47.3%	43.8%	41.2%	36.3%
2 week	40.8%	45.5%	45.8%	46.4%	38.4%	39.5%	37.0%
Δ	-1.8%	-0.6%	-0.5%	-0.9%	-5.4%	-1.7%	0.7%
Initial	44.7%	47.6%	45.3%	43.5%	38.6%	37.8%	40.7%
3 week	43.7%	42.0%	41.4%	41.4%	35.2%	30.8%	47.3%
Δ	-1.0%	-5.6%	-3.9%	-2.0%	-3.4%	-7.0%	6.5%
Initial	42.1%	46.2%	41.2%	45.5%	39.3%	38.3%	41.9%
6 week	36.6%	41.5%	40.2%	38.6%	35.9%	34.8%	52.3%
Δ	-5.6%	-4.7%	-1.0%	-6.9%	-3.4%	-3.6%	10.4%

* Before storage values are based on one sample per sample point. After storage values are based on four samples per sample point.

6.2.3 Ash content

The average ash content varied marginally during storage in all sections except. This marginal increase in ash content, due to the degradation and loss of organic matter, can lead to the relative increase in ash contents. The percentage content of ash becomes thereby higher. However since the material was so heterogeneous initially such changes and fluctuations in ash content are expected.

Table 6.3, *Weighted average ash content* (AC) in waste wood before and after storage with standard deviation (SD) and with a 95% confidence interval (95% CI)*

	AC Before storage (SD)	AC After storage (SD)	Change in AC (95% CI) After - Before
1 week	12.53 (3.52)	12.65 (5.17)	0.12 ± 0.09
2 week	15.77 (4.34)	16.21 (5.69)	0.44 ± 0.33
3 week	21.93 (8.22)	21.73 (7.31)	-0.21 ± 0.15
6 week	21.44 (8.28)	21.85 (7.51)	0.41 ± 0.31

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section

6.2.4 Heating value

The gross heating value or calorific value varied considerably between different measurement points. The reason for that is the overall high ash content. Since ash is incombustible it does not contribute to the heating value. The gross heating value was generally increased during storage except for the two weeks storage samples. That is logical since microbes more easily degrade low energy compounds such as cellulose and hemicellulose rather than high energy ones such as lignin. There are however uncertain results with large standard deviations mainly because of the difficulty to correctly sample corresponding material due to the very heterogeneity of the fuel.

Table 6.4, *Weighted average gross heating value (W_{gross}) in waste wood before and after storage with the standard deviation (SD) and with a 95% confidence interval (95% CI).*

	W_{gross} Before (SD)	**W_{gross} After (SD)**	**Change in W_{gross} (95% CI) After - Before**
1 week	17.52 (0.89)	17.66 (1.52)	0.15 ± 0.08
2 week	17.22 (1.03)	16.66 (1.21)	- 0.57 ± 0.30
3 week	15.97 (1.30)	16.13 (1.03)	0.16 ± 0.08
6 week	15.90 (1.67)	16.14 (1.44)	0.24 ± 0.13

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section

The change in net heating value which also reflects the change in moisture content shows similar tendencies as the gross heating values. Here again, these values are uncertain with high standard deviations due to the same reasons mentioned above.

Table 6.5, *Weighted average net heating value (W_{net} [MJ/kg DM]) in waste wood before and after storage with standard deviation (SD) and with a 95% confidence interval (95% CI).*

	W_{net} Before (SD) [MJ/kg DM]	**W_{net} After (SD) [MJ/kg DM]**	**Change in W_{net} (95% CI) After - Before**
1 week	15.1 (0.9)	15.3 (1.5)	0.2 ± 0.1
2 week	14.8 (1.1)	14.3 (1.3)	- 0.5 ± 0.4
3 week	13.6 (1.4)	13.8 (1.1)	0.2 ± 0.2
6 week	13.5 (1.7)	13.8 (1.3)	0.3 ± 0.2

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section

6.2.5 Dry matter losses

All of the stored material in different cross sections had dry matter losses during storage. The general trend was that the loss rate was larger in the beginning of storage and then declined with time. The material that was stored for one week had the largest loss rate among the four cross sections while the smallest loss per week was found in the material that was stored for six weeks. The losses presented in *Figure 6.7* are weighted arithmetic mean values from the 28 sample bags at each and every cross section.

The losses in figure 6.7 are plotted directly with the results from the 28 sample bags in each cross section, even if a few sample bags showed an increase in dry matter. An increase in dry matter is however not possible and that is discussed in chapter 6.6. The cross section stored for three weeks is for example affected by a major positive loss in one sample bag. The losses for week three become slightly higher if that point is replaced with a zero value or an average value. The overall losses will not drastically change but they will become somewhat higher if the same method is applied to the other seven sample bags with significant positive losses, see appendix 1.

Figure 6.7, Accumulated, dry matter losses (DML % dry weight basis) for each cross section based on an average from the 28 sample bags at the seven measuring points. A 95% confidence interval for each section is also included.

However, the losses were not evenly distributed in the cross sections which can be seen in *table 6.6.* The losses in the point at the top layer are the smallest for all cross sections. The largest losses were found in the middle of the bottom layer and the middle layer in each cross section (point 3 and 6). The losses were otherwise close.

The losses for each cross section based on the original raw data are listed in table 6.6. However, since some of the losses were misleading the results were also recalculated. The misleading and incorrect values were than replaced by the average of the other accepted values at the same point (mean correction) or by a zero value (zero correction). All of the three different ways to present the results is listed in table 6.6.

Table 6.6, *Accumulated dry matter losses (DML % dry weight basis) at each measuring point* in the pile.*

Sample point	Storage time 1 week	2 week	3 week	6 weeks
1	0.7%	0.5%	0.7%	1.6%
2	0.8%	0.4%	3.3%	2.2%
3	2.3%	3.5%	1.4%	2.8%
4	0.8%	1.6%	0.2%	2.4%
5	-0.1%	2.0%	1.1%	0.5%
6	1.2%	1.8%	3.7%	4.4%
7	0.0%	0.0%	-1.4%	-0.2%
Average (Raw data)	0.8%	1.4%	1.3%	2.0%
Average (Mean correction)	0.9 %	1.8 %	1.5 %	2.5 %
Average (Zero correction)	0.9 %	1.6 %	1.5 %	2.2 %

* Average of four sample bags per sample point

6.2.6 Change in energy content

The change in net energy content is a function of changes in dry matter, moisture content and calorific value. The analysis of the calorific value of waste wood chips before and after storage shows a sometimes large variation, probably due the very heterogeneous material, which impacts the change in energy content. The changes in moisture content and the dry matter losses were on the other hand quite small. The irregular changes in calorific value affected the standard deviation considerably (Table 6.7).

Table 6.7, *Weighted average change in energy content (CEC) for each section in waste wood after storage with the standard deviation (SD). The changes are compared to initial amount of energy.*

	Storage Time 1 week	2 weeks	3 weeks	6 weeks
CEC	0.7 %	-4.7 %	1.8 %	1.6 %
SD	10.0	5.2	10.7	10.1

6.2.7 Correlations between variables

There is a rather small positive correlation between the initial moisture content and the dry matter losses in the waste wood trial. The correlation coefficient is 0.19 and the R^2-value is 0.038. Higher initial moisture contens tended to result in slightly larger dry matter losses, as can be seen in figure 6.8.

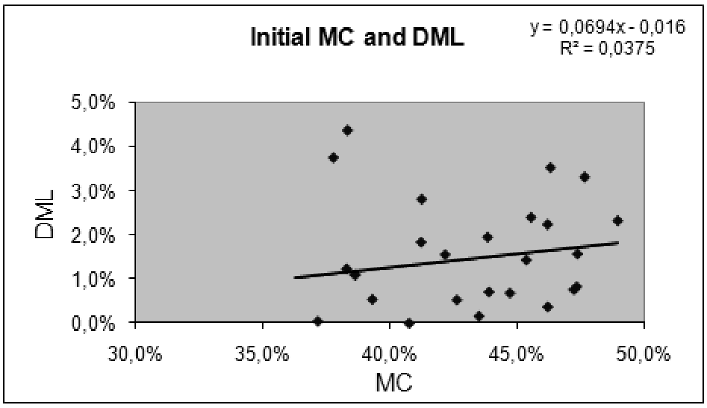

Figure 6.8, The correlation between the initial moisture content and the accumulated dry matter losses (DML % dry weight basis) at each point and a linear regression line. Major positive losses are excluded.

6.3 Storage of stem wood chips

The general results for stem wood storage is presented in 6.3.1 to 6.3.7, se appendix 1, 2, 3 and 4 for more detailed results.

6.3.1 Temperature

Within the first weeks of storage a steady increase in temperature to about ten to 15 °C was recorded. The temperature remained at this level in many points throughout the first week of storage.

A similar behaviour was observed in section 2. There was a general decrease in the temperature down to approximately five °C for most of the points in the second week of storage. However, all points had a temperature higher than the ambient temperature.

There were temperature variations between 0 and 15 °C in the material stored for three weeks. The highest temperature was reached in point (C5) and (C14) which were located in the bottom and middle layer on the west side of the pile. These points showed however a temperature drop at the end of the storage period. This could be explained by the fact that the second section was opened at the same time which caused an airflow that also ventilated the third section. It could also be explained by the large snow fall that happened at the time. The other points were more or less following the ambient temperature, but a couple of degrees warmer and with some lag.

The six weeks storage part was following the ambient temperature, but not exceeding

0 °C. The temperature was pulsing at the points (C7), (C8) and (C16) between five and 15 °C. C16 and C8 had a temperature drop around October 8 when the first major snow fall occurred. The last week’s temperatures were not recorded correctly due to a damage of all cables by a snowplough.

The top point in almost all cases roughly followed the ambient temperature, which could be explained by the more exposed location with more cooling effect. Some dips in the temperature can be related to the opening of a nearby section in the pile or partly due to a change in the weather.

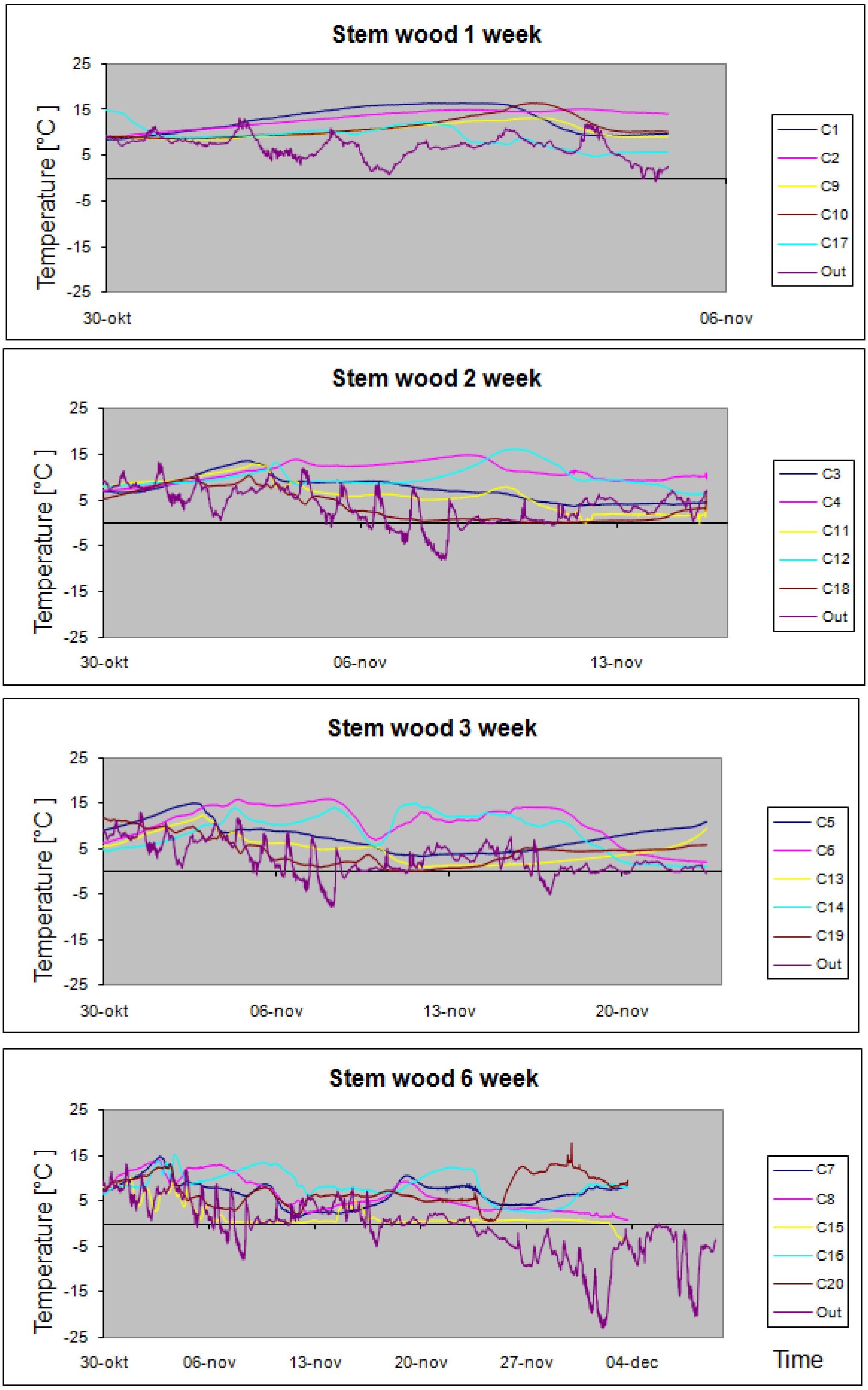

Figure 6.9, The temperature profile inside the different sections of the pile. The first two temperatures are from the bottom layer, the following two are from the middle layer, the fifth are from the top layer. The points Cx corresponds to Tx in fig. 5.6.

6.3.2 Moisture content

Minor changes in the average moisture content were measured during storage. The tendency was marginally wetter material after storage and especially after two and three weeks. The changes in moisture content were, however, small and could be explained by natural variations, which was reflected by the relatively high standard deviations.

Table 6.8. *Weighted average moisture content* (MC) in stem wood before and after storage with standard deviation (SD) and the change in moisture content during storage with a 95% confidence interval (95% CI).*

	MC Before (SD)	MC After (SD)	Change in MC (95% CI) After - Before
1 week	43.7 (1.9)	43.9 (2.2)	0.2 ± 0.1
2 week	42.2 (3.8)	45.4 (2.2)	3.2 ± 1.2
3 week	41.8 (3.9)	45.3 (3.6)	3.5 ± 1.3
6 week	42.5 (7.1)	44.2 (5.6)	1.7 ± 0.6

* Before storage values are based on seven samples per section. After storage values are based on 28 (4*7) samples per section

The change in moisture content was not evenly distributed between the measurement points. The points from the top-layer (3.5 m above ground) had a significant increase in moisture content after 2, three and six weeks storage. This could be explained by the precipitation or by the fact that moisture was condensed in more cold parts. The other points had more irregular fluctuations with no or unclear trend (Table 6.9).

Table 6.9, *The initial moisture content* and the after storage data at each measuring point. Δ-value is the moisture content change at each point.*

Sample point	1	2	3	4	5	6	7
Initial	43.8%	45.1%	45.8%	46.0%	41.1%	42.8%	41.3%
1 week	43.5%	45.6%	45.7%	46.0%	41.2%	43.2%	42.2%
Δ	-0.2%	0.5%	-0.1%	0.0%	0.1%	0.5%	1.0%
Initial	45.1%	44.2%	46.3%	44.6%	40.5%	40.1%	34.7%
2 week	45.9%	45.5%	46.8%	47.5%	45.0%	41.4%	45.9%
Δ	0.9%	1.3%	0.4%	2.9%	4.5%	1.3%	11.2%
Initial	47.4%	46.9%	42.3%	39.0%	41.1%	40.1%	35.9%
3 week	47.3%	45.8%	42.7%	46.1%	41.1%	43.7%	50.3%
Δ	-0.1%	-1.0%	0.4%	7.1%	-0.1%	3.6%	14.4%
Initial	46.4%	46.9%	46.2%	53.0%	31.9%	36.7%	36.4%
6 week	48.0%	45.2%	44.5%	45.9%	33.4%	41.4%	50.8%
Δ	1.6%	-1.7%	-1.8%	-7.1%	1.5%	4.7%	14.4%

* Before storage values are based on one sample per sample point. After storage values are based on four samples per sample point.

6.3.3 Ash content

Storage for six weeks affected the ash content marginally. The presence of dry matter losses during storage can be reflected by higher ash content since only organic matter is degraded. All of the sections had a very small increase in ash content (Table 6.10). The changes in ash content were evident in the regions with measurable dry matter losses.

Table 6.10, *Weighted average ash content* (AC) in waste wood before and after storage with standard deviation (SD) and with a 95% confidence interval (95% CI)*

	AC Before (SD)	AC After (SD)	Change in AC (95% CI) After - Before
1 week	0.74 (0.27)	0.80 (0.24)	0.05 ± 0.04
2 week	0.62 (0.17)	0.69 (0.08)	0.07 ± 0.05
3 week	0.65 (0.22)	0.69 (0.10)	0.04 ± 0.03
6 week	0.58 (0.19)	0.68 (0.12)	0.11 ± 0.08

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section

6.3.4 Heating value

The changes in calorific value or gross heating values of stem wood were minimal and probably insignificant during storage. The first two weeks showed a slight increase. The third weeks ash content were unchanged and the latest storage week had a small decrease. Higher calorific values can be expected due to dry matter losses. Low energy components are more easy to degrade which can lead to a higher calorific value in [MJ/kg]. The actual changes are small in comparison to the 95% confidence interval (Table 6.11).

Table 6.11, *Weighted average gross heating value (W_{gross}) in stem wood before and after storage with standard deviation (SD) and with a 95% confidence interval (95% CI).*

	W_{gross} Before (SD)	**W_{gross} After (SD)**	**Change in W_{gross} (95% CI) After - Before**
1 week	19.91 (0.11)	19.94 (0.13)	0.03 ± 0.02
2 week	19.88 (0.12)	20.00 (0.09)	0.13 ± 0.09
3 week	19.99 (0.05)	19.99 (0.15)	0.00 ± 0.00
6 week	19.99 (0.04)	19.92 (0.15)	- 0.07 ± 0.05

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section.

The changes in average net heating value were marginal (Table 6.12) and reflect the minor changes in gross heating value and moisture content.

Table 6.12, *Weighted average net heating value (W_{net} [MJ/kg DM]) in stem wood before and after storage with standard deviation (SD) and with a 95% confidence interval (95% CI).*

	W_{net} Before (SD) [MJ/kg DM]	**W_{net} After (SD) [MJ/kg DM]**	**Change in W_{net} (95% CI) After - Before**
1 week	17.5 (0.1)	17.5 (0.1)	0.0 ± 0.0
2 week	17.5 (0.2)	17.6 (0.1)	0.0 ± 0.1
3 week	17.6 (0.1)	17.6 (0.1)	- 0.1 ± 0.1
6 week	17.6 (0.2)	17.5 (0.1)	- 0.1 ± 0.1

* Before storage values are average of seven samples per section. After storage values are based on 28 samples merged into seven per section

6.3.5 Dry matter losses

The dry matter losses over time had the same general behaviour as in the trial with waste wood. All sections of the pile had dry matter losses during the storage period. The losses per week were larger in earlier storage periods and stabilised towards the end of the storage period.

The losses in figure 6.10 are plotted directly by the results from the 28 sample bags in each cross section, even if a few sample bags also here showed an increase in dry matter. The overall losses will not drastically change but will become somewhat higher if the same correction method mentioned in 6.2.5 is applied to the five sample bags with major positive losses, see appendix 1.

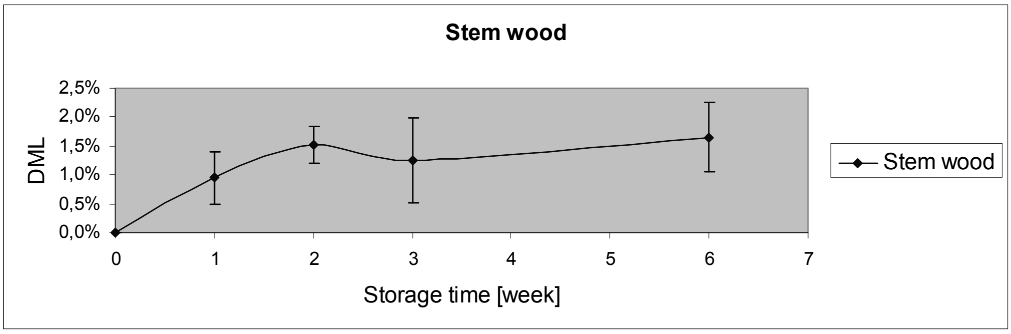

Figure 6.10, Accumulated, dry matter losses (DML % dry weight basis) for each cross section based on an average from 28 samples reflected the seven measuring points. A 95% confidence interval for each section is also included.

However the losses were not evenly distributed in the cross sections. The losses at different locations are listed in table 6.13. Point seven at the top layer has the smallest losses which can be reflected by the lower temperature and the more exposed location. The largest losses were found in the middle of the bottom layer. The other losses were evenly distributed between different measuring points.

The losses for each cross section presented in table 6.13 are based on the original data, the correction of positive values by using mean values (mean correction) or by consider the unaccepted values as zero (zero correction).

Table 6.13, *Accumulated dry matter losses* (DML % dry weight basis) at each measuring point* in the pile.*

Sample point	Storage time 1 week	2 weeks	3 weeks	6 weeks
1	0.7%	1.3%	1.5%	2.2%
2	1.3%	1.5%	2.3%	3.3%
3	1.3%	2.4%	2.6%	0.7%
4	1.5%	2.3%	0.1%	2.3%
5	0.4%	1.1%	1.9%	1.3%
6	1.4%	1.7%	1.9%	1.6%
7	0.2%	0.3%	-1.5%	0.2%
Average (Raw data)	0.9%	1.5%	1.3%	1.7%
Average (Mean correction)	1.1 %	1.5 %	1.7 %	1.8 %
Average (Zero correction)	1.1 %	1.5 %	1.6 %	1.7 %

* Average of four sample bags per sample point

6.3.6 Change in energy content

The total change in energy content is a function of the changes in dry matter, moisture content and in calorific value. The amount of energy was decreased during storage mainly due to increase in moisture content and dry matter losses.

Table 6.14, *Weighted average change in energy content (CEC) for each section in stem wood after storage with the standard deviation (SD). The changes are compared to initial amount of energy.*

	Storage Time 1 week	2 weeks	3 weeks	6 weeks
CEC	-0.9 %	-2.2 %	-2.8 %	-2.6 %
SD	0.7	1.3	1.4	2.9

6.3.7 Correlations between variables

There was a clear and positive correlation between the initial moisture content and the dry matter losses in the stem wood trial. The correlation coefficient is 0.53 and the R^2-value is 0.29. Higher initial moisture content resulted in larger dry matter losses.

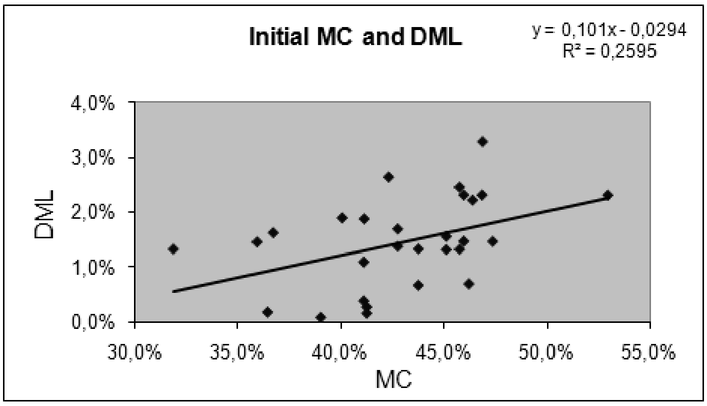

Figure 6.11, The correlation between the initial moisture content and the accumulated dry matter losses (DML % dry weight basis) at each point and a linear regression line. Major positive losses are excluded.

6.4 Economical effects of biomass losses

The fuel storage at site has, as mentioned before, a maximum volume of 35 000 m^3. The actual fuel volume at site varies a lot during the heating season from almost empty up to full storage. A fuel volume of 15 000 m^3 to 25 000 m^3 is not unusual. The average storage time also varies considerably. Some fuel is used almost directly as it arrives to the plant while some other fuel is stored for longer times, up to month (Nordqvist, U., 2011). The dry matter loss in the stored material depends on the storage time, initial moisture content and stored volume, as shown by the results from the storage trials performed in this study.

Assumptions for the economical calculation (Nordqvist, 2011):

- Average storage time at site Idbäcken is 1-2 weeks
- Average storage volume of 20 000 m^3
- Waste wood prices of 80 to 120 SEK/MWh
- Forest fuel prices of 160-240 SEK/MWh
- 70% Waste wood and 30% forest fuel in the storage
- Energy content of 0.9 MWh/ m^3
- Average dry matter losses based on this thesis results of 0.75 to 0.9% per week

Based on these assumptions the economical consequence of dry matter losses in the stored material at the site Idbäcken is, in the interval of 14 000 to 25 000 SEK per week. There are large variation in the economical losses due to different fuel prices, amount of stored material and different loss rates.

The results of this thesis were used to calculate the costs of the losses. However, it was done in smaller piles then the actual fuel storage at Idbäcken. The losses in larger piles can be larger. A study by Thörnqvist and Jirjis (1990) showed dry matter losses in large piles in the region of 2.3 to 3.6 % per week in the initial phase under similar conditions as in Idbäcken, but with a different fuel (forest residues). That further implies that the economical losses for Idbäcken CHP-plant can be larger. Estimated economical costs of doubled or even larger due to dry matter losses might be the case. However the presented values should be seen as benchmarks.

6.5 Storage on heated surface

The general results for storage on heated surface is presented in section 6.5, see appendix 4 and 5 for more detailed results.

6.5.1 Heated surface parameters

The momentary delivered power or heat to the surface can be calculated from the water flow in the pipes, the temperature difference between the water to and from the surface and the heat capacity of the water. Not all power delivered to the surface was absorbed by the pile. Some heat went down in the ground and some to the sides. But one fraction went up through the steel plates and further up in the pile. The measured delivered power varied a lot due to a lag in the temperature fluctuation response. It is a lag in time when a new water temperature is delivered until the new equilibrium was reached. The temperature difference can during that time be too high or too low which instantly affects the measurement of the delivered power.

The temperature difference was in average 0.9°C, the average delivered power 23.7 kW and the average flow rate was 19.3 m^3/h.

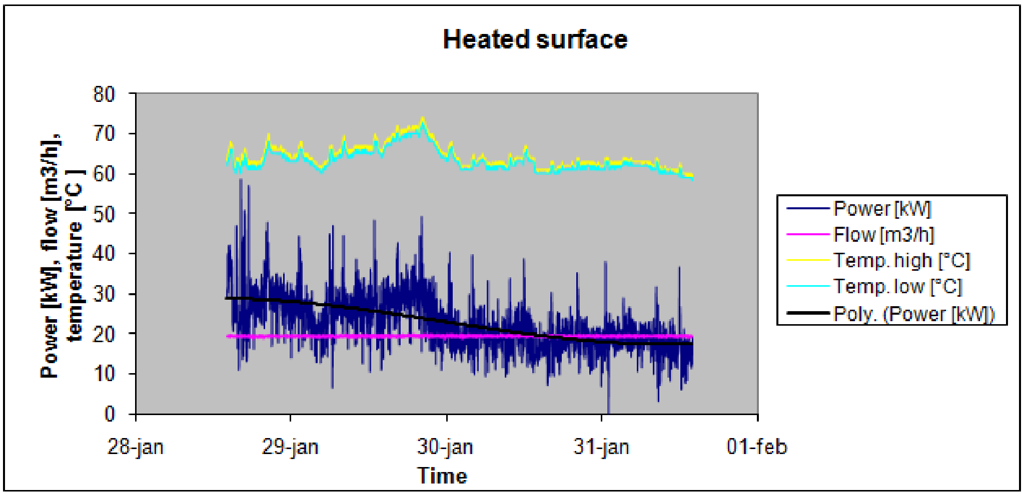

Figure 6.12, The temperature difference, the water flow and the delivered power to the heat sink or surface. A trend line has been inserted to more easily follow the power.

6.5.2 Temperature

The temperature measured in the sand under the steel plates varied between 30 and 40°C. It was measured both on the larger distribution pipe, the smaller pipes and 10 cm away from them. The fifth sand temperature measured in the middle of the surface underneath the steel plates showed similar temperatures. The temperatures on the steel plates started directly to rise when the wood chips was placed on the surface and was risen up to a maximum of 48°C (Table 6.15) towards the end of the four days. The temperature at 0.5 m above the surface showed maximum values about 15, 16, and 22°C. The measurements at one m above the surface showed temperatures in the region of nine to 22°C. Table 6.15 shows that there are some difference in temperature between the reference surface and the heated surface at the height of 0.5 m. The heated surface shows higher temperatures at that level. However, the temperatures higher up in the piles do not show the same pattern although one point at one m showed significant higher temperature compared to the reference pile. There was still no general significant difference concerning temperature between the piles higher up.

The temperatures were measured continuously and the maximum was reached in the end of storage. These temperatures are the ones presented in table 6.15.

Table 6.15, *The maximum temperature in °C at different heights [m] for the heated surface pile and the reference pile. Temperatures of the ground were not measured in the reference pile.*

Height [m]	**0**			**0.5**			**1**			**1.5**	**2.5**
Sample point	**0.1**	**0.2**	**0.3**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Heated surface	38.1	36.3	47.9	15.5	14.6	21.6	19.4	8.8	8.5	7.1	12.6
Reference	-	-	-	5.3	4.5	9.3	8.9	14.0	10.5	13.5	9.1

6.5.3 Moisture content

There was no significant difference between the drying of the heated pile and the reference (Table 6.16). There was neither a significant difference in different height concerning the drying effects. A potential drying front starting from the bottom and moving ahead up in the pile could not be seen in the heated pile.

Table 6.16, *Moisture content (MC % wet basis) before and after four days storage on heated surface. Δ-value is the change in MC at each point.*

	Heated surface storage			**Reference storage**		
Sample point	**MC Before**	**MC After**	**Δ**	**MC Before**	**MC After**	**Δ**
1	33,8	34,7	0,9	31,5	n.d.	n.d.
2	40,0	n.d.	n.d.	41,4	40,0	-1,4
3	26,9	28,2	1,3	37,9	38,3	0,3
4	36,6	34,9	-1,7	35,7	32,9	-2,9
5	44,5	40,7	-3,8	39,7	38,5	-1,2
6	29,8	34,7	4,9	36,1	36,2	0,1
7	31,6	31,8	0,3	32,7	32,6	-0,1
8	25,3	25,9	0,7	42,6	41,1	-1,5
Average	32,6	33,0	0,4	38,0	37,1	-1,0

6.6 General discussion

6.6.1 6 weeks storage trials

Extrapolation of results from other trials can not be done uncritically. There is many parameters, both known and unknown, in a trial that together contributes to the results. It is almost impossible to achieve exactly the same conditions in two storage trials. Therefore it is difficult to predict the result in one case, based on result from another case.

For example, when storing whole-tree chips in piles Bergman and Nilsson (1979) presented material losses in the region of 1-2 % per month. Gislerud (1974 and 1978) and Gislerud and Grönlien (1978) presented however losses of up to 4.8 % per month for similar material, se section 3.7.

The general trend of declining loss rate in this thesis work is in agreement with the results reported by Thörnqvist and Jirjis (1990). The losses were largest in the first week of storage and reached a plateau or a stagnation phase after about three weeks. In the reported study, the piles were much larger than the ones in this thesis (5 times the length and 1.5 times the width and height). Therefore, dry matter losses were doubled the ones measured in this study. In addition to larger pile size, the biomass type which was forest residues is known to support higher growth of microorganism which will lead to higher temperature development and higher dry matter losses. Higher dry matter losses in high moisture areas were evident in both Thörnqvist and Jirjis (1990) and in this study.

Jirjis and Lehtikangas (1998) study with similar properties concerning pile size, fuel and storage period showed also a redistribution of moisture to the upper parts but without a change in the overall moisture content. Gjölsjö (1994) also showed similar temperatures for two similar sized piles. He showed somewhat higher temperatures in a pile with smaller chips and lower in a pile with larger chips. The results of this thesis showed slightly higher temperatures in the waste wood pile. This could be due to larger proportion of small fraction in the waste wood pile compared to the stem wood pile. Similar observations were reported by Gjölsjö (1994) when storage of different sizes was studied.

Mitchel (1978) showed higher dry matter losses, 3.8 %/month, for chunks then for chips, 1.7 %/month. The losses were slightly higher in the waste wood pile in this study which might be explained by the same factor, particle size.

The temperature measurement had some problems with cable wear which gave some noise and some spikes in the signal. That was however successfully filtrated and the plotted temperatures are reliable. The data for the last week on both of the storage trials could not be fully captured. The temperature developments in both trials were moderate but significant higher than ambient temperature. Moderate temperatures inside the pile was suitable for many microbes since they have their temperature optimum in the region of 20 to 40 °C, which could explained the dry matter losses.

There were no or small changes in the average moisture content for each cross section during storage in both of the trials. The higher moisture content in the top point that could be seen in both of trials can be explained by the chimney effect. However, the fluctuations in the initial moisture content were high. It is difficult to correctly sample representative material for the initial moisture content since the waste wood was so heterogeneous. The moisture content will be different if for example some more stones or insulation materials ended up in one sample but not in the other one.

The ash content was generally higher after storage in almost all sections, except in waste wood stored for three weeks. The larger ash content was, as expected, in the regions with measurable dry matte losses. These changes are, however, uncertain since the waste wood was so heterogeneous and had a high and varying ash content. The material for ash content before storage was sampled from each point and the material for the ash content after storage was sampled from the same area and then placed in the pile. However it is not the same material. A heterogeneous material, as this waste wood, can have large natural variations which makes it very difficult to select a representative sample with the same properties.

The common method used to determine the dry matter losses has some weaknesses. The method is based on the assumption that two identical samples from the same area have the same moisture content. One used to determine the initial moisture content and the other one is placed in net plastic bags inside the pile. After storage bags are retrieved and weighted to determine the dry matter losses. Exactly the same material can't both be dried in order to calculate the moisture content and be stored. If the initial moisture content is not close enough due to for example, heterogeneous material, the dry matter losses can be miscalculated, i.e. under or over estimated. In the method other possible source of error is the possibility that fine fractions can adhere to or falls out from the sample bag. The sample bags with a positive dry matter loss, meaning an increase in dry matter inside the bag, could be explained by these weaknesses in the method. The heterogeneous material in the waste wood trial (lots of gravel, sand, metallic pieces, plastic, insulation material etc.) could make it even more complicated to correctly sample an initial moisture content that corresponds to the ones in the sample bags. There are alternative to the method used in this thesis work to determine the dry matter losses. One way is to study the change in ash content and from that calculate the losses. Another method could be to weight all of the stored fuel before and after and then sample the moisture content in order to calculate the losses. All of the known methods involve some approximations. The choice of method was based on previous experiences in this method. It is a well tested and commonly used method in these sorts of trials and the results could in that way more easily be compared to other ones.

If the bags with positive dry weight change are excluded from the calculations slightly larger dry matter losses are achieved but with the same general behaviour. Some of these points were obviously incorrect and influenced the overall results in some extent. These losses have to be dealt with somehow. The method used in this study is to eliminate them by replacing them with a zero value or an average of the accepted values from that storage part.

The change in gross heating value is affected by the large and varying ash content in the waste wood pile. It is difficult to obtain a representative sample from a waste wood pile which makes it extremely difficult to draw conclusions about the exact changes in energy contents. The change in net heating value and change in energy content in the waste wood case is unreliable for the same reason.

6.6.2 Heating surface trial

The heating surface was planned and constructed according to the same principals and with the same material as some other heated surfaces in Sweden, e.g. Råghustorget, the town hall square, in Helsingborg and the area outside the Malmö Stadsteater, city theatre (LK Ground heating systems, 2011). The difference was that waste heat water with higher temperature was used in this trial. These heated surfaces are used to keep the ground snow free.

The concept could, as shown in this thesis, act as a heat sink, prevent the ground from freezing but not to pre dry the fuel.

The temperature of the heated surface was quite high but there was almost no heat propagation further up in the pile. Wood chips are bad conductors of heat and the air movements in the pile were too low to reach a drying effect. There is however other methods for drying biomass and wood chips which in most cases involve larger fluid movements through the material. Conventional techniques use air, smoke gases or super heated steam.

7 Conclusions

Storage of waste wood during six weeks in unventilated outdoor pile resulted in some degradation of the fuel. The temperatures rose to a maximum of 30 °C. The moderate dry matter losses were largest during earlier weeks of storage and then reached a plateau after two weeks. Small negative changes in moisture content were observed but there were no significant drying effect. The results of changes in ash content, gross heating value, net heating value and change in energy content could be misleading due the heterogeneous material with large natural variations.

Storage of newly chipped stem wood during six weeks in unventilated outdoors pile resulted in dry matter losses in the same region as in the waste wood case. No major changes in moisture content could be observed. The ash content did become slightly higher during storage but it is in the expected region due to the dry matter loss of the organic material. Higher gross heating values were also observed after storage which also indicates fuel degradation, and the removal of especially low energy compounds.

Storage for six weeks did not cause any major deterioration of the fuel quality as such, beside the moderate substance losses.

Although the dry matter losses were less than one per cent per week it has economical consequences for the plant. A rough estimation shows losses in the order of 14 000 to 25 000 SEK per week and it is depending on the amount of stored fuel and the fuel prices. These losses can, however, be larger if the loss rate is larger than the one obtained in this thesis. Higher loss rate and thereby larger economical losses, estimated to double or four times as much can be expected in larger piles.

It is not possible to pre dry large amount of fuel on a heated surface. A heated surface can in some way act as a heat sink but the design used in this thesis work could not achieve the drying of the fuel.

8 Storage recommendations

The storage recommendation is based on both the results from storage trials at Idbäcken CHP-plant and a literature survey. The recommendations are valid for outdoor storage of wood chips in piles.

In order to minimize the dry matter losses:

- Try to store as dry fuel as possible since a high initial moisture content increase the risk for larger dry matter losses due to microbial activity. Seasoned material could have lower losses compared to fresh material due to the lower moisture content.

- Store the material according to the LIFO principle rather than FIFO to minimize the dry matter losses, especially when the material is fresh.

- Try to comminute the material as close in time as possible to the combustion process in order to reduce the dry matter losses.

- If possible when buying fuel, try to purchase fuel that has been stored for a while. There is a possibility that the largest losses already have occurred and the more easily degraded compounds are consumed. If possible avoid easily degradable and nitrogen rich material such as needles and bark in the fuel.

- If possible, try to store chips with larger particles since it could give less microbial activity due to more ventilation inside and less specific area for the microbes to attack.

- Try to build the piles in elongated strings with a width of double the height. When enlarging the pile try to make it longer and not wider and higher. In that way you can maximize the cooling effect from the surroundings and thereby both minimize the dry matter losses and the risk for spontaneous combustion. The loss rate is also often larger in larger piles.

In order to minimize the risk of spontaneous ignition inside the storage:

- Store the fuel in smaller piles rather than one big pile, since a larger size of the storage will result in greater risk of spontaneous combustion.

- Try to store as homogeneous material as possible in order to avoid or at least minimize the risk for spontaneous ignition inside the pile. The material should be homogenous concerning, fuel type, chip size, moisture content and degree of compaction. Do not store different fuels in the same pile.

- Avoid if possible metal pieces inside the piles since they can act as a catalyst for the ignition process.

- Try to observe changes in the pile and its temperature development.

In order to secure the employers health and maintain a healthy working environment:

- Wear protective mask when handling infected fuel.

- Store the fuel for as short time as possible.

- Store the fuel outdoors since the emissions will be diluted by the surrounding air.

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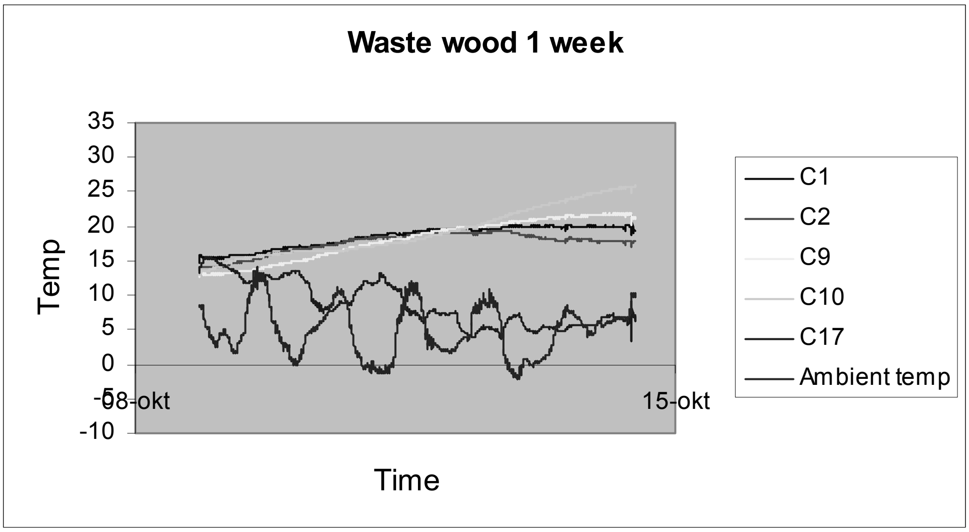
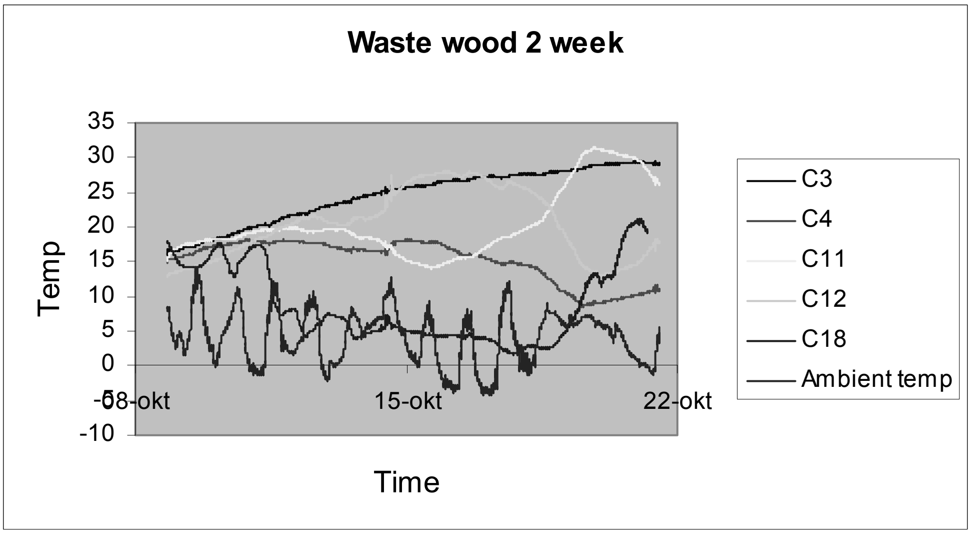
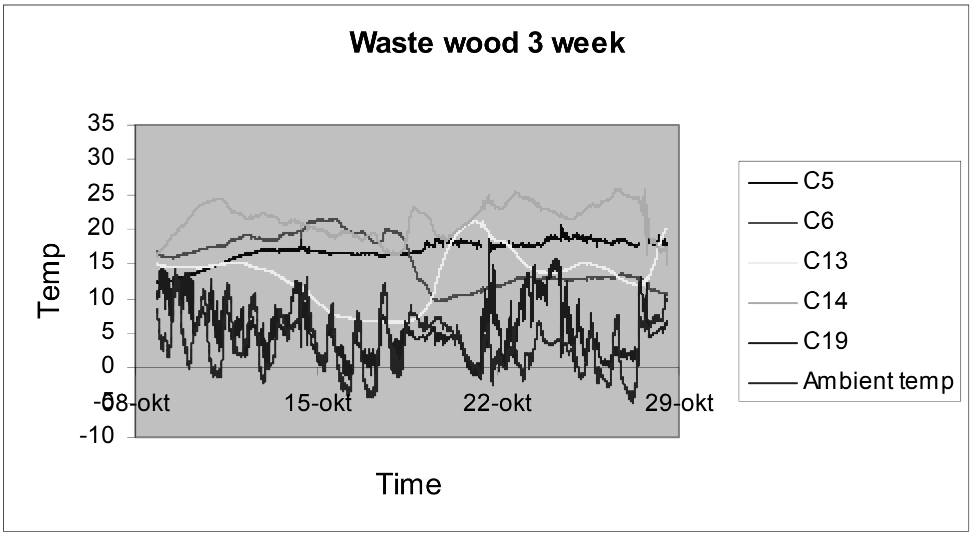
Appendix 1 Change in temperature in the 6 weeks trial

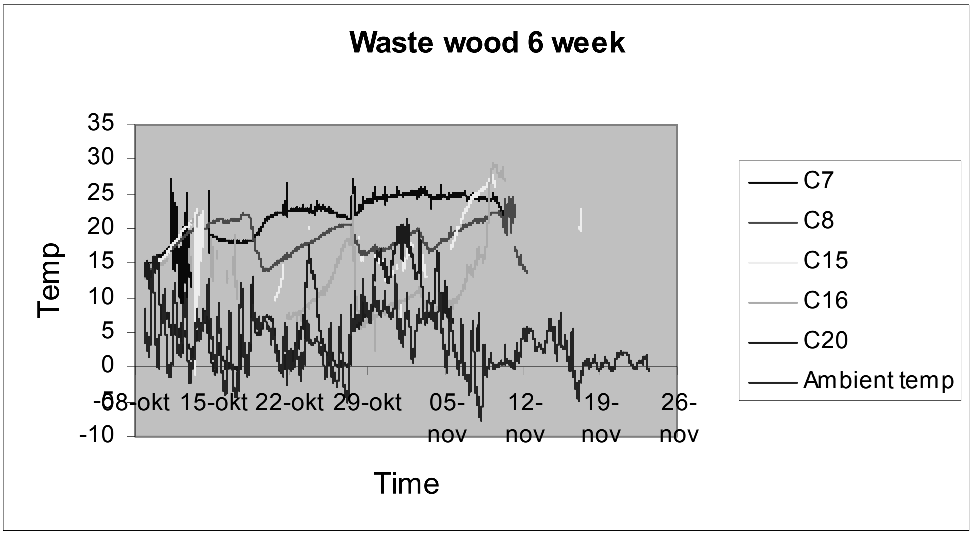
Waste wood

The temperatures measured in the waste wood pile in [°C].

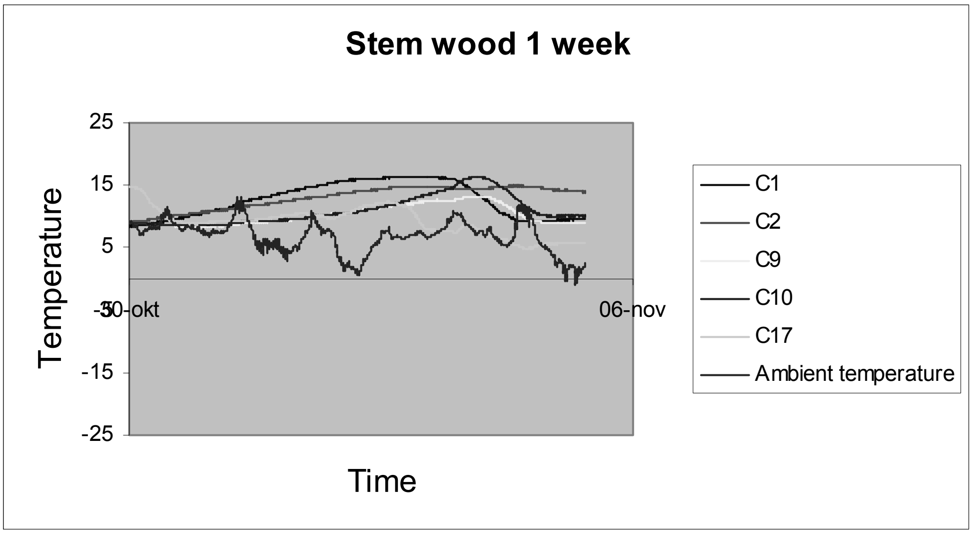


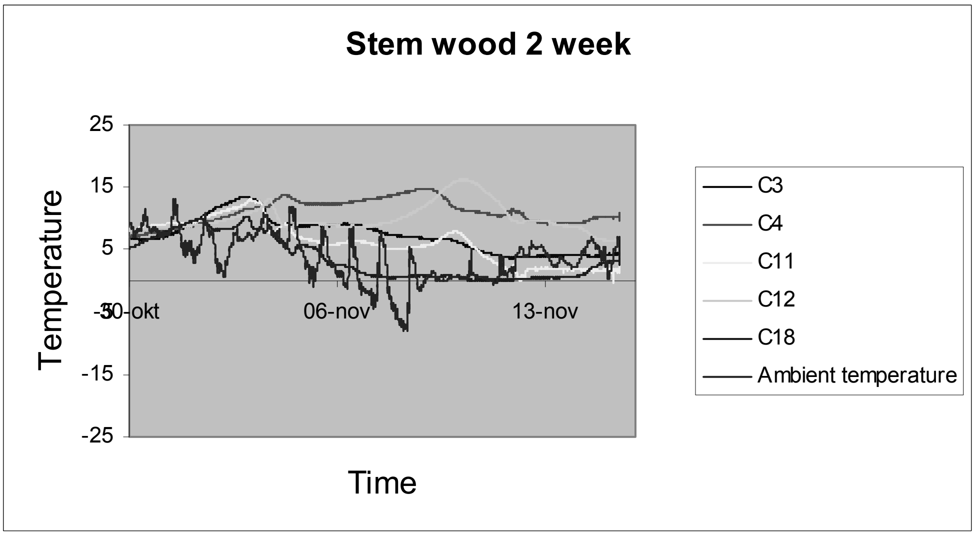


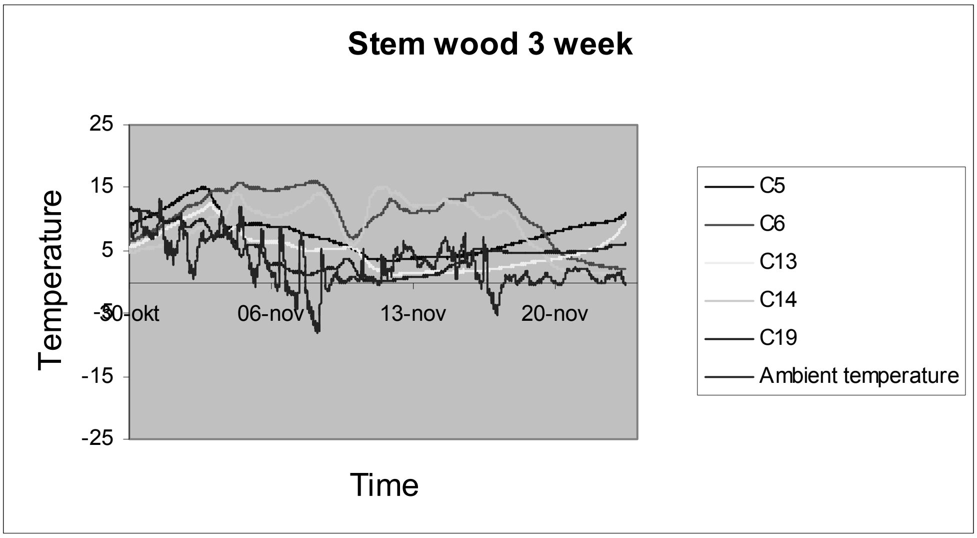

Waste wood 3 week
Temp
35
30
25
20
15
10
5
0
-5
-10
08-okt
15-okt
22-okt
29-okt
Time
C5
C6
C13
C14
C19
Ambient temp

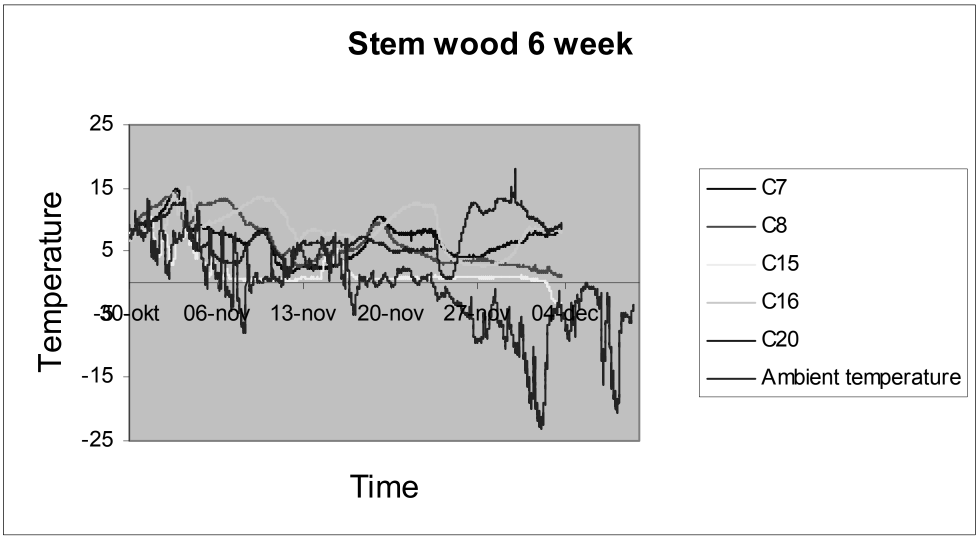

Waste wood 6 week
Temp
35
30
25
20
15
10
5
0
-5
-10
08-okt
15-okt
22-okt
29-okt
05-nov
12-nov
19-nov
26-nov
Time
C7
C8
C15
C16
C20
Ambient temp

Stem wood
The temperatures measured in the waste wood pile in [°C].






Stem wood 3 week
25
15
5
-5
-15
-25
Temperature
30-okt
06-nov
13-nov
20-nov
Time
C5
C6
C13
C14
C19
Ambient temperature


Stem wood 6 week
25
15
5
-5
-15
-25
Temperature
30-okt
06-nov
13-nov
20-nov
27-nov
04-dec
Time
C7
C8
C15
C16
C20
Ambient temperature

Appendix 2 DML and change in MC for 6 weeks storage trial

Waste Wood - DML and change in MC during storage for waste wood

All dry matter losses, moisture contents, change in moisture content for all sample points are listed below. An increase in moisture content is listed as a positive value and vice versa for a decrease. All points with negative losses larger then 1% and marked with a correction sign are replaced with zero values or average values in the figures below. Sample bags that were not found after storage has no moisture content and dry matter losses.

Storage time [weeks]	Sample bag	MC before [GW%]	App. DW before [g]	MC after [GW%]	DW after [g]	Change in MC incr.(+) /decr.(-) [%GW]	DML [%DM]	Correction
1 w	**1.1**	43.9%	216.7	46.7%	216.4	2.8%	0.1%	
1 w	**1.2**	43.9%	211.6	40.6%	207.2	-3.2%	2.1%	
1 w	**1.3**	43.9%	272.8					
1 w	**1.4**	43.9%	284.6	41.3%	284.8	-2.5%	-0.1%	
1 w	**2.1**	47.3%	192.8					
1 w	**2.2**	47.3%	231.3					
1 w	**2.3**	47.3%	208.5	49.4%	206.8	2.1%	0.8%	
1 w	**2.4**	47.3%	207.6					
1 w	**3.1**	48.9%	230.8	46.0%				
1 w	**3.2**	48.9%	181.8	45.8%	178.2	-3.1%	2.0%	
1 w	**3.3**	48.9%	299.2	48.3%	296.1	-0.6%	1.0%	
1 w	**3.4**	48.9%	282.4	44.0%	271.2	-5.0%	4.0%	
1 w	**4.1**	47.2%	191.1	47.2%	189.7	-0.1%	0.7%	
1 w	**4.2**	47.2%	290.9	48.7%	291.6	1.5%	-0.2%	
1 w	**4.3**	47.2%	143.8	49.3%	143.5	2.1%	0.2%	
1 w	**4.4**	47.2%	164.2	47.3%	160.3	0.1%	2.4%	
1 w	**5.1**	37.4%	229.1	37.0%	230.5	-0.4%	-0.6%	
1 w	**5.2**	37.4%	198.4	36.0%	203.0	-1.4%	-2.3%	←
1 w	**5.3**	37.4%	200.3	36.3%	198.8	-1.1%	0.7%	
1 w	**5.4**	37.4%	266.7	38.6%	262.2	1.2%	1.7%	
1 w	**6.1**	38.3%	335.8	34.9%	327.3	-3.3%	2.5%	
1 w	**6.2**	38.3%	409.2	37.8%	408.6	-0.5%	0.2%	
1 w	**6.3**	38.3%	277.1	36.9%	273.8	-1.4%	1.2%	
1 w	**6.4**	38.3%	171.6	35.2%	169.8	-3.1%	1.1%	
1 w	**7.1**	37.1%	218.1	39.7%	218.1	2.6%	0.0%	
1 w	**7.2**	37.1%	204.3	40.5%	204.7	3.3%	-0.2%	
1 w	**7.3**	37.1%	213.1	32.8%	213.6	-4.3%	-0.2%	
1 w	**7.4**	37.1%	219.4	33.3%	218.0	-3.8%	0.6%	

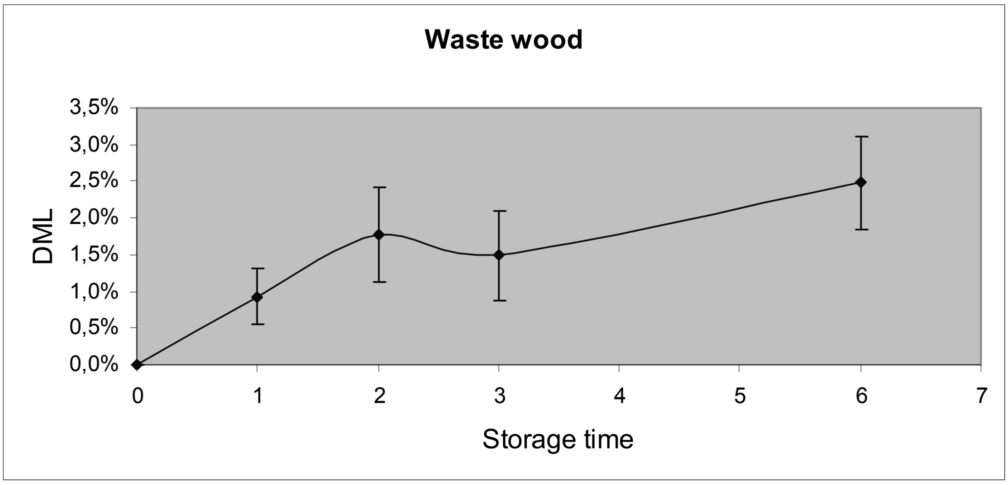
2 w	**1.1**	42.6%	249.6	42.3%	252.86	-0.3%	-1.3%	←
2 w	**1.2**	42.6%	326.5	38.8%	323.5	-3.8%	0.9%	
2 w	**1.3**	42.6%	338.6	38.3%	342.94	-4.3%	-1.3%	←
2 w	**1.4**	42.6%	326.0	43.7%	313.64	1.1%	3.8%	
2 w	**2.1**	46.2%	329.4	45.4%	332.12	-0.8%	-0.8%	
2 w	**2.2**	46.2%	394.0	46.8%	378.52	0.6%	3.9%	
2 w	**2.3**	46.2%	326.7	45.2%	325.39	-1.0%	0.4%	
2 w	**2.4**	46.2%	305.2	44.8%	311.2	-1.4%	-2.0%	←
2 w	**3.1**	46.3%	229.9	47.4%	228.91	1.1%	0.4%	
2 w	**3.2**	46.3%	299.2	44.1%	288.32	-2.2%	3.6%	
2 w	**3.3**	46.3%	205.2	45.6%	190.92	-0.7%	6.9%	
2 w	**3.4**	46.3%	307.4	46.1%	297.95	-0.2%	3.1%	
2 w	**4.1**	47.3%	272.3	46.2%	267.6	-1.2%	1.7%	
2 w	**4.2**	47.3%	328.6	46.1%	321.75	-1.2%	2.1%	
2 w	**4.3**	47.3%	367.9	47.1%	360.58	-0.3%	2.0%	
2 w	**4.4**	47.3%	434.8	46.5%	432.55	-0.9%	0.5%	
2 w	**5.1**	43.8%	245.0	40.1%	240.99	-3.8%	1.6%	
2 w	**5.2**	43.8%	400.0	36.9%	384.49	-6.9%	3.9%	
2 w	**5.3**	43.8%	301.7	39.4%	301.21	-4.4%	0.2%	
2 w	**5.4**	43.8%	319.7	37.3%	312.85	-6.5%	2.1%	
2 w	**6.1**	41.2%	344.6	39.2%	340.32	-2.0%	1.2%	
2 w	**6.2**	41.2%	304.6	39.2%	300.99	-2.0%	1.2%	
2 w	**6.3**	41.2%	241.7	40.2%	236.14	-1.0%	2.3%	
2 w	**6.4**	41.2%	296.4	39.5%	288.55	-1.7%	2.6%	
2 w	**7.1**	36.3%	186.1	42.3%	188.12	6.0%	-1.1%	
2 w	**7.2**	36.3%	258.1	41.7%	257.11	5.4%	0.4%	
2 w	**7.3**	36.3%	239.0	33.4%	235.69	-2.9%	1.4%	
2 w	**7.4**	36.3%	190.5	30.5%	191.83	-5.8%	-0.7%	

3 w	**1.1**	44.7%	339.0	44.0%	336.9	-0.7%	0.6%	
3 w	**1.2**	44.7%	266.5					
3 w	**1.3**	44.7%	293.1	44.3%	292.2	-0.4%	0.3%	
3 w	**1.4**	44.7%	352.3	42.8%	348.2	-1.9%	1.2%	
3 w	**2.1**	47.6%	309.5	45.2%	300.8	-2.4%	2.8%	
3 w	**2.2**	47.6%	262.4	37.1%	248.4	-10.5%	5.3%	
3 w	**2.3**	47.6%	273.9	43.2%	266.9	-4.4%	2.6%	
3 w	**2.4**	47.6%	291.7	42.4%	284.4	-5.2%	2.5%	
3 w	**3.1**	45.3%	211.6	41.3%	207.3	-4.1%	2.0%	
3 w	**3.2**	45.3%	322.0	40.7%	317.9	-4.6%	1.3%	
3 w	**3.3**	45.3%	326.4	43.3%	323.6	-2.0%	0.8%	
3 w	**3.4**	45.3%	286.5	40.3%	281.9	-5.0%	1.6%	
3 w	**4.1**	43.5%	267.9	42.3%	265.9	-1.2%	0.8%	
3 w	**4.2**	43.5%	260.0					
3 w	**4.3**	43.5%	269.6	41.7%	269.8	-1.8%	-0.1%	
3 w	**4.4**	43.5%	352.2	40.3%	352.9	-3.2%	-0.2%	
3 w	**5.1**	38.6%	292.2	34.4%	283.5	-4.2%	3.0%	
3 w	**5.2**	38.6%	254.8	35.8%	255.6	-2.8%	-0.3%	
3 w	**5.3**	38.6%	275.7	35.2%	273.5	-3.4%	0.8%	
3 w	**5.4**	38.6%	313.1	35.4%	310.2	-3.2%	0.9%	
3 w	**6.1**	37.8%	389.0	33.9%	381.2	-3.8%	2.0%	
3 w	**6.2**	37.8%	298.8	29.6%	282.2	-8.2%	5.5%	
3 w	**6.3**	37.8%	336.7	29.2%	326.5	-8.6%	3.0%	
3 w	**6.4**	37.8%	441.9	30.5%	422.6	-7.3%	4.4%	
3 w	**7.1**	40.7%	188.6	46.0%	198.9	5.2%	-5.5%	←
3 w	**7.2**	40.7%	183.2	50.2%	183.3	9.5%	-0.1%	
3 w	**7.3**	40.7%	185.5	43.2%	184.8	2.4%	0.4%	
3 w	**7.4**	40.7%	273.8	49.8%	274.8	9.0%	-0.4%	

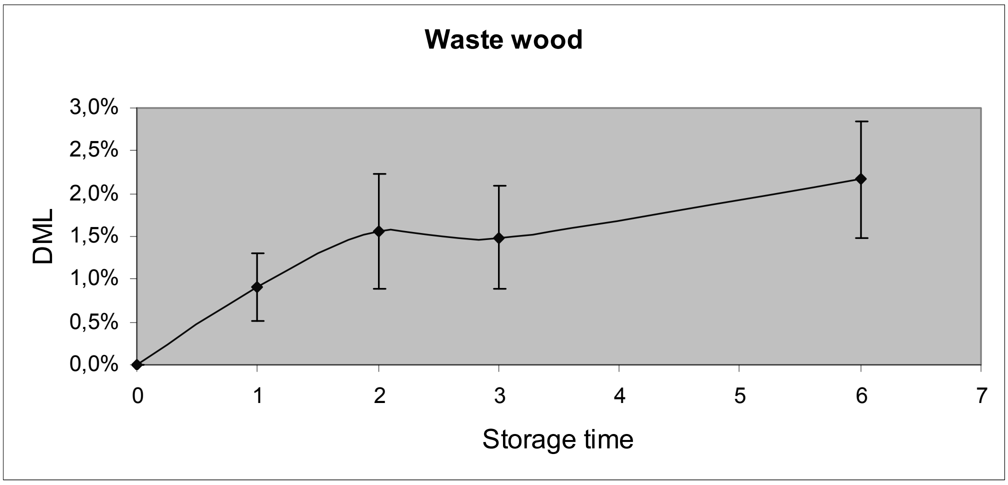
6 w	**1.1**	42.1%	208.8	33.5%	204.5	-8.6%	2.1%	
6 w	**1.2**	42.1%	226.8	40.3%	223.4	-1.9%	1.5%	
6 w	**1.3**	42.1%	295.6	36.2%	291.4	-5.9%	1.4%	
6 w	**1.4**	42.1%	216.9	36.4%	214.3	-5.8%	1.2%	
6 w	**2.1**	46.2%	292.3	41.3%	282.6	-4.9%	3.3%	
6 w	**2.2**	46.2%	278.3	39.8%	267.7	-6.4%	3.8%	
6 w	**2.3**	46.2%	316.0	45.7%	320.5	-0.5%	-1.4%	←
6 w	**2.4**	46.2%	296.0	39.1%	286.3	-7.0%	3.3%	
6 w	**3.1**	41.2%	240.4					
6 w	**3.2**	41.2%	298.6	41.1%	289.3	-0.1%	3.1%	
6 w	**3.3**	41.2%	334.5	41.5%	323.2	0.3%	3.4%	
6 w	**3.4**	41.2%	326.2	37.9%	319.9	-3.3%	1.9%	
6 w	**4.1**	45.5%	260.4	42.6%	251.5	-2.9%	3.4%	
6 w	**4.2**	45.5%	243.5	37.0%	246.6	-8.5%	-1.3%	←
6 w	**4.3**	45.5%	370.5	37.9%	358.6	-7.7%	3.2%	
6 w	**4.4**	45.5%	308.4	37.0%	295.4	-8.5%	4.2%	
6 w	**5.1**	39.3%	264.1	34.6%	259.1	-4.7%	1.9%	
6 w	**5.2**	39.3%	214.9	39.9%	212.2	0.6%	1.3%	
6 w	**5.3**	39.3%	315.7	35.4%	309.5	-3.9%	2.0%	
6 w	**5.4**	39.3%	224.1	33.8%	230.7	-5.5%	-3.0%	←
6 w	**6.1**	38.3%	261.5	36.5%	253.4	-1.9%	3.1%	
6 w	**6.2**	38.3%	225.1	28.3%	207.5	-10.0%	7.8%	
6 w	**6.3**	38.3%	233.8	35.9%	224.2	-2.4%	4.1%	
6 w	**6.4**	38.3%	188.1	38.4%	183.6	0.1%	2.4%	
6 w	**7.1**	41.9%	197.0	49.8%	197.4	8.0%	-0.2%	
6 w	**7.2**	41.9%	231.3	54.0%	233.6	12.1%	-1.0%	
6 w	**7.3**	41.9%	174.4	54.3%	173.4	12.4%	0.6%	
6 w	**7.4**	41.9%	206.9	51.1%	207.1	9.2%	-0.1%	

Waste wood

The negative losses which could be found in some of the sample bags are here replaced with an average from the other losses at the same measuring point. All sample bags with negative losses larger than 1 % are eliminated.



The negative losses larger than 1% is here replaced with zero losses, 0%.



Stem Wood - DML and change in MC during storage for stem wood

All dry matter losses, moisture contents, change in moisture content for all sample points are listed below. An increase in moisture content is listed as a positive value and vice versa for a decrease. All points with negative losses larger then 1% and marked with a correction sign are replaced with zero values or average values in the figures below. Sample bags that were not found after storage has no moisture content and dry matter losses.

Storage time [weeks]	Sample bag	MC before [GW%]	App. DW before [g]	MC after [GW%]	DW after [g]	Change in MC incr.(+) /decr.(-) [%GW]	DML [%DM]	Correction
1 w	**1.1**	43.8%	427.9	43.4%	425.6	-0.4%	0.5%	
1 w	**1.2**	43.8%	339.0	44.1%	335.0	0.3%	1.2%	
1 w	**1.3**	43.8%	440.3	42.5%	439.8	-1.3%	0.1%	
1 w	**1.4**	43.8%	316.1	44.1%	313.5	0.3%	0.8%	
1 w	**2.1**	45.1%	274.9	45.5%	271.4	0.4%	1.3%	
1 w	**2.2**	45.1%	294.1	43.6%	288.5	-1.5%	1.9%	
1 w	**2.3**	45.1%	274.9	45.8%	269.5	0.7%	2.0%	
1 w	**2.4**	45.1%	284.8	47.4%	284.5	2.2%	0.1%	
1 w	**3.1**	45.75%	326.6	44.5%	326.8	-1.2%	-0.1%	
1 w	**3.2**	45.75%	330.9	46.1%	323.3	0.4%	2.3%	
1 w	**3.3**	45.75%	352.6	45.8%	347.6	0.0%	1.4%	
1 w	**3.4**	45.75%	354.2	46.2%	348.5	0.5%	1.6%	
1 w	**4.1**	46.0%	345.9	46.0%	339.4	0.1%	1.9%	
1 w	**4.2**	46.0%	278.9	46.3%	275.1	0.3%	1.3%	
1 w	**4.3**	46.0%	288.6	45.3%	282.0	-0.7%	2.3%	
1 w	**4.4**	46.0%	262.4	46.4%	261.5	0.4%	0.3%	
1 w	**5.1**	41.1%	275.0	42.1%	269.7	1.0%	1.9%	
1 w	**5.2**	41.1%	282.1	42.3%	275.9	1.2%	2.2%	
1 w	**5.3**	41.1%	220.9	41.4%	219.2	0.3%	0.7%	
1 w	**5.4**	41.1%	192.6	38.9%	199.1	-2.2%	-3.4%	←
1 w	**6.1**	42.8%	241.4	44.4%	237.7	1.7%	1.5%	
1 w	**6.2**	42.8%	282.7	43.2%	280.1	0.4%	0.9%	
1 w	**6.3**	42.8%	304.5	43.0%	302.3	0.3%	0.7%	
1 w	**6.4**	42.8%	368.0	42.3%	359.6	-0.5%	2.3%	
1 w	**7.1**	41.3%	230.3	39.2%	231.1	-2.0%	-0.4%	
1 w	**7.2**	41.3%	195.0	45.2%	191.9	3.9%	1.6%	
1 w	**7.3**	41.3%	245.6	44.2%	246.0	3.0%	-0.2%	
1 w	**7.4**	41.3%	218.5	40.3%	219.6	-0.9%	-0.5%	

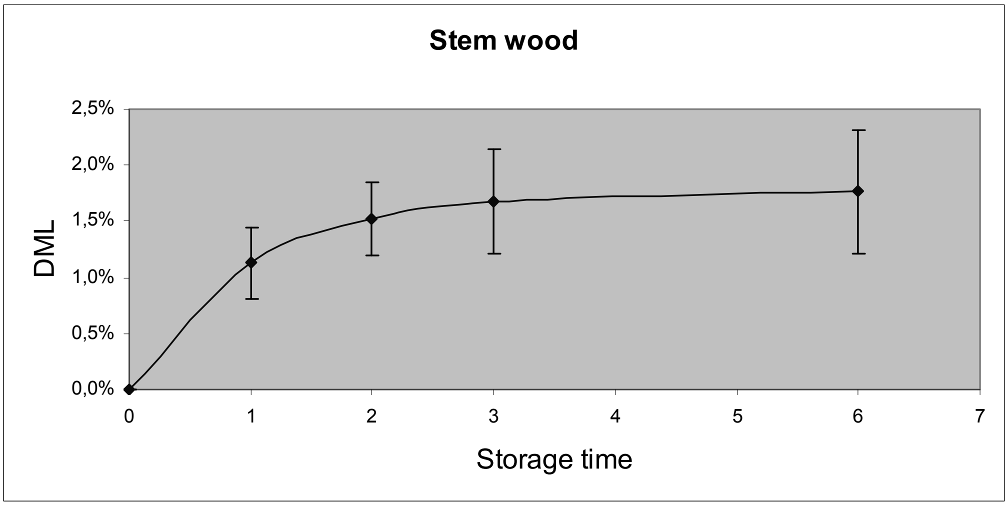
2 w	**1.1**	45.1%	280.7	44.0%	275.2	-1.1%	2.0%
2 w	**1.2**	45.1%	307.6	48.3%	303.3	3.3%	1.4%
2 w	**1.3**	45.1%	252.2	45.7%	250	0.6%	0.9%
2 w	**1.4**	45.1%	297.7	45.7%	294.6	0.6%	1.1%
2 w	**2.1**	44.2%	250.5	45.6%	247.3	1.4%	1.3%
2 w	**2.2**	44.2%	289.1	44.9%	284.1	0.7%	1.7%
2 w	**2.3**	44.2%	282.1	45.6%	277.3	1.4%	1.7%
2 w	**2.4**	44.2%	280.7	46.0%	276.5	1.9%	1.5%
2 w	**3.1**	46.3%	287.0	47.0%	278.1	0.7%	3.1%
2 w	**3.2**	46.3%	300.7	45.7%	295.4	-0.7%	1.8%
2 w	**3.3**	46.3%	255.8	48.1%	249.6	1.8%	2.4%
2 w	**3.4**	46.3%	288.3	46.3%	281.2	0.0%	2.5%
2 w	**4.1**	44.6%	265.4	47.1%	257.5	2.5%	3.0%
2 w	**4.2**	44.6%	257.1	46.4%	251	1.8%	2.4%
2 w	**4.3**	44.6%	262.7	49.6%	256	5.0%	2.5%
2 w	**4.4**	44.6%	250.2	47.0%	246.9	2.4%	1.3%
2 w	**5.1**	40.5%	275.3	42.7%	272.6	2.3%	1.0%
2 w	**5.2**	40.5%	270.4	44.7%	265.1	4.3%	1.9%
2 w	**5.3**	40.5%	298.9	47.0%	296.5	6.5%	0.8%
2 w	**5.4**	40.5%	269.2	45.5%	267.6	5.1%	0.6%
2 w	**6.1**	40.1%	270.2	39.0%	268.8	-1.1%	0.5%
2 w	**6.2**	40.1%	253.1	40.4%	249.1	0.3%	1.6%
2 w	**6.3**	40.1%	272.0	41.0%	266	0.9%	2.2%
2 w	**6.4**	40.1%	282.8	45.0%	276	4.9%	2.4%
2 w	**7.1**	34.7%	248.9	44.9%	249.4	10.2%	-0.2%
2 w	**7.2**	34.7%	243.0	48.3%	242.6	13.7%	0.2%
2 w	**7.3**	34.7%	231.3	46.0%	228.6	11.4%	1.2%
2 w	**7.4**	34.7%	171.2	44.2%	171.3	9.6%	-0.1%

3 w	**1.1**	47.4%	268.4	47.8%	260.1	0.4%	3.1%	
3 w	**1.2**	47.4%	255.8	49.0%	250.7	1.6%	2.0%	
3 w	**1.3**	47.4%	300.0	44.9%	306.4	-2.5%	-2.1%	←
3 w	**1.4**	47.4%	271.6	47.4%	263.7	0.1%	2.9%	
3 w	**2.1**	46.9%	341.8	47.0%	329.5	0.1%	3.6%	
3 w	**2.2**	46.9%	264.2	45.0%	263.4	-1.9%	0.3%	
3 w	**2.3**	46.9%	325.8					
3 w	**2.4**	46.9%	317.8	45.5%	313.6	-1.4%	1.3%	
3 w	**3.1**	42.3%	274.0	41.5%	268.5	-0.9%	2.0%	
3 w	**3.2**	42.3%	282.6	45.2%	275.2	2.9%	2.6%	
3 w	**3.3**	42.3%	298.8	42.9%	286.9	0.6%	4.0%	
3 w	**3.4**	42.3%	319.0	41.2%	312.9	-1.1%	1.9%	
3 w	**4.1**	39.03%	281.1	41.2%				
3 w	**4.2**	39.03%	331.1	50.0%	335.4	10.9%	-1.3%	
3 w	**4.3**	39.03%	304.8					
3 w	**4.4**	39.03%	242.7	47.2%	244.5	8.2%	-0.8%	
3 w	**5.1**	41.1%	236.1	40.9%	235.1	-0.3%	0.4%	
3 w	**5.2**	41.1%	240.8	45.2%	236.5	4.1%	1.8%	
3 w	**5.3**	41.1%	231.7	36.9%	222.8	-4.2%	3.8%	
3 w	**5.4**	41.1%	278.8	41.3%	274.8	0.2%	1.4%	
3 w	**6.1**	40.1%	307.7	44.2%	304.8	4.1%	0.9%	
3 w	**6.2**	40.1%	251.7	40.1%	246.5	0.0%	2.1%	
3 w	**6.3**	40.1%	244.8	44.7%	239.7	4.6%	2.1%	
3 w	**6.4**	40.1%	246.9	45.9%	240.8	5.8%	2.5%	
3 w	**7.1**	35.9%	198.0	51.9%	208.5	16.0%	-5.3%	←
3 w	**7.2**	35.9%	289.6	50.5%	292.8	14.6%	-1.1%	←
3 w	**7.3**	35.9%	253.7	51.8%	251.6	15.8%	0.8%	
3 w	**7.4**	35.9%	264.0	47.2%	264.7	11.3%	-0.3%	

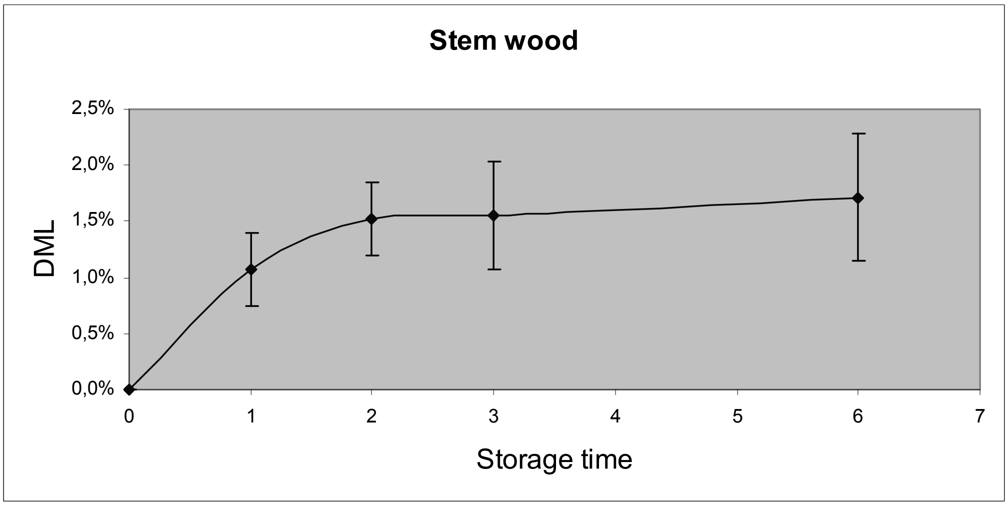
6 w	**1.1**	46.4%	294.6	50.5%	288.2	4.1%	2.2%	
6 w	**1.2**	46.4%	293.0	45.7%	287.3	-0.7%	1.9%	
6 w	**1.3**	46.4%	292.2	46.6%	286.4	0.2%	2.0%	
6 w	**1.4**	46.4%	298.1	49.0%	289.9	2.6%	2.7%	
6 w	**2.1**	46.9%	301.2	45.9%	288.4	-0.9%	4.3%	
6 w	**2.2**	46.9%	247.6	44.5%	241.8	-2.4%	2.3%	
6 w	**2.3**	46.9%	270.4	45.6%	260.8	-1.3%	3.5%	
6 w	**2.4**	46.9%	286.3	44.6%	277.9	-2.3%	2.9%	
6 w	**3.1**	46.2%	354.5	45.1%	347	-1.1%	2.1%	
6 w	**3.2**	46.2%	225.7	46.2%	219.5	0.0%	2.7%	
6 w	**3.3**	46.2%	273.3	43.4%	274.3	-2.8%	-0.4%	
6 w	**3.4**	46.2%	285.6	43.1%	290.5	-3.1%	-1.7%	←
6 w	**4.1**	53.0%	275.2	43.4%	262.3	-9.5%	4.7%	
6 w	**4.2**	53.0%	255.6	46.5%	255.1	-6.5%	0.2%	
6 w	**4.3**	53.0%	282.7	45.8%	271.6	-7.1%	3.9%	
6 w	**4.4**	53.0%	294.9	47.8%	293.8	-5.2%	0.4%	
6 w	**5.1**	31.9%	206.5	30.2%	207.9	-1.7%	-0.7%	
6 w	**5.2**	31.9%	241.2	35.1%	233.8	3.2%	3.1%	
6 w	**5.3**	31.9%	212.9	33.9%	209.5	2.0%	1.6%	
6 w	**5.4**	31.9%	302.5	34.4%	298.6	2.6%	1.3%	
6 w	**6.1**	36.7%	236.7	44.3%	233.6	7.6%	1.3%	
6 w	**6.2**	36.7%	299.7	37.5%	289.2	0.8%	3.5%	
6 w	**6.3**	36.7%	306.9	41.9%	303.3	5.2%	1.2%	
6 w	**6.4**	36.7%	241.8	41.8%	240.6	5.1%	0.5%	
6 w	**7.1**	36.4%						
6 w	**7.2**	36.4%	268.6	47.5%	266.4	11.1%	0.8%	
6 w	**7.3**	36.4%	302.4	52.0%	303.3	15.6%	-0.3%	
6 w	**7.4**	36.4%	317.8	53.0%	317.8	16.6%	0.0%	

Stem wood

The negative losses which could be found in some of the sample bags are here replaced with an average from the other losses at the same measuring point. All sample bags with negative losses larger than 1 % are eliminated.



The negative losses larger than 1% is here replaced with zero losses, 0%.



Appendix 3 Change in AC for the 6 weeks storage trials

Waste wood

Ash content for all 28 measuring points and for the, from 4 sample bags, merged sample for all 28 measuring points are listed below. Two ash contents are calculated for each measuring point both before and after.

Ash content, AC [%DM]				Ash content, AC [%DM]			
		Initial	After storage			Initial	After storage
1 w	1	11.86%	13.29%	3 w	1	19.38%	27.56%
		11.77%	12.81%			19.60%	27.55%
	2	14.65%	15.25%		2	27.66%	28.82%
		14.83%	15.22%			27.02%	27.76%
	3	16.13%	9.82%		3	32.08%	29.74%
		16.80%	10.41%			31.35%	29.93%
	4	8.05%	9.73%		4	30.94%	21.88%
		8.29%	10.00%			31.49%	23.80%
	5	13.58%	12.09%		5	15.24%	15.53%
		13.54%	11.93%			15.61%	15.52%
	6	15.62%	22.28%		6	17.73%	17.04%
		15.23%	22.41%			17.71%	17.20%
	7	7.57%	5.98%		7	10.59%	10.93%
		7.49%	5.87%			10.63%	10.90%
2 w	1	16.96%	18.47%	6 w	1	12.45%	15.43%
		16.99%	18.33%			12.35%	15.64%
	2	16.95%	15.88%		2	22.55%	18.92%
		17.14%	15.63%			23.38%	19.41%
	3	22.71%	25.03%		3	23.71%	29.76%
		22.97%	24.84%			23.82%	29.29%
	4	17.52%	19.05%		4	28.89%	27.11%
		17.40%	18.86%			28.86%	27.37%
	5	9.11%	6.14%		5	25.43%	22.63%
		8.75%	6.35%			25.88%	21.57%
	6	12.74%	15.24%		6	28.44%	30.71%
		13.28%	15.32%			29.34%	28.43%
	7	14.17%	13.92%		7	7.62%	9.51%
		14.07%	13.90%			7.48%	10.20%

Stem wood

Initial ash content for all 28 measuring points and for the, from 4 sample bags, merged sample for all 28 measuring points are listed below. Two ash contents are calculated for each measuring point both before and after.

Ash content, AC [%DM]			
		Initial	After storage
1 w	1	0.71%	0.88%
		0.73%	0.90%
	2	0.61%	0.74%
		0.64%	0.71%
	3	0.90%	0.89%
		0.85%	0.85%
	4	0.48%	0.55%
		0.50%	0.56%
	5	0.54%	0.60%
		0.52%	0.58%
	6	1.32%	1.28%
		1.25%	1.24%
	7	0.65%	0.69%
		0.71%	0.68%
2 w	1	0.34%	0.74%
		0.44%	0.69%
	2	0.81%	0.83%
		0.85%	0.77%
	3	0.46%	0.76%
		0.49%	0.79%
	4	0.78%	0.64%
		0.83%	0.67%
	5	0.58%	0.66%
		0.49%	0.68%
	6	0.71%	0.67%
		0.69%	0.67%
	7	0.62%	0.58%
		0.65%	0.55%

Ash content, AC [%DM]			
		Initial	After storage
3 w	1	0.37%	0.69%
		0.44%	0.73%
	2	0.93%	0.82%
		0.81%	0.84%
	3	0.64%	0.63%
		0.68%	0.68%
	4	0.98%	0.75%
		0.93%	0.77%
	5	0.58%	0.60%
		0.67%	0.58%
	6	0.64%	0.74%
		0.68%	0.73%
	7	0.36%	0.57%
		0.36%	0.54%
6 w	1	0.99%	0.86%
		0.82%	0.86%
	2	0.51%	0.61%
		0.43%	0.61%
	3	0.53%	0.57%
		0.51%	0.59%
	4	0.53%	0.79%
		0.53%	0.89%
	5	0.63%	0.69%
		0.86%	0.68%
	6	0.37%	0.55%
		0.25%	0.57%
	7	0.52%	0.61%
		0.59%	0.64%

Appendix 4 Gross and net heating values for the 6 weeks storage trials

Waste wood

Initial gross heating value for all 28 measuring points and for the, from the 4 sample bags, merged sample for all 28 measuring points are listed below. Two gross heating values are measured for each measuring point both before and after. The net heating values are calculated from the mean value of the gross heating value and moisture content for that measuring point.

		Gross Heating value, Wgross [MJ/kg]		Net Heating value, Wnet [MJ/kg]	
		Initial	After storage	Initial	After storage
1 w	1	16.07	17.86		
		16.13	17.78	12.9	14.7
	2	17.69	17.38		
		17.63	17.47	14.1	13.7
	3	17.21	18.26		
		17.16	18.25	13.5	14.8
	4	17.57	18.23		
		17.63	18.16	14.1	14.6
	5	17.92	18.24		
		17.86	18.15	15.1	15.4
	6	17.12	14.50		
		17.16	14.44	14.3	11.8
	7	19.01	19.29		
		19.06	19.29	16.3	16.6
2 w	1	17.01	16.87		
		16.93	16.96	13.8	13.9
	2	17.25	15.64		
		17.18	15.51	13.8	12.2
	3	15.30	14.43		
		15.22	14.50	11.8	11.1
	4	17.06	16.85		
		17.01	17.16	13.5	13.6
	5	18.55	17.44		
		18.47	17.39	15.3	14.6
	6	18.01	17.25		
		17.94	17.28	14.9	14.3
	7	17.55	17.89		
		17.59	17.97	14.9	15.2

3 w	1	17.06	14.90		
		16.98	14.87	13.7	11.7
	2	14.91	14.89		
		14.84	14.85	11.3	11.8
	3	14.57	16.26		
		14.52	16.32	11.2	13.2
	4	14.48	15.93		
		14.53	15.87	11.3	12.8
	5	17.44	17.72		
		17.50	17.61	14.6	15.0
	6	17.12	17.02		
		17.06	16.94	14.3	14.6
	7	16.23	16.36		
		16.33	16.28	13.3	12.8
6 w	1	17.09	17.17		
		16.98	17.13	13.9	14.4
	2	15.23	17.03		
		15.16	17.06	11.8	14.0
	3	15.75	14.54		
		15.85	14.60	12.8	11.6
	4	14.07	15.01		
		14.15	15.00	10.7	12.1
	5	15.69	16.27		
		15.60	16.05	12.7	13.5
	6	14.51	14.76		
		14.50	14.67	11.7	12.1
	7	18.97	18.32		
		19.04	18.32	15.9	14.3

Stem wood

Initial gross heating value for all 28 measuring points and for the, from the 4 sample bags, merged sample for all 28 measuring points are listed below. Two gross heating values are measured for each measuring point both before and after. The net heating values are calculated from the mean value of the gross heating value and moisture content for that measuring point.

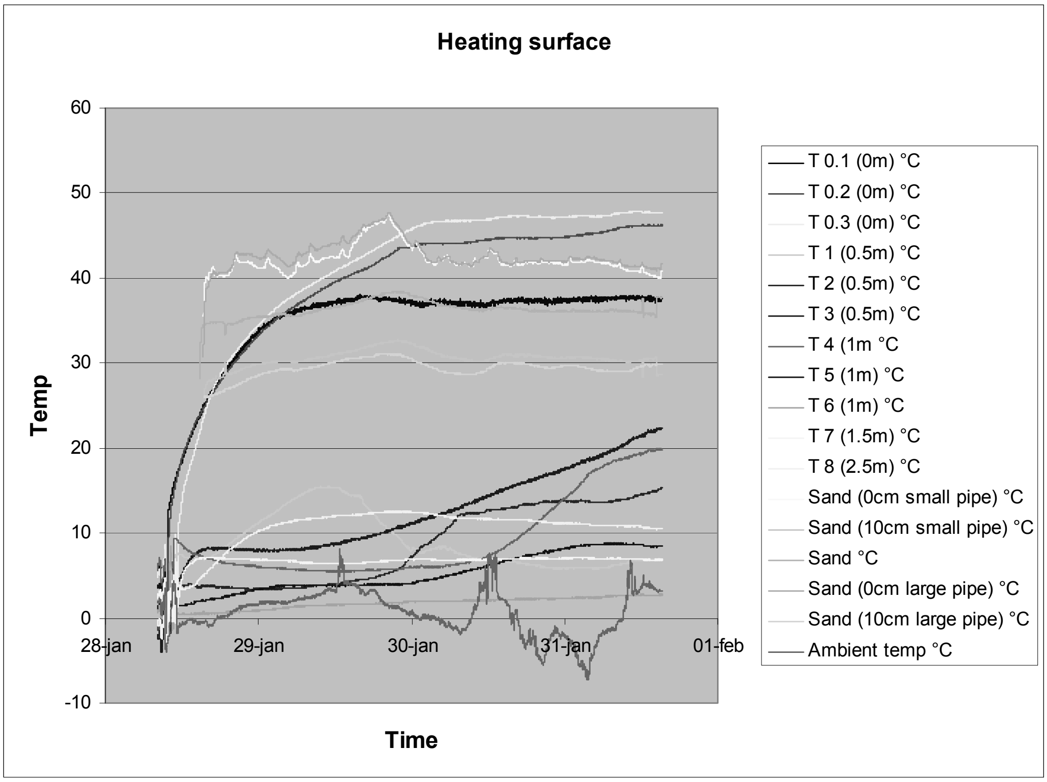
		Gross Heating value, Wgross [MJ/kg]		Net Heating value, Wnet [MJ/kg]	
		Initial	After storage	Initial	After storage
1 w	1	19.86	19.96		
		19.95	19.91	16.7	16.7
	2	19.86	19.97		
		19.86	19.95	16.5	16.6
	3	20.15	20.11		
		20.05	20.09	16.7	16.7
	4	19.84	19.87		
		19.90	19.92	16.5	16.5
	5	20.01	20.12		
		19.99	20.07	17.0	17.1
	6	19.77	19.68		
		19.75	19.76	16.6	16.5
	7	19.85	19.93		
		19.92	19.87	16.8	16.8
2 w	1	19.75	20.00		
		19.82	19.98	16.4	16.6
	2	19.89	19.99		
		20.00	19.87	16.7	16.6
	3	19.84	19.99		
		19.76	19.95	16.4	16.5
	4	19.67	19.94		
		19.77	19.87	16.4	16.4
	5	19.87	19.93		
		19.96	19.99	16.9	16.6
	6	19.98	20.19		
		19.91	20.12	17.0	17.1
	7	20.04	20.13		
		20.05	20.07	17.4	16.7

3 w	1	20.01	20.15		
		19.93	20.13	16.4	16.6
	2	19.87	19.56		
		19.96	19.82	16.4	16.3
	3	19.97	19.97		
		20.03	19.93	16.9	16.8
	4	20.01	20.02		
		20.01	20.15	17.1	16.7
	5	19.97	19.94		
		19.96	19.99	16.9	16.9
	6	20.10	20.07		
		20.04	20.00	17.1	16.8
	7	19.96	20.03		
		20.00	20.05	17.3	16.2
6 w	1	19.93	20.00		
		19.96	19.92	16.5	16.4
	2	19.87	19.86		
		19.97	19.98	16.4	16.6
	3	20.01	19.93		
		20.02	20.02	16.6	16.7
	4	20.03	19.97		
		20.01	20.09	15.9	16.6
	5	20.03	19.59		
		19.97	19.62	17.5	17.1
	6	20.01	20.00		
		20.07	20.04	17.3	17.0
	7	19.94	19.87		
		20.02	19.94	17.3	16.0

Appendix 5 Temperatures in the heating surface trial

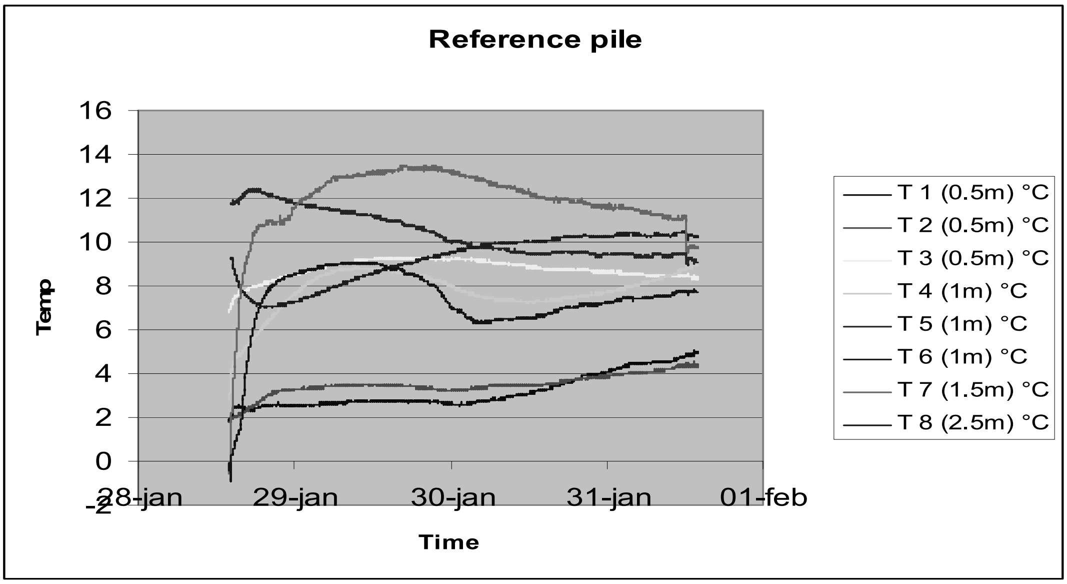
Heated surface

Temperatures measured in the pile on the heated surface. The temperature was measured at 5 places in the sand, 3 places directly on the surface below the pile and at eight places in the pile.



Reference pile

Temperatures measured in the reference pile. The temperatures were measured at eight places in the pile in 3 different heights.



Appendix 6 Changes in MC in the heating surface trial

Heated surface

Initial moisture content and the moisture content after storage for the eight measuring points. 2 sample bags were used to analyze the moisture content after storage in order to more easily find them. (-) indicates that the sample bag not could be found.

Heating surface storage

Sample point	Initial	After storage
1	33.8%	35.2%
		34.1%
2	40.0%	-
		-
3	26.9%	27.3%
		29.1%
4	36.6%	32.2%
		37.6%
5	44.5%	40.0%
		41.4%
6	29.8%	33.4%
		36.1%
7	31.6%	25.6%
		38.1%
8	25.3%	26.0%
		25.8%
Mean	33.5%	33.6%

Reference pile

Initial moisture content and the moisture content after for the eight measuring points. 2 sample bags were used to analyze the moisture content after storage in order to more easily find them. (-) indicates that the sample bag not could be found.

Reference storage

Sample point	Initial	After storage
1	31.5%	-
		-
2	41.4%	40.0%
		-
3	37.9%	38.3%
		-
4	35.7%	-
		32.9%
5	39.7%	35.3%
		41.7%
6	36.1%	-
		36.2%
7	32.7%	36.5%
		28.7%
8	42.6%	40.2%
		41.9%
Mean	37.2%	37.2%

SLU
Institutionen för energi och teknik
Box 7032
750 07 UPPSALA
Tel. 018-67 10 00
pdf.fil: www.slu.se\energiochteknik

SLU
Department of Energy and Technology
Box 7032
SE-750 07 UPPSALA
SWEDEN
Phone +46 18 671000