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Cover: Decomposed bark after storage, photo: Martin Anheller

Abstract

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Storage of biomass is associated with problems like heat development, biomass losses, and reduction of the fuel quality. Certain processes such as biological- and chemical degradation are responsible for these storage problems. This master's thesis was carried out at Vattenfall Research and Development AB and is aligned towards quantifying the biomass losses from short-term storage (1-2 months) of bark and recovered wood. The biomass was stored in outdoor piles during different seasons, campaign 1 (summer) and campaign 2 (autumn). Partial covering with tarpaulins of some of the piles were also investigated. The stored biomass was analysed for moisture content, ash content and heating value.

The biomass losses that were based on the dry matter losses and reduction of the net heating value of the fuel were limited in the piles of recovered wood. The bark piles had higher biomass losses due to higher moisture content and smaller particle size distribution. Storage of moist bark in large piles leads to temperature development and subsequently a few percent losses in dry weight. The temperature development in the piles of recovered wood is limited and more dependent on ambient conditions. No effects of partial covering of the piles were found since the covering was most likely too small.

It was found out that the method of quantifying biomass losses used in this report needs to be improved to be able to quantify small biomass losses during short-term storage, since it is not sensitive enough. The best way to store biomass at a heating plant for minimal fuel losses is under roof and with as low initial moisture content and large particle size distribution as possible.

Sammanfattning

En ökad användning av biobränslen, som är biomassa avsedd för att användas som bränsle, är viktig inför en framtida omställning av energisystemet. Innan biobränslen nyttjas måste de mer eller mindre alltid lagras, vilket medför en del problem. Temperaturutveckling i bränslestackar med risk för självantändning, försämring av bränslekvaliteten och bränsleförluster är exempel på dessa problem.

Detta examensarbete har genomförts på Vattenfall Research and Development AB, Älvkarleby. Innebörden av examensarbetet har varit att undersöka och kvantifiera bränsleförluster vid korttidslagring (1-2 månader) av bark och RT-flis i stackar utomhus vid Johannes kraftvärmeverk, Gävle. Två lagringskampanjer har genomförts, kampanj 1, två månaders sommarlagring av bark och RT-flis, och kampanj 2, höstlagring av RT-flis under 1 månad.

I kampanj 1 lagrades fem stackar, två stora RT-flisstackar samt tre barkstackar (två stora och en liten). Vardera en av de stora RT- samt barkstackarna var täckta på toppen av en presenning för att undersöka täckningseffekter. Den lilla barkstacken byggdes upp för att undersöka skalförhållanden mellan en stor och en liten stack. Kampanj 2 utgjordes av två stycken stora RT-flisstackar, varvid den ena hade en presenning på toppen. Temperaturen mättes på tre olika nivåer för de stora stackarna samt på en nivå för den lilla barkstacken i kampanj 1 samt på två olika nivåer i kampanj 2. Biomassan i båda kampanjerna studerades och analyserades utifrån fukthalt, askhalt samt värmevärde. Från den otäckta stacken i kampanj 1 samlades även lakvatten upp. Bränsleförlusterna definierades som förluster i torrmateria samt minskning av det effektiva värmevärdet.

I kampanj 1 så var temperaturutvecklingen stor i barkstackarna, där de stora stackarna nådde en temperatur på cirka 75°C och den lilla stacken en temperatur på cirka 60°C. Anledningen varför temperaturutvecklingen var så häftig var förmodligen på grund av barkmaterialets höga initiala fukthalt samt den relativt lilla partikelstorleken. I RT-flisstackarna var dock temperaturutvecklingen marginell, låg som oftast runt 15-20°C, där temperaturen till stor del följde utomhustemperaturen. Detta tros bero på att RT-flisen hade mycket låg initial fukthalt samt stor partikelstorlek. I kampanj 2 sågs samma mönster för temperaturutvecklingen, där stacktemperaturen till stor del följde utomhustemperaturen. Dock var RT-flisens fukthalt i kampanj 2 högre än 20 vikt-%, vilket anses vara gränsen för att mikrobiell tillväxt skall vara möjlig. Mikrobiell tillväxt är den största orsaken till ökad temperatur i en biobränslestack. Av detta kan slutsatsen om att partikelstorleken är mer betydande än fukthalten för temperaturutvecklingen i en biobränslestack.

Askhaltsanalyserna visade i båda kampanjerna på marginella förändringar som inte kan kopplas till själva lagringen utan endast av naturlig karaktär. Förändringarna i både det kalorimetriska samt det effektiva värmevärdet var också marginella för RT-flisstackarna i båda kampanjerna. Den lilla barkstacken visade en minskning av

det effektiva värmevärdet med cirka 2.8 %, medan de stora barkstackarna visade en ökning på drygt 3.2 %. Det ökade värmevärdet i de stora barkstackarna var förmodligen på grund av torkingseffekten i stackarna.

Torrmateriaförluster är minskning i det lagrade materialets torrvikt. RT-flisstackarna visade marginala torrmateriaförluster i båda kampanjerna. Den lilla barkstacken visade ej tillförlitliga data varför inte mycket kan sägas om eventuella substansförluster. De stora barkstackarna visade substansförluster dock med för osäkra data för att göra en kvantifiering av dess storlek.

Inga synbara effekter av presenningarna sågs eftersom de med all sannolikhet täckte för liten del av stackarna. En slutsats av försöken är att metoden som använts för att kvantifiera bränsleförluster behöver förbättra eftersom den inte är känslig nog i nuläget att kvantifiera små bränsleförluster under korttidslagring.

Det bästa sättet att lagra biomassa för minimala bränsleförluster vid ett värmeverk är med så stor partikelstorlek samt med så låg initial fukthalt som möjligt. Lagringen skall också fördelaktigt hållas under tak och under så kort tid som möjligt.

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1 Nomenclature

Abbreviations

MC	Moisture content
AC	Ash content
W_{net}	Net heating value (also called low heating value)
W_{gross}	Gross heating value (also called high heating value)
DML	Dry matter loss
CEC	Changes in energy content
DM	Dry matter weight
DM%	Percentage of dry matter weight (unit for ash content and dry matter losses)
GW	Green weight
%GW	Percentage of green weight (unit for moisture content)
wt%	Weight percent (unit for particle size distribution)
vol-%,	Volume percent
MJ/kg DM	Mega Joule per kg dry matter (unit for heating value)
VOC	Volatile organic compounds
TOC	Total organic carbon
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
SMHI	Swedish Meteorological and Hydrological Institute
Recovered wood	Chips from used wood (also called waste wood)

2 Introduction

2.1 Background

Biofuels are biologic materials that are used as fuel. In Sweden, biofuels primarily consist of wood fuels, black liquor and tall oil pitches, peat, waste, and bioethanol. The wood fuel group includes fuels such as logs, bark, branches and tops, energy forests and plantations [1].

Recovered wood, also called waste wood or demolition wood, refers to residual products that have been consumed and are being reused or recovered, e.g. construction wood from buildings. Recovered wood often contains impurities of both chemical and mechanical origin such as paint, impregnations, metals and plastics. These can give large contributions of certain chemical metal compounds, e.g. zinc, lead and copper, which may give corrosion problems during combustion.

Bark is a by-product from the saw milling and the pulp industry. Bark from coniferous trees is the most common bark used as fuel. Depending on which type of bark, the moisture content is often very varying, normally between 40-60 %, green weight basis [2][3].

Wood fuels are utilized in different main areas. These are for example the forest products industry, in district heating plants and the single house sector, mainly for heat production, but also for production of electricity [1]. Wood fuels are produced all year, but the consumption is concentrated to the cold periods of the year. Because of this, the material needs to be stored until needed. Large volumes are often necessary to ensure sufficient heat production when needed. A buffer fuel should also be available at the heating plant in case deliveries are temporarily delayed [4][5].

Wood fuels can be stored in many different ways depending on factors such as type of material and the demands of the end user [6]. Storage of raw material can require a different type of storage compared to storage of upgraded fuels. Storage of uncomminuted wood fuels gives fewer problems associated to the storage itself. However, the uncomminuted material compared to wood chips becomes more difficult to handle and more expensive to transport [7]. Comminuted material is more difficult to store than uncomminuted material since heat-generating processes can be initiated. Biological, economic and logistic factors often influences how and where to store wood fuels [8]. Wood fuels delivered to heating plants, such as wood chips or bark, are in most cases stored in outdoor piles. Some upgraded wood fuels, such as wood powder, are normally stored in closed systems, e.g. silos, to prevent spill of wood powder [7].

The chemical composition of woody biomass can change when the material is exposed to the different conditions when stored, such as microbial activity and temperature development. These conditions can lead to degradation of the material [7]. Basically, the two major chemical components in wood are carbohydrate and lignin. Cellulose is the main component of the carbohydrates and represents around 40-50 % of the dry wood weight while hemicellulose constitute about 25-35 %. Lignin represents around 18-35 % of the wood substance [9]. The energy content of the major chemical components in wood is: cellulose 17-18 MJ/kg DM, hemicellulose 16-17 MJ/kg DM, lignin 25-26 MJ/kg DM. Cellulose and hemicellulose is more easily biologically degradable than lignin and is always attacked first in microbial attacks. The pattern of changes directly affects the heating value because of the differences in energy content of the different components [10].

The rate of degradation is generally a function of temperature, moisture content, oxygen concentration and nutrition. During aerobic conditions, the degrading reactions consume oxygen and organic material and produce water, carbon dioxide and heat. If there is no available oxygen, aerobic microorganisms are inhibited. Anaerobic organisms producing methane, alcohols and organic acids then take over the degradation [11]. The anaerobic reactions are normally of a much less extent than the aerobic reactions in a pile of stored wood fuels since the required oxygen levels are low and the fact that oxygen is often accessible [12].

A stored pile of any chipped organic material frequently develops heat if the moisture content is high enough that microbial growth is possible, usually >20 % for wood fuels [8]. The process when a stored pile of biomass increases in temperature is a several step procedure. In fresh wood chips, the respiration heat from the living cells can contribute to the initial heat development. In addition, the chipping process itself can also increase the temperature of the wood fuel. The chipping process releases soluble sugar from the wood, which together with heat, moisture and oxygen can create a favorable environment for microbes [13]. By chipping the material, the area where the microbes can attack increases. In a pile of chipped material, the air movement is also more limited because of the smaller material, which prevents heat dissipation and causes heat accumulation and thereby increases degradation losses. In large piles, the material can additionally become more compact because of weight, which further amplifies the abovementioned factors [8].

Microbial growth is possible up to circa 70°C. Microbes can also tolerate a wide temperature range [8]. Chemical reactions, such as chemical oxidation, can take place at circa 40-50°C and can raise the temperature above 100°C [10]. Temperature development in a pile occurs more easily if the material has low thermal conductivity, which is common for fuels such as sawdust, bark and wood chips. In these materials, only a small part of the accumulated heat is transported to the surroundings [8].

The question “what is good fuel quality?” does not have an unambiguous answer. Fuel quality is often seen from a relative point of view and can be defined as the “suitability of a certain type for a specific purpose” [8]. Some fuel quality factors are controllable, while some are not. Built-in factors that are not controllable are dry and raw density of the fuel as well as chemical composition. Factors that can be influenced are for instance moisture content, fraction distribution and fuel temperature [10].

The fuel quality is affected during storage. Microbial activity, which is dominated by fungi and bacteria, can cause degradation of the stored material. This can give dry matter losses, which is a reduction of the dry weight of the material. Microbial activity depends on the nature and the moisture content of the biomass components [8]. Not only the moisture content is important for the fuel quality but also the moisture content distribution within the pile. Moisture is often migrated from the center of a pile, because of high temperatures, and then condensates in the cooler areas of the pile [8]. This is especially a problem during wintertime since the increased moisture content of the material at the surface makes it freeze more easily and becomes unusable. Microbial activity can also make the wood fuel difficult to handle because of the high presence of allergenic spores [10].

Several abiotic processes, including moisture adsorption and chemical oxidation, can cause additional temperature development in a pile and by so cause dry matter losses [8]. If chemical oxidation is in progress in a stored pile of wood chips and the temperature reaches elevated levels, the pile can be in danger of self-ignition [10]. The oxygen concentration is one of the most central aspects affecting self-ignition in a pile. The minimum temperature required for self-ignition increases with reduced oxygen concentrations. Nevertheless, self-ignition is possible at very low oxygen concentrations of about 4vol-%, which almost always is exceeded during storage of biomass [8][10].

The moisture content is connected to the heating value, which represents the energy content that can be extracted from the fuel when it is combusted [14]. After felling the moisture content is influenced by different conditions such as ambient temperature, precipitation, relative humidity and wind speed [8]. Logging residues are often stored in windrows by the roadside, which can be either covered or uncovered. In a storage study of unchipped logging residues in windrows, positive effects were seen by covering the top of one of the two windrows with an impregnated paper. The purpose with the impregnated paper was to protect the windrow from precipitation. The moisture content of the logging residues was clearly lower in the covered windrow during the entire 11 months of storage [7]. Once the material has been chipped, the particle size distribution of the biomass also affects the degradation. The smaller the particle size, the faster the microbial degradation, and thereby the dry matter losses [6].

In addition to the combustible organic part, biofuels also contain an inorganic fraction in the form of ash. The ash content gives information regarding how the amount of the combustible part of the biofuel is changed during storage. The ash content is connected to the heating value [14]. An indirect consequence of dry matter losses is the increased ash content [8]. The ash content often increases with the moisture content of the biomass. However, this should be connected to the increased ability of the biomass to bind impurities when handled and stored [10].

The dry matter losses become generally higher when stored for longer periods and in larger piles. The shape of the piles influences the heat development during storage of biomass, since it determines the aeration effects in the piles. In a study about self-heating in wood chip piles it was concluded that the width of a pile affected self-heating more than the height, in piles of equal volumes, since the airflow through the pile was reduced [12]. The aeration provides the piles with oxygen that the heat developing processes, such as microbial activity, are highly dependent on, but it also cools the piles by convection [8].

The most advantageous way to store wood fuels is as uncomminuted fuels, such as whole tree logs. This decreases the microbial activity and thereby degradation losses. It is also more beneficial to store the material under roof and as uncompacted as possible [15]. Reduction of the size of fuelwood, such as chipping of the material, should be done as close in time as possible to the combustion process. The motive for this is to shorten the time of storage as chips and thereby to reduce storage losses [8].

2.2 Overview of the project

This master’s thesis investigates short-term storage (1-2 months) in piles of recovered wood and bark in terms of temperature changes and quality parameters of material properties. These parameters are used in estimating biomass losses and possible changes of the fuel properties from the piles. Different storage ways are investigated including different pile sizes, partial covering of the piles and storage in different seasons (summer and autumn). Two storage campaigns are done, campaign 1 (two months of summer storage of bark and recovered wood) and campaign 2 (one month of autumn storage of recovered wood).

3 Objectives

Short-term storage of bark and recovered wood was investigated to evaluate changes of the fuel properties and to quantify or estimate biomass losses and changes in energy content. The state-of-knowledge on biomass losses and biological degradation of biomass fuels with the aim to suggest measures how to reduce biomass losses during storage was reported.

4 Material and methods

The storage site was at the Johannes combined power and heating plant (CHP) in Gävle, Sweden, with a storage area of approximately 40000 m^2 [16]. The ground material was asphalt and the storage area was open, which meant that external environmental effects such as precipitation and wind influenced the storage process.

Figure 4.1, Johannes combined power and heating plant in Gävle, Sweden

Bark and recovered wood were the main wood fuels used at Johannes CHP. Trucks delivered the fuel and tipped it on the ground. Afterwards, the piles were built. Most of the recovered wood was delivered as untreated demolition wood and chipped directly at the site. The bark was already crushed when delivered.

4.1 Materials

Two types of wood fuels were studied, viz. recovered wood and bark. The recovered wood material was chips with a rather large particle size distribution, as can be seen in Figure 4.2. The particle size was measured during campaign 2. The recovered wood consisted mostly of spent construction wood and was delivered to the storage site unchipped. It also contained several different components other than wood. Fractions of metals (mainly nails and screws from boards), plastics of various kind, and cardboards were found. The recovered wood, used in campaign 1, was chipped and stored in a 6.5 meter high and 50 meter long pile, for 2-4 months before the start of campaign 1. One-month-old recovered wood of the same type was used in campaign 2 [16]. The outermost layer of this pile was not used when building the piles to make the biomass as homogenous as possible.

The bark used had a smaller particle size distribution compared to the recovered wood. The crushed bark had been delivered to Johannes CHP, about 2-3 weeks before the start of campaign 1, and placed in piles [16]. These piles were approximately 4 meters high and 15 meters long. The bark was more homogenous, with respect to particle size, than the recovered wood. However, many different particle sizes were present.

In order to study the stored material, sample bags were used, Figure 4.2. The sample bags consisted of white nylon material with a length of 40 cm and a width of 30 cm. The volume was estimated to approximately 5 liters. The holes in the sample bags were circular with a diameter of 2 mm.

Figure 4.2, Sample bag filled with recovered wood

The thermocouples used in this project were Pentronic TF/TF-24 copper-constantan [17]. The inner metal wires of the thermocouples were surrounded with polyvinyl chloride (PVC) and had an outer layer of polytetrafluoroethylene (PTFE) as isolation. The idée was first to use stiff thermocouples of metal with no isolation. However, it was chosen not to use these thermocouples since they could be damaged by the weight of the piles and also that none-isolated metal could work as a catalyst of unnatural effects in the piles. To further protect the thermocouples, shrinking tubing of polyolefin was used. The shrinking tubing was placed around the measuring point with the aim to protect and extend its endurance, Figure 4.3.

Figure 4.3, Thermocouple with measuring point covered with shrinking tubing

In campaign 1, the thermocouples were connected to two micro data loggers that measured and stored the temperature data. Two different models of data loggers were used. These were the Campbell Scientific micro logger 21X and the Campbell Scientific micro logger CR10 [18]. Only the 21X micro logger was used in campaign 2. The data loggers measured the temperature every fifth second and every ten minutes an average value of these five-second values was calculated and stored in the memory of the data logger. With the Campbell Scientific CR10, a modification was made. The Campbell Scientific 107 temperature probe was connected to one of its channels with the aim to increase the accuracy of the measurement [18].

In campaign 1, one tarpaulin with the dimension of 10×12 m was placed underneath the uncovered pile of recovered wood. This was done with the aim to facilitate the leachate collection. To investigate partial covering effects in campaign 1, two tarpaulins with the dimension of 4×6 m were placed at the top of one of the recovered wood and bark piles respectively. In campaign 2, one of the piles of recovered wood was covered with a tarpaulin. A couple of loading pallets were placed both underneath and above the tarpaulins. This was done with the purpose of creating an air gap as well as to make the tarpaulin to stay on the pile. Additional strings were also attached in the tarpaulins and fasten in the piles to strengthen the placement of these.

4.2 Experimental work

Before the thermocouples and the micro loggers were used in the study they were tested for functionality. The thermocouples were tested in air, at room temperature, and in boiling hot water.

4.2.1 Fieldwork, campaign 1

In the beginning of July 2008, the construction of the piles was initiated. A total of five piles were constructed, two piles of recovered wood and three piles of bark. The piles were as follows.

- **Uncovered large pile of recovered wood:**
  Height 4.5 m, base 9×10 m^2, volume 160 m^3, weight 32.58 ton
- **Partially covered large pile of recovered wood:**
  Height 5.5 m, base 14×15 m^2, volume 620 m^3, weight 128.07 ton
- **Uncovered small pile of bark:**
  Height 3 m, base 6×7 m^2, volume 60 m^3, weight 32.57 ton
- **Uncovered large pile of bark:**
  Height 5 m, base 10×15 m^2, volume 520 m^3, weight 210.29 ton
- **Partially covered large pile of bark:**
  Height 5 m, base 10×15 m^2, volume 560 m^3, weight 221.63 ton

The uncovered pile of recovered wood was built on a tarpaulin. Another tarpaulin was used to collect the leachate down the ditch into a small plastic bucket. The bucket was connected to a plastic tube leading the leachate into a 1 m^3 accumulation tank, placed at the bottom of the ditch, Figure 4.4. To cover the piles partially, tarpaulins were used.

Figure 4.4, Leachate collection system

A total of 24 sample bags, used for the determination of material properties and dry matter losses, were placed in each of the large pile as follows:

- Layer 1 (1-1.5 m above ground): 12 sample bags
- Layer 2 (2.5-3 m above ground): 8 sample bags
- Layer 3 (3.5-4 m above ground): 4 sample bags

Five sample bags were placed in the small bark pile (1.5 m above ground) in campaign 1. The placement of the sample bags was set according to a specific pattern to cover an area as large as possible, Figure 4.5. Three thermocouples per pile in the large piles and one in the small bark pile were placed. The placement of these was at the center of the piles at three different levels, the same as for the sample bags. To measure the temperature at three different levels made it possible to compare the temperature within each pile as well as between the piles.

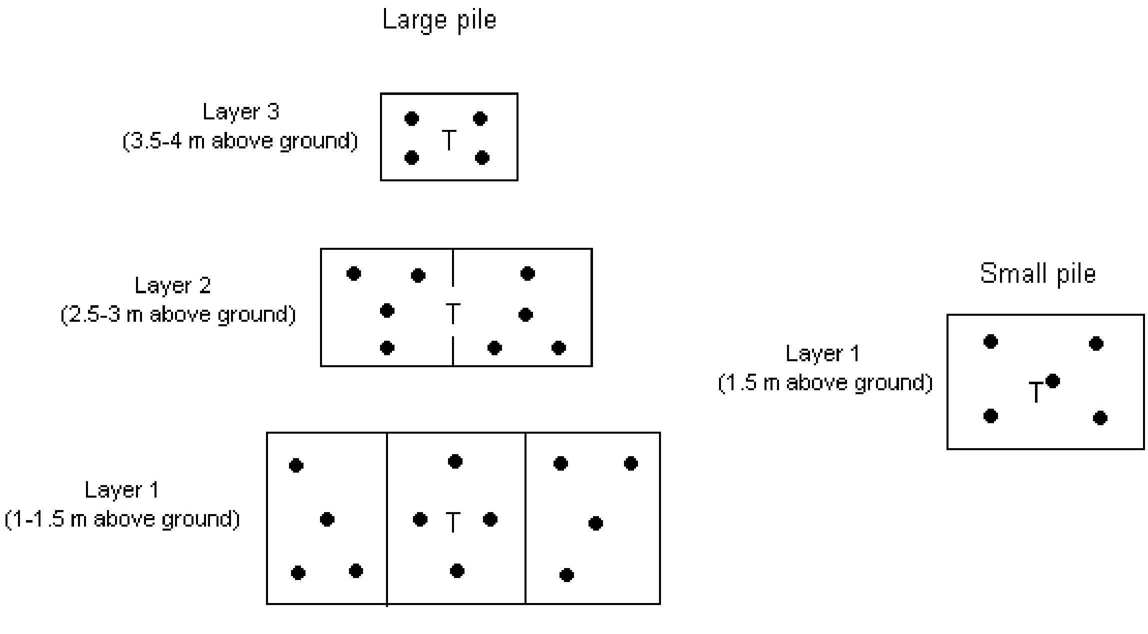

Figure 4.5, Placement of sample bags (●) and thermocouples (T) in large and small pile, seen from above

The sampling took place when the piles were built. A sample bag was filled with material and weighed on a scale with the accuracy of 1 g. From the same place as the sample bag was placed, a paper bag was filled with material and weighed on the same scale. The moisture content as well as the heating value and the ash content was analyzed from the material in the paper bags.

The demolition of the piles was done at the end of August 2008. For the uncovered pile of recovered wood all the sample bags were found but for the partially covered pile one were missing. The number of lost sample bags was three and two for the uncovered large bark pile and the partially large bark pile respectively.

At the end of the storage period of campaign 1, the leachate was collected. A number of ten bottles, with the volume of 33 cl each, was collected. Five of these were taken from the accumulation tank in the ditch and five from the bottom tarpaulin. At the storage site, pH was measured with a mobile pH-meter.

4.2.2 Fieldwork, campaign 2

At the end of September 2008 the construction of the piles for campaign 2 started. Two piles of recovered wood were built. The sizes of the piles were as follows:

- **Uncovered large pile of recovered wood:**
  Height 4.5 m, base 11×13.5 m^2, volume 300 m^3, weight 62.57 ton
- **Partially covered large pile of recovered wood:**
  Height 4.5 m, base 11×13.5 m^2, volume 300 m^3, weight 56.47 ton

The sampling process was the same as for campaign 1. Only two thermocouples were used per pile in campaign 2. The demolition of the piles was done at the beginning of November 2008. One sample bag was found missing for the uncovered pile while four were lost for the partially covered pile.

4.3 Laboratory analyses

4.3.1 Moisture content

The determination of the moisture content was made at the storage site. Biomass-filled paper bags were weighed and put in an oven at 105 ± 2°C shortly after the sampling process. The samples were kept in the oven for 21 hours, until the material was completely dry, and then weighed again. The moisture content was determined using the following formula [5].

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

MC: Moisture content (%, green weight basis)
DM: Dry matter weight (kg)
GW: Green weight (kg)

4.3.2 Ash content

The dried material from the moisture content determination was grinded to smaller pieces before the ash content and the heating value analyses were initiated. Two samples from the same layer were put together to reduce the amount of samples. For the small bark pile in campaign 1, that contained five samples, one sample was analyzed separately. The ash content was defined as the ratio between the mass of the ash and the mass of the dry matter before combustion. In campaign 1 the ash content analyses were made according to SS 18 71 71 and in campaign 2 according to CEN TS 14775 [19][20].

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

AC: Ash content (%DM)
AW: Ash weight (kg)
DM: Dry matter weight (kg)

4.3.3 Heating value

The gross heating value was measured with a Leco AC 300 bomb calorimeter according to SS ISO 1928 in campaign 1 and in campaign 2 according to CEN TS 14918 [21][20]. The net heating value for moist materials (W_{net}) was calculated by the following formula [22].

$$W_{net} = W_{gross} - \left(2.45 \times 9 \times \frac{H_2}{100} \right) - \left(2.45 \times \frac{MC}{100 - MC} \right) \qquad (3)$$

W_{net}: Net heating value (MJ/kg DM)
W_{gross}: Gross heating value (MJ/kg DM
2.45: Heat of evaporation for water at 20°C (MJ/kg)
9: Number of created parts water from one unit hydrogen
H_2: Percentage of hydrogen in forest fuels[1] (wt%)
MC: Moisture content (%)

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[1] The percentage of hydrogen in forest fuels is approximately 6 wt% [22].

4.3.4 Particle size distribution

The particle size distribution of the recovered wood and the bark was determined[2] with a shaking sieve.

4.4 Biomass losses

4.4.1 Dry matter losses

The dry matter losses were calculated as the percentage reduction of the dry weight during storage by the following formula [22][4].

$$DML = \left(1 - \left(\frac{DM_A}{DM_B}\right)\right) \times 100 \qquad (4)$$

DML: Dry matter losses (%DM)
DM_A: Dry matter weight after storage (kg)
DM_B: Dry matter weight before storage (kg)

4.4.2 Changes in energy content

The changes in energy content were dependant of both the dry matter losses and the changes in the net heating values and were calculated by the following formula [4].

$$CEC = \left(\left[\left(1 - \left(\frac{DML}{100}\right)\right) \times \mathrm{W_{netA}}\right] - \mathrm{W_{netB}}\right) \times \frac{100}{\mathrm{W_{netB}}} \qquad (5)$$

CEC: Change in energy content (%)
DML: Dry matter losses (%DM)
W_{netA}: Net heating value after storage (MJ/kg DM)
W_{netB}: Net heating value before storage (MJ/kg DM)

[2] The determination of the particle size distribution was not made by the master’s thesis worker but by staff at Johannes heating plant, Gävle.

5 Results

5.1 Campaign 1, summer storage of recovered wood and bark

Temperature

Figure 5.1 shows the maximum temperature development of the piles of recovered wood as well as the ambient temperature and precipitation from a nearby weather station[3] during the storage period. The piles showed no temperature development at all and the temperature was mostly between 10-20ºC. The pile temperatures followed the change in ambient temperature to a great extent during the whole time of storage. No specific differences in temperature were seen between the uncovered or the partially covered pile.

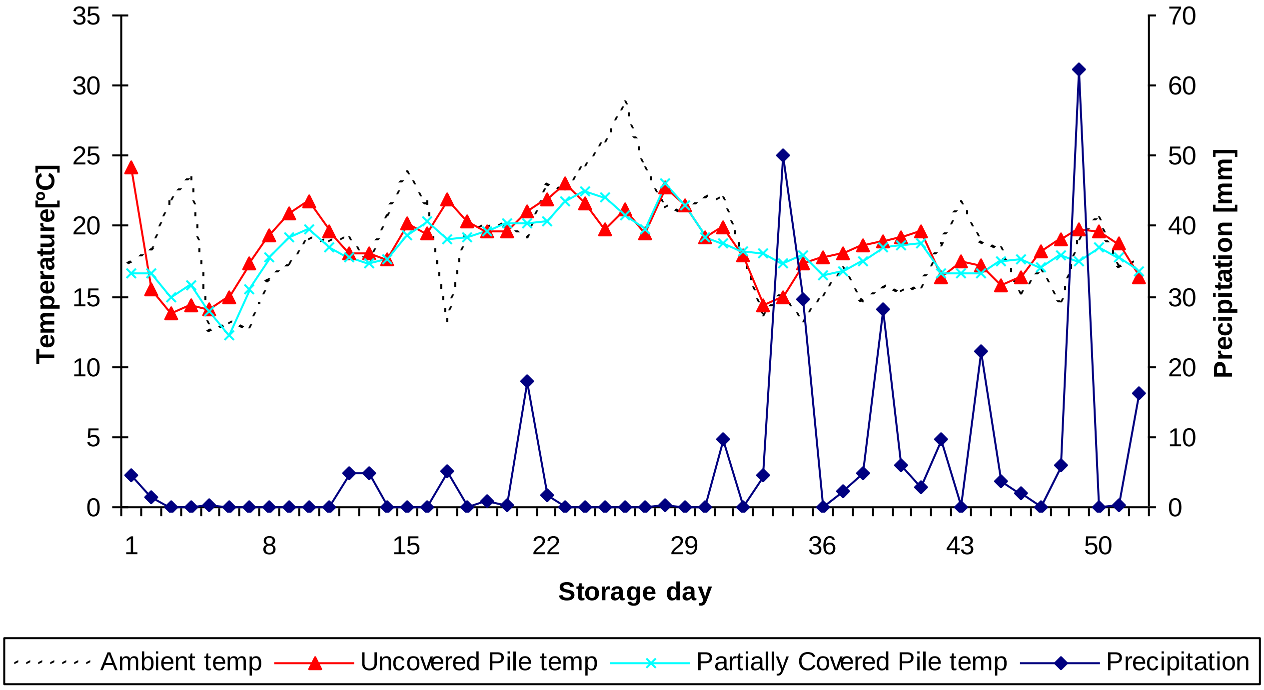


Figure 5.1, Maximum temperature development in recovered wood piles (ºC), ambient temperature (ºC) and precipitation (mm) during summer storage (July-Aug)

[3] The SMHI weather station was situated approximately 10 km north of the storage site.

In Figure 5.2, the maximum temperatures of the three bark piles are presented. The temperature in the small bark pile increased in the beginning of storage and after two days reached circa 50ºC. From there on, the temperature rose and reached a maximum level of circa 60ºC after two weeks, and stayed at that level for the remaining time of storage. The temperature in the large bark piles showed the same pattern as the small bark pile and reached a constant level of circa 75ºC after one week of storage. The uncovered and the partially covered pile showed almost identical temperatures throughout the storage period. The partially covered pile was built one day before the uncovered and the small pile, which explains the differences in the initial temperature, since the temperature measurement was not started until the two last-mentioned piles were built.

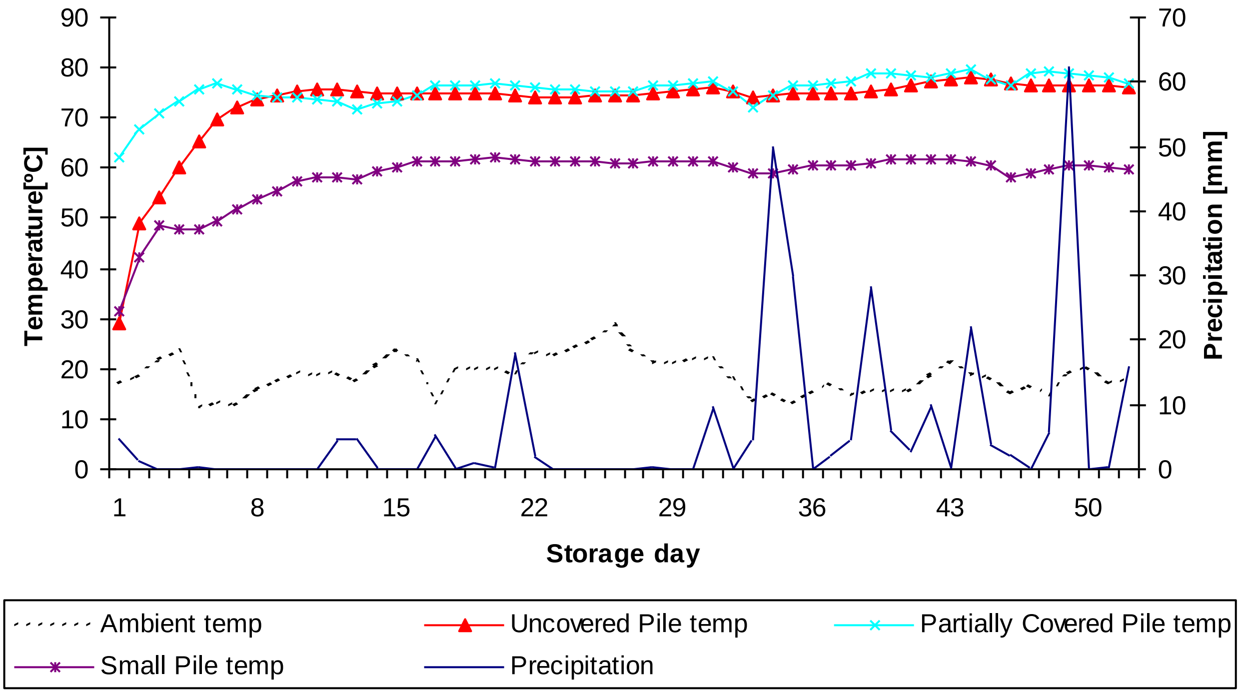


Figure 5.2, Maximum temperature development in bark piles (ºC), ambient temperature (ºC) and precipitation (mm) during summer storage (July-Aug)

Moisture content

The moisture content was practically unchanged for the piles of recovered wood and the small bark pile after storage, Table 5.1. The only considerable changes in moisture content were seen for the large bark piles. After storage the average moisture contents had decreased with 4.6 % for the uncovered large bark pile and with 5.3 % for the partially covered pile.

Table 5.1, Average* moisture content (%) of recovered wood and bark with standard deviation (SD) and change before and after 50 days of summer storage with 95 % confidence interval (95 % CI)

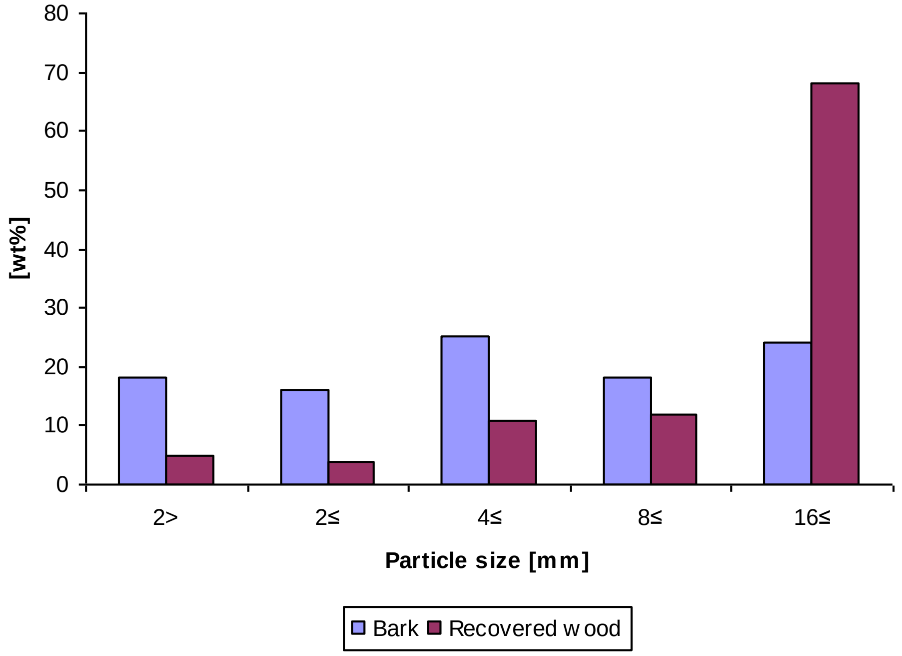
Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	10.9 (1.2)	12.5 (1.7)	1.6 (0.6, 2.6)
Recovered wood	Yes	Large (5.5 m)	12.5 (1.6)	11.5 (1.6)	1.0 (-1.7, -0.2)
Bark	No	Small (3 m)	60.2 (3.7)	61.0 (1.2)	0.8 (-4.2, 5.9)
Bark	No	Large (5 m)	41.2 (8.8)	36.6 (12.2)	-4.6 (-8.6, -0.6)
Bark	Yes	Large (5 m)	46.3 (2.2)	41.0 (3.9)	-5.3 (-7.3, -3.5)

*Average value of 24 samples (Small bark pile: average value of 5 samples)

Particle size distribution

The particle size distribution of the recovered wood and the bark is illustrated in Table 5.2. The recovered wood had a bigger particle size distribution with 68 wt% above 16 mm, compared to only 24 wt% for the bark. According to Table 5.2 the particle size distribution of the bark was evenly spread with the dominant particle size between 4-8 mm. The estimated dominant particle size of the recovered wood chips was around 10-15 cm but pieces of up to 30 cm were present.

Table 5.2, Particle size distribution of bark and recovered wood



Ash content

The initial ash contents were higher for the bark material than the recovered wood, which was expected. However, the changes after storage were marginal for both of the materials and for the different ways of storage.

Table 5.3, Average* ash content (%DM) of recovered wood and bark with standard deviation (SD) and difference before and after 50 days of summer storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	1.2 (0.3)	1.5 (0.5)	0.3 (-0.1, 0.5)
Recovered wood	Yes	Large (5.5 m)	1.1 (0.3)	1.1 (0.2)	0
Bark	No	Small (3 m)	2.6 (0.2)	2.9 (0.2)	0.3 (-0.4, 0.9)
Bark	No	Large (5 m)	2.7 (1.2)	2.4 (0.3)	-0.3 (-1.1, 0.4)
Bark	Yes	Large (5 m)	2.5 (0.2)	2.4 (0.4)	-0.1 (-0.2, 0.3)

*Average value of 12 samples (Small bark pile: average value of 3 samples)

Heating values

The bark piles had slightly higher initial gross heating values than the recovered wood piles with a difference of 1-1.7 MJ/kg DM, Table 5.4. No significant changes were seen for the piles of recovered wood after storage. The changes were higher for the bark piles, although they were small, 1.6 % decrease for the small bark pile as well as an increase of 1.8 % for the uncovered large pile. The partially covered large pile had an increased gross heating value of 0.7 %.

Table 5.4, Average* gross heating values (MJ/kg DM) of recovered wood and bark with standard deviation (SD) and change before and after 50 days of summer storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	20.0 (0.1)	20.0 (0.1)	0
Recovered wood	Yes	Large (5.5 m)	20.1 (0.1)	20.1 (0.1)	0
Bark	No	Small (3 m)	21.0 (0.2)	20.6 (0.1)	-0.6 (-0.4, 0.9)
Bark	No	Large (5 m)	21.2 (0.5)	21.6 (0.6)	0.4 (0.1, 0.7)
Bark	Yes	Large (5 m)	21.7 (0.5)	21.8 (0.6)	0.1 (-0.4, 0.7)

*Average value of 12 samples (Small bark pile: average value of 3 samples)

The net heating values were slightly higher for the piles of recovered wood than the bark piles, mainly because of the low moisture content of the recovered wood material. Because of the high moisture content, the initial net heating value was clearly lower for the small bark pile compared to the large bark piles. No changes were seen for the piles of recovered wood after storage. The net heating value had decreased with 2.8 % for the small bark pile while it had increased with 3.2 % for both of the large bark piles, Table 5.5.

Table 5.5, Average* net heating values (MJ/kg DM) of recovered wood and bark with standard deviation (SD) and change before and after 50 days of summer storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	18.4 (0.1)	18.3 (0.2)	-0.1 (-0.2, 0)
Recovered wood	Yes	Large (5.5 m)	18.4 (0.1)	18.4 (0.3)	0
Bark	No	Small (3 m)	15.9 (0.7)	15.5 (0.1)	-0.4 (-2.4, 1.5)
Bark	No	Large (5 m)	17.9 (1.4)	18.5 (1.5)	0.6 (0.2, 1.0)
Bark	Yes	Large (5 m)	18.2 (0.5)	18.8 (0.6)	0.6 (0.1, 1.1)

*Average value of 12 samples (Small bark pile: average value of 3 samples)

Dry matter losses and changes in energy content

The dry matter losses for the five piles in campaign 1 are presented in Table 5.6. The values that are left blank were either not found or damaged except for the small bark pile which only had five samples.

The changes in energy content of the piles are dependent of both the dry matter losses and the changes in the net heating values. The net heating values were unchanged after storage for the recovered wood piles while the changes were larger for the bark piles. However, since the dry matter loss determination was not reliable the change in energy content was not quantifiable.

Table 5.6, Dry matter losses (%DM) for recovered wood and bark after 50 days of summer storage

Sample bag number*	Uncovered Recovered wood	Partially covered Recovered wood	Small Bark	Uncovered Bark	Partially covered Bark
1	4.1	-8.3	-1.4		-7.2
2	-2.7	-6.2	-7.6	4.4	7.4
3	1.8		-0.5	10.7	
4		-2.6	2.4		-7.7
5	-3.0	-6.2	1.6		-3.7
6	-7.0	-12.9		5.1	1.1
7	5.5	-2.5		-8.3	2.4
8	-1.3	-1.2		-1.9	-0.2
9	1.7	-3.9		11.4	-0.8
10		-0.6		16.0	
11	-0.9	-15.6		0.6	6.3
12		2.6		17.0	4.8
13				6.7	2.5
14	-1.2	-1.4		3.0	-10.2
15	-2.8	0.3		-9.8	
16		-0.1		11.8	-2.1
17	-2.3	1.2		11.1	5.3
18	-1.6	1.7		2.0	6.6
19	-0.9	-4.0		11.2	-2.8
20	-10.3	-1.7		10.9	
21	-3.7	-0.6		8.6	0.3
22	-2.9	-2.8		4.2	6.9
23	-1.3	-2.6			
24	-9.8				

*Sample bag number (1-12: bottom layer, 13-20: middle layer, 21-24: top layer)

Leachate

The mean pH value of the leachate from the uncovered pile of recovered wood for the ten collected samples with standard deviation (SD) was 6.2 (0.16).

5.2 Campaign 2, autumn storage of recovered wood

Temperature

Figure 5.3 shows the maximum temperature development for the two piles of recovered wood during storage as well as the outdoor temperature and precipitation from the same nearby weather station as in campaign 1. During the storage time the temperature was mostly between 5-15ºC in the piles, the same as the outdoor temperature, except for the last week of storage where both the ambient temperature and the pile temperatures was around 0-5ºC.

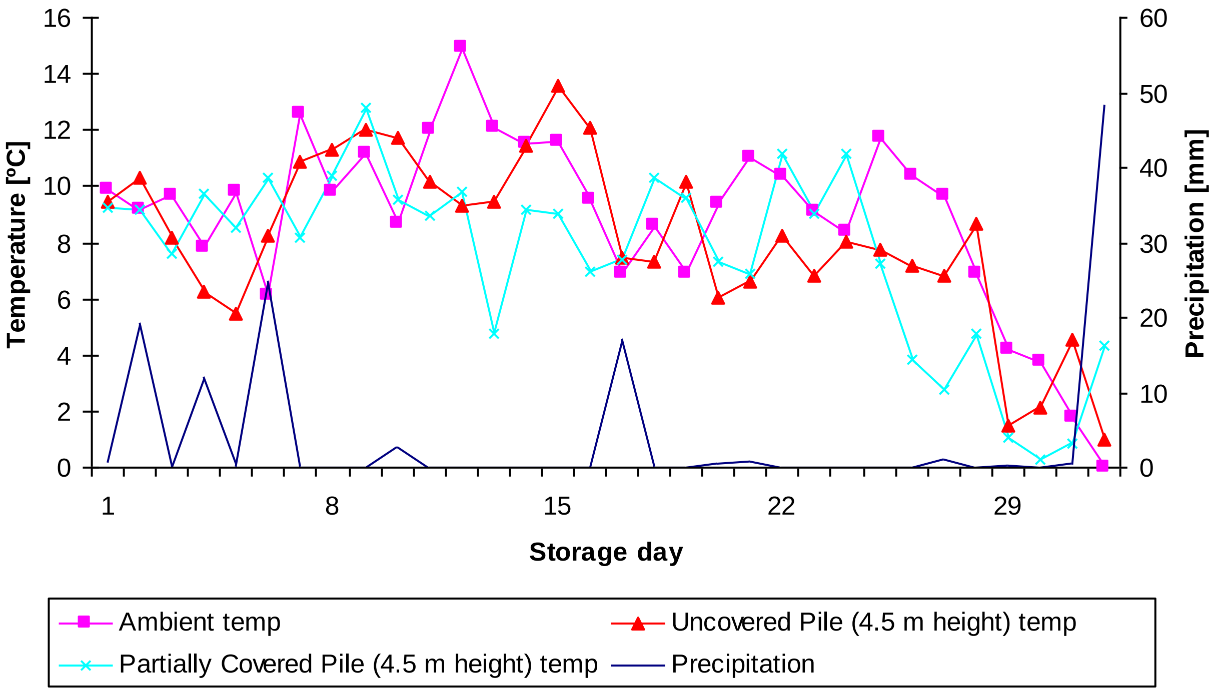


Figure 5.3, Temperature development in recovered wood piles (ºC), ambient temperature (ºC) and precipitation (mm) during autumn storage (Oct-Nov)

Moisture content

The initial moisture content was higher for the recovered wood piles in campaign 2, than in campaign 1. The uncovered pile had an average value of 23.5 % whereas it was 18.9 % for the partially covered pile. Table 5.7 shows the mean values of the moisture content before and after storage for the two piles. Both piles of the piles had marginal changes in moisture content.

Table 5.7, Average* moisture content (%) of recovered wood with standard deviation (SD) and change before and after 30 days of autumn storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	23.5 (3.0)	23.2 (4.6)	-0.3 (-2.5, 2.0)
Recovered wood	Yes	Large (4.5 m)	18.9 (1.8)	19.5 (5.6)	0.6 (-2.5, 3.6)

*Average value of 24 samples

Ash content

Table 5.8 shows the average values of the ash content before and after storage for the two piles. The average ash content was unchanged for the uncovered pile while the average change was small for the partially covered pile.

Table 5.8, Average* ash content (%DM) of recovered wood with standard deviation (SD) and change before and after 30 days of autumn storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	1.6 (0.5)	1.5 (0.3)	-0.1 (-0.5, 0.3)
Recovered wood	Yes	Large (4.5 m)	1.4 (0.3)	2.2 (2.0)	0.8 (-1.2, 2.9)

*Average value of 6 samples

Heating values

The initial gross heating values were almost identical as for campaign 1, around 20 MJ/kg DM, Table 5.9. For both of the piles, the gross heating value showed marginal changes.

Table 5.9, Average* gross heating values (MJ/kg DM) of recovered wood with standard deviation (SD) and change before and after 30 days of autumn storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	20.0 (0.1)	20.0 (0.2)	0
Recovered wood	Yes	Large (4.5 m)	20.0 (0.1)	20.1 (0.5)	0.1 (-0.4, 0.7)

*Average value of 6 samples

The net heating values before storage was slightly lower than in campaign 1, probably because of the higher moisture content of the recovered wood, Table 5.10. The differences were of the same size as for the gross heating values, unchanged for the uncovered pile and a minimal change of 0.8 % for the partially covered pile.

Table 5.10, Average* net heating values (MJ/kg DM) of recovered wood with standard deviation (SD) and change before and after 30 days of autumn storage with 95 % confidence interval (95 % CI)

Material	Partial Covering	Pile Size (Height)	Before (SD)	After (SD)	Before - After (95% CI)
Recovered wood	No	Large (4.5 m)	18.0 (0.1)	18.0 (0.2)	0
Recovered wood	Yes	Large (4.5 m)	18.1 (0.1)	18.2 (0.5)	0.1 (-0.5, 0.8)

*Average value of 6 samples

Dry matter losses and changes in energy content

The dry matter losses for the two piles in campaign 2 are presented in Table 5.11. The arithmetic mean value of both the uncovered and the partially covered pile showed increased dry matter contents. Almost all of the samples showed increased dry matter contents and they are therefore unreliable, but are presumably marginal. Since also the net heating values showed marginal changes, the change in energy content was also considered marginal.

Table 5.11, Dry matter losses (%DM) for recovered wood after 30 days of autumn storage

Sample bag number*	Uncovered Recovered wood	Partially covered Recovered wood
1	-8.6	
2	-13.5	-3.0
3	-7.5	-2.1
4	1.6	-13.5
5	-1.1	-1.4
6		-3.7
7	-3.9	-8.4
8	0.2	-0.5
9	-7.5	-2.8
10	-5.7	-0.9
11	3.0	-4.7
12	-0.3	-0.2
13		
14	0.4	
15	-7.3	
16	-7.4	-9.2
17	-8.4	-2.7
18	-0.1	-1.4
19	-7.3	0.1
20	-9.1	1.7
21	0.5	-4.8
22		-0.3
23	-1.9	-4.4
24	-3.4	-5.2

*Sample bag number (1-12: bottom layer, 13-20: middle layer, 21-24: top layer)

6 Discussion

The bark piles had an extensive heat development. The small bark pile reached a maximum temperature of circa 60ºC, while it was around 75ºC in the large bark piles. A difference between the piles was expected since a larger pile size makes the pile more compact and has a decreased surface-to-volume ratio compared to smaller piles. The bark piles were not affected notably by the ambient conditions. The moisture content is one of the most important factors affecting fungal and bacterial growth on stored biomass and therefore also the heat developing processes. The likely reasons for the high temperature development in the bark piles were the high moisture content and the small particle size of the bark material, which provides a large surface area for microbial growth.

The initial temperature in the partially covered large bark pile was around 60ºC, compared to circa 30ºC for the uncovered large bark pile and the small bark pile. This was likely due to the fact that the partially covered pile was built one day before the others. Since the thermocouples were first connected to the temperature logger after the last-mentioned piles were built, the partially covered pile had begun to accumulate heat.

As was expected, the moisture content decreased most in the large bark piles. The probable reason for this was that the material had dried to a great extent because of the high temperatures in the piles. The small bark pile instead showed minor changes after storage, despite the high temperatures. The probable reason for this scenario was because of the high initial moisture [23].

The ash contents in campaign 1 showed changes <0.5 %DM, for all bark piles. The minor changes were likely because of natural variations in the bark material, which is a very inhomogeneous and often comminuted material, and not to the storage itself [24].

The average gross heating value of the small bark pile in campaign 1 decreased with circa 1.6 %. The gross heating values for the large bark piles had instead an increase of 1.8 % and 0.7 %, for the uncovered and the partially covered pile respectively. However, these changes are too small to be coupled to the actual storage process [24].

Both of the large bark piles showed an average increased heating value of 3.2 % after storage. The increased net heating value after storage for the large bark piles was most likely coupled to the decreased average moisture content [24]. The initial net heating value was clearly lower for the small bark pile because of the high initial moisture content. For the small bark pile, the average net heating value decreased with 2.8 %. Since the change in moisture content was minimal, the decreased net heating value could not be linked to this. However, since only three samples were analyzed these values are uncertain, which is confirmed by the wide confidence interval.

The maximum temperature in the piles of recovered wood was circa 20ºC in campaign 1 (summer storage) and around 15ºC in campaign 2 (autumn storage). The pile temperatures followed the change in outdoor temperature. This was evident in both campaigns. The probable reason why there was no temperature development was the low initial moisture content and the large particle size of the recovered wood.

For the recovered wood in campaign 1, the moisture content was below the value of 20% where microbial activity can accelerate, while it was slightly above for the uncovered pile in campaign 2. However, the heat development was limited because of the large particle size of the recovered wood material. A large particle size affects the permeability of the piles and makes it difficult for heat to be established since it is easily out-ventilated [17].

The piles of recovered wood in campaign 1 were different in size and height. Despite this difference, no major temperature difference was observed between the piles. The tarpaulin on the pile also seemed to have no particular effect on the temperature, or the material properties, in the pile. Similar results were seen in campaign 2. The piles of recovered wood had marginal changes in moisture content in both campaigns, which cannot be connected to storage. Because of the limited heat development in the piles, no drying of the material was expected.

The ash contents of the recovered wood piles were marginal in campaign 1. In campaign 2, minor changes were seen but not of the extent to be connected to storage of the material.

The gross heating values showed no observed changes before and after storage in both campaigns, which were expected regarding the very limited heat development and therefore limited aerobic activity in the piles. The net heating values were also unchanged, mainly because the moisture content was unaffected during storage.

The biomass losses were based upon the dry matter losses and the changes in energy content. Considering the low initial moisture content, the short time of storage, the large particle size distribution of the chips as well as the low temperature development in the piles, the dry matter losses were most probably marginal in the piles of recovered wood in both campaigns. The majority of the recovered wood data showed an increased dry matter content after storage. The reliability of some of the data can therefore be discussed. Similar results were obtained in the case of bark storage where some samples also showed higher dry matter contents after storage. However, many data showed signs of dry matter losses in the uncovered and the partially covered bark pile.

The uncertainty in the measurement of the dry matter losses is high for an inhomogeneous material as bark [24]. The small bark pile had too few data to estimate the dry matter losses but considering the pile temperature of 60°C, high moisture content and the small size of the pile, dry matter losses were expected [23]. The large bark piles showed signs of dry matter losses, however to quantify them accurately were too uncertain. Also with the uncertainty in the data, it was impossible to compare the uncovered and the partially covered storage methods. Regarding that the piles were of the same size and had a similar temperature development and a similar change in moisture content, along with similar changes in heating value and ash content, no major differences in dry matter losses between the piles were observed.

Increased dry matter contents are questionable. The dry matter losses were calculated from the dry weight of the sample bags before and after storage. The method used in this project, with biomass filled sample bags that were put in piles, entailed a risk that biomass could have been added to the sample bags through the holes. This could have happened when the sample bags were placed in the piles and the next layer was built up. Obviously this means that material could also have slipped out of the sample bags. Since the holes in the sample bags were 2 mm in diameter and the particle size distribution <2 mm of the recovered wood and the bark material were 5 and 18 wt% respectively, this possible error was more connected to the bark piles than the piles of recovered wood.

Increased dry matter contents could be linked to the dry matter loss determination method of today, which involves determining the dry weight in oven at >100 °C. It has been shown that during drying at this temperature, not only water is released. By comparing the dry weight from drying at 102°C and lyophilization (freeze drying), it was concluded that the two techniques released different amounts of volatile extractive compounds (VOC) from the material. By drying at 102°C, a greater loss of VOC was released and this was assumed to be the most likely factor of the increase in dry matter content. Drying at 60°C was also tested, which gave results in the region of drying at 102°C. Because of loss of VOC during drying of biomass, dry matter losses are often underestimated. Besides experimental errors, oxidation of cellulose and hemicellulose by microbes, which could add weight to the biomass, is another possible reason for negative dry matter losses [25]. This source of error might have influenced the case with increased dry matter contents. However, since the moisture content was determined in the same way before and after storage it is likely that the same amount of VOC would be released from the samples. Nevertheless, there was no guarantee that this was the case.

When the sample bags were filled and placed in the pile, another sample from the same area was taken and placed in a paper bag. The determination of the moisture content and the analyses of ash content and heating value were from the material in the paper bags. The analyses were based upon the material in the sample bags after storage. The problem with this method was that the biomass put in the sample bag, as well as the paper bag, were two different samples. It cannot be guaranteed that the biomass of the two samples had the same properties. A slight difference in moisture content, between the two samples, results in errors in the dry weight. The more heterogeneous the fuel was with respect to the moisture content, the harder it was to estimate the dry matter losses because of a decreased margin for errors [24].

As an example of what was mentioned above, the biomass used in this project was very inhomogeneous in moisture content, especially the bark material. In campaign 1, the initial moisture content for the samples at the building of the piles varied between 55.4-64.2 % for the small bark pile, between 33.6-66.9 % for the uncovered large bark pile and between 40.8-49.5 % for the partially covered large bark pile. The recovered wood was more homogenous regarding the initial moisture content and varied between 9.4-13.9 % for the uncovered large pile and between 10.8-15.5 % for the partially covered pile. In campaign 2 the initial moisture content variations were 18.6-30.1 % for the uncovered recovered wood pile and 17.0-23.9 % for the partially covered pile. The high variations in initial moisture content were a large uncertainty regarding the dry matter loss determination.

The differences in the dry matter weight before and after storage could also have depended on moisture content variations within the piles as a consequence of temperature differences. When the temperature increases to higher levels in the central parts of a pile, moisture is migrated, which then condensates further out in the pile where the temperature is lower.

The biomass used in this project was not fresh. In campaign 1, the recovered wood had been stored for 2-4 months in and the bark material for 2-3 weeks at the storage site. The recovered wood had been stored for one month before the start of campaign 2. The biomass was not mixed before the piles were built, which may explain the large variations in initial moisture content. By mixing the material, possible irregularities in the fuel quality could have been minimized [24]. It has been shown that dry matter losses and energy losses, during storage of clear-cut residue fuel chips, are highest the first week of storage, and then gradually decreases [4]. The residue chips contained about 11 wt% bark. If the same scenario is applied on the bark used in this project, it means that the bark material already have had the largest loss in dry matter since it was stored for 2-3 weeks. This could explain the large variations in dry matter weight before and after storage. Since the material was not mixed before the piles were built up, it would have been good to have several sample bags at the same sampling point. This would have given indications on how the moisture content varied within each sampling point.

Since the net heating value only showed marginal changes for the piles of recovered wood in both campaigns it could be that the changes in energy content almost solely depended on the dry matter losses of the recovered wood. However, the dry matter losses were marginal for the piles of recovered wood in both campaigns. With the uncertainty in the dry matter loss determination, the change in energy content is not determined within this master's thesis work.

Possible reasons why the big bark piles showed an increased heating value are connected to the composition of wood. The main wood components have different energy contents per unit of weight. Cellulose and hemicellulose have much lower energy content than lignin. Cellulose and hemicellulose are also more easily degraded than lignin. This means that proportionally, the material could have showed an increased energy content per kg, since only a small part of each sample was analyzed for heating value, even if it was the opposite [10].

During storage of biomass, when biomass is degraded, substances are released both through air and by water. Gaseous VOC, such as terpenes, are released through air and different substances are also released as leachate [26]. Analyzing the amount of total organic carbon (TOC) of the leachate can give partial indications on how large the biomass losses are. However, since the leachate collection system was exposed for rainwater, the proportion of leachate and rainwater was therefore not known. The obtained pH value was similar to the pH value that would be expected from rainwater, which is normally around 5-6 [27]. No specific smell in the accumulation tank as well as the transparent color of the water in the tank supported that the water was mainly rainwater.

7 Conclusions and Recommendations

- In general, the recovered wood piles had marginal biomass losses after storage. No major differences in biomass losses were seen between summer and autumn storage of recovered wood.

- The bark piles had higher biomass losses than the recovered wood piles due to higher moisture content and smaller particle size distribution. Storage of bark in large piles leads to temperature development and subsequently a few percent losses in dry weight.

- For biomass loss determination, it is not recommended to further analyze the collected leachate in campaign 1 since it is most likely mainly rainwater and because of the fact that the biomass losses from the recovered wood piles is presumably marginal.

- The methods used for quantifying biomass losses are not sensitive enough to determine small biomass losses during short-term storage. The differences in dry matter losses between the bark piles are most likely because of the inhomogeneous material that causes errors in the moisture content determination.

- Recommendations for further experiments are first of all to use as fresh material as possible. By mixing the material well before the piles are built up, possible differences in the material properties could be evened out. By using several sample bags at each sampling point, information about the moisture content variations in each sampling point would be given. One thermocouple per sampling point should advantageously also be used since it would give more direct information between the temperature and the degradation in each point.

- Recommendations to minimize biomass losses are to keep the biomass as dry as possible before storage. The biomass should also have as large particle size as possibly, preferably uncomminuted, as long as possible before combustion. Piles at heating plants should preferably be stored under roof, uncompacted and for as short time as possible.

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9 References

[1] "Energy in Sweden 2006", Swedish Energy Agency, Sweden, http://www.swedishenergyagency.se/web/biblshop_eng.nsf/FilAtkomst/ET2006_45.pdf/$FILE/ET2006_45.pdf?OpenElement, 2008-11-20

[2] Strömberg, B., "Bränslehandboken" (Handbook of fuels), Värmeforskrapport nr 911, 2005, ISSN 0282-3772

[3] Carlberg, M., "Application of the ChlorOut concept in a Waste Wood fired CFB Boiler" Swedish University of Agricultural Sciences, Department of Energy and Engineering, 2008, Examensarbete 2008:02, ISSN 1652-3237

[4] Jirjis, R., Thörnqvist, T., "Bränsleflisens förändring över tiden – vid lagring I stora stackar" (Changes in fuel chips during storage in large piles), Sveriges Lantbruksuniversitet, Institutionen för virkeslära, Rapport nr. 219, 1990, ISSN 0348-4599

[5] Jirjis, R., "Storage of forest residues in bales", Swedish University of Agricultural Sciences, Department of Bioenergy, 2003, Report no. 3, ISSN 1651-0720

[6] Dyrke, J., Lindberg, M., Morelius, P., "Problematik vid lagring och hantering av biobränslen – en förstudie (Problems when storing and handling biofuels – a prestudy), Värmeforskrapport nr 661, 1999, ISSN 0282-3772

[7] Jirjis, R., "Bioenergy – technology and systems" (Course compendium, Master of Science Program in Energy Systems Engineering, 2006), Swedish University of Agricultural Sciences, Department of Bioenergy, E-mail: Raida.Jirjis@et.slu.se

[8] Andersson, G., Asikainen, A., Björheden, R., Hall, P. W., Hudson, J. B., Jirjis, R., Mead D. J., Nurmi, J., Weetman, G. F., "Bioenergy from Sustainable Forestry: Guiding Principles and Practice - Chapter 3: Production of Forest Energy", 2002, ISBN 978-1-4020-0676-0

[9] Pettersen, R.C., "The chemical composition of wood" - Chapter 2, US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI 53705

[10] Lehtikangas, P., "Lagringshandbok för trädbränslen" (second edition), Sveriges Lantbruksuniversitet, Institutionen för virkeslära, 1999, ISBN 91-576-5564-2

[11] Erntsson, M-L., Jirjis, R., Rasmuson, A., "Experimental determination of the degradation rate for some forest residue fuel components at different temperatures and oxygen concentrations", 1991, Scandinavian Journal of Forest Research 6: 271-287

[12] Private conversation with Raida Jirjis at Swedish University of Agricultural Sciences, Department of Energy and Technology, 2009-01-22

[13] Andersson, J., "Hantering av bränsleflis – Enkätundersökning och bedömning av kvalitetsaspekter (Handling of wood chips for fuel - Questionnaire and quality aspects), Växjö Universitet, Institutionen för teknik och design, Avdelning för Bioenergiteknik, 2008, Examensarbete nr: TD 06/2008

[14] "Bioenergi Tidskriften – Bioenergihandboken", http://www novator.se/bioenergy/facts/fuelinvest.pdf, 2008-08-08

[15] Löwegren G., Jonsson L., "Storing of chipped logging residues and chipped oak stemwood in big piles", Swedish University of Agricultural Sciences, Department of Forest Products, 1987, Report no. 191, ISSN 0348-4599

[16] Private conversation with Tommy Pettersson at Johannes combined power and heating plant, Gävle, 2008-10-03

[17] Pentronic AB, Sweden. http://www.pentronic.se, 2008-06-04

[18] Campbell Scientific Ltd, United Kingdom. http://www.campbellsci.com, 2008-09-08

[19] Svensk Standard SS 18 71 71, 1984, Biobränslen - Bestämning av askhalt

[20] Bränsle & Energilaboratoriet AB, Sweden. http://www.belab.nu, 2008-10-15

[21] Svensk Standard SS ISO 1928, 1996, Fasta bränslen - Bestämning av kalorimetriskt värmevärde med bombkalorimeter och beräkning av effektivt värmevärde

[22] Jirjis, R., "Large scale storage of sawdust", Swedish University of Agricultural Sciences, Department of Bioenergy, 2005, Report no. 11, ISSN 1651-0720

[23] Fredholm R., Jirjis, R., "Seasonal storage of bark from wet stored logs", Swedish University of Agricultural Sciences, Department of Forest Products, 1988, Report no. 200, ISSN 0348-4599

[24] Lehtikangas, P., Jirjis, R., "Storage of wood chips and bark in northern Sweden", Swedish University of Agricultural Sciences, Department of Forest Products, 1998, Report no. 254, ISSN 0348-4599

[25] Bjurman, J., Jirjis, R., "A Possible Reason for Variations in the Determination of Dry Matter Losses in Logging Residues", Proceedings of IEA/BA joint workshop, Garpenberg, Sweden, 1994, Department of Operational Efficiency, Research notes no. 278: 42-45

[26] Jirjis, R., Andersson P., Aronsson, P., ”Gasavgång och lakvatten från barklagring: laboratorie- och fältstudier”, Sveriges Lantbruksuniversitet, Institutionen för bioenergi, 2005, Slutrapport – Projekt nr. 20063-1

[27] Andersson, C., Ludvigsson, L., "Uppkomsten av Sipperrännor", Earth Sciences centre, Göteborgs Universitet, Sweden, 2004, http://www.gvc2.gu.se/BIBLIO/B-serien/B400.pdf, 2008-12-23

[28] Thörnqvist T., "Logging residues as a feedstock for energy production – Drying, storing handling and grading", Swedish University of Agricultural Sciences, Department of Forest Products, 1984, Report no. 152, ISSN 0348-4599

Appendix 1 ΔT (Pile - Ambient Temperature)

Figures A1.1-A1.7 shows the temperature differences (ΔT = pile temperature-ambient temperature) between ambient and pile temperatures in campaign 1 (summer storage of five piles) and campaign 2 (autumn storage of two piles). Shown are the thermocouples at the different levels in the piles. Only the bottom- and the top thermocouple were used in campaign 2. All of the measuring points within each pile showed fairly similar temperatures. The exception was the bottom thermocouple in the uncovered large bark pile, which temperature was situated about 10-20ºC below the other thermocouples. Overall, the thermocouples placed at the top of the piles recorded the highest temperatures.

Campaign 1 (summer storage)

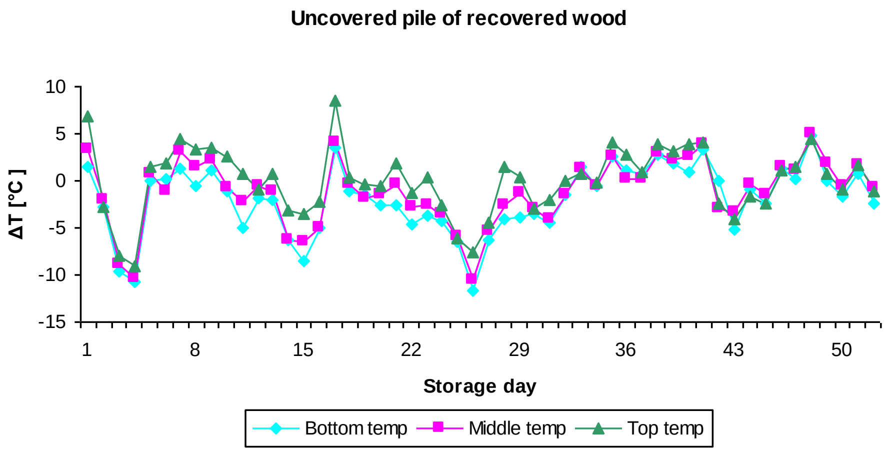

Figure A1.1, Temperature difference between ambient temperature and the three measuring points in the uncovered recovered wood pile during summer storage

Partially covered pile of recovered wood

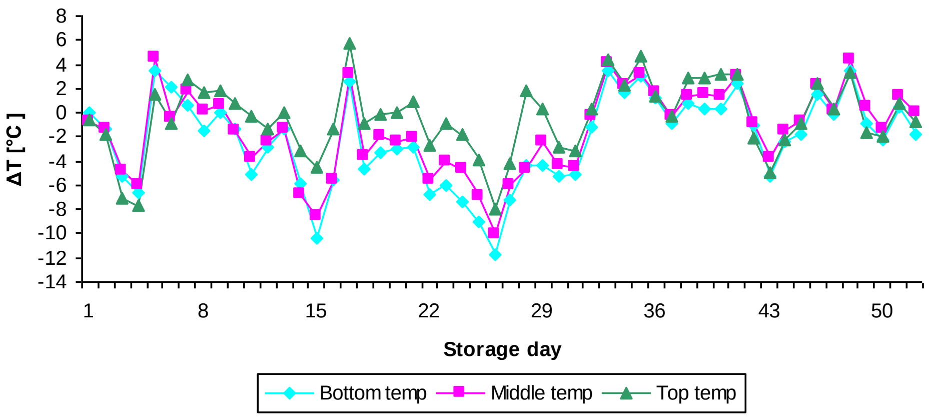

Figure A1.2, Temperature difference between ambient temperature and the three measuring points in the partially covered recovered wood pile during summer storage

Small bark pile

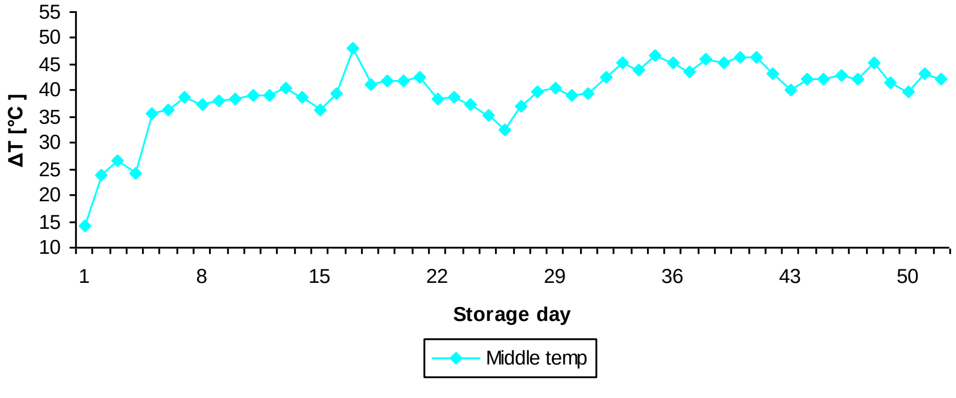

Figure A1.3, Temperature difference between ambient temperature and the single measuring point in the small bark pile during summer storage

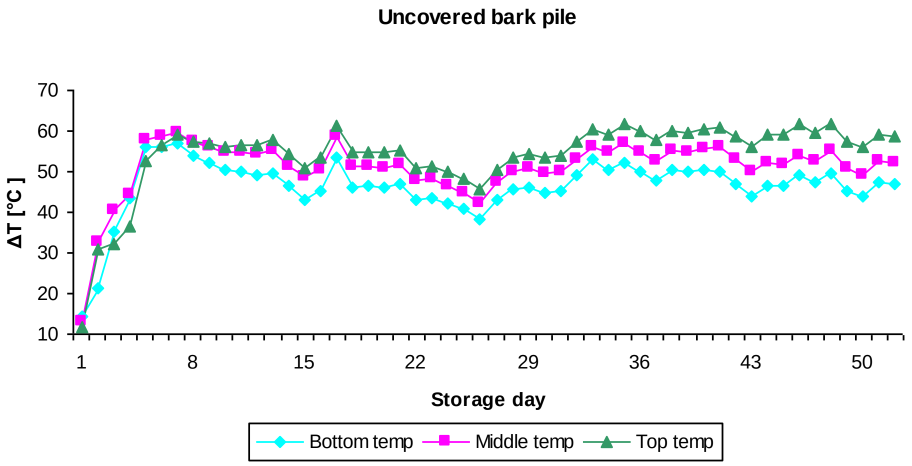

Figure A1.4, Temperature difference between ambient temperature and the three measuring point in the uncovered large bark pile during summer storage

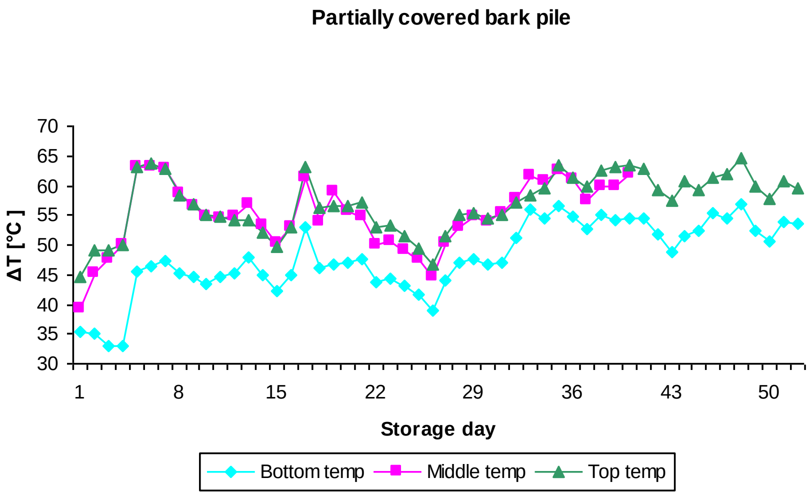

Figure A1.5, Temperature difference between ambient temperature and the three measuring point in the partially covered large bark pile during summer storage

Campaign 2 (autumn storage)

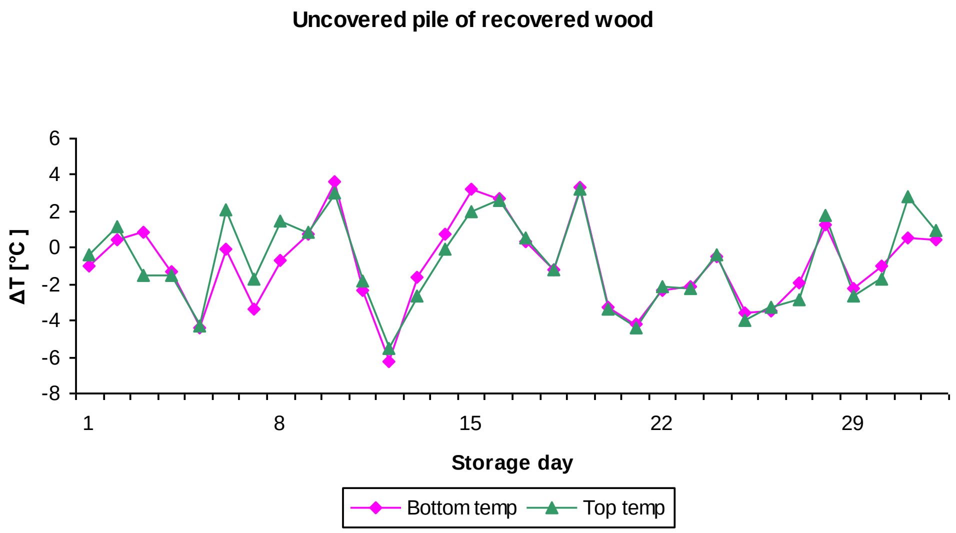

Figure A1.6, Temperature difference between ambient temperature and the two measuring points in the uncovered recovered wood pile during autumn storage

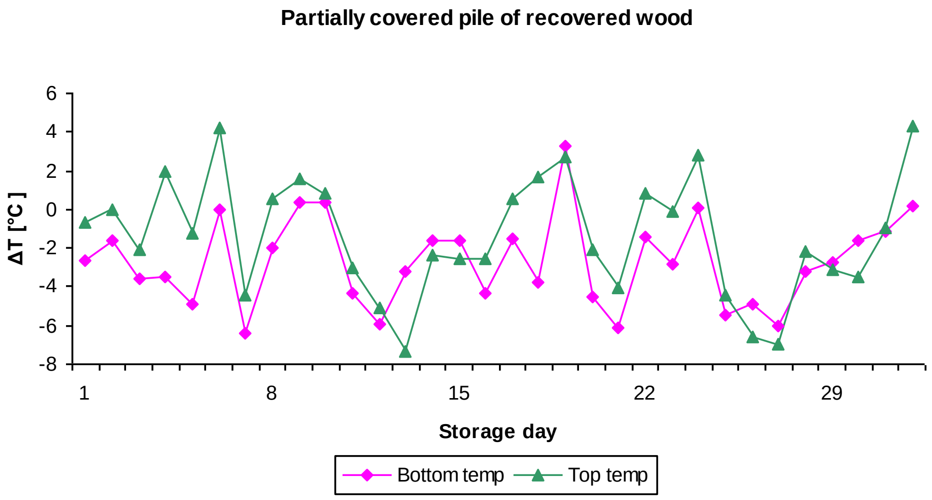

Figure A1.7, Temperature difference between ambient temperature and the two measuring points in the partially covered recovered wood pile during autumn storage

Appendix 2 Dry matter loss determination

Table A2.1, Dry matter loss determination of the uncovered large recovered wood pile in campaign 1 (summer storage)

Campaign 1									
Recvered wood									
Uncovered large pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
	1.1	390	375	11,8	12,0	0,2	344,0	330,0	4,1
	1.2	403	410	12,9	12,1	-0,8	351,0	360,4	-2,7
	1.3	345	343	12,6	13,7	1,1	301,5	296,0	1,8
(error in measurement)	1.4						0,0	0,0	
	1.5	366	379	11,6	12,0	0,4	323,5	333,5	-3,1
	1.6	374	442	10,1	18,6	8,5	336,2	359,8	-7,0
	1.7	366	349	10,9	11,7	0,8	326,1	308,2	5,5
	1.8	432	435	12,4	11,9	-0,5	378,4	383,2	-1,3
	1.9	334	342	9,9	13,5	3,6	300,9	295,8	1,7
(error in measurement)	1.10								
	1.11	357	367	9,7	11,4	1,7	322,4	325,2	-0,9
(broken)	1.12			10,8	11,6	0,8			
(broken)	1.13			11,2	12,2	1,0			
	1.14	368	372	11,2	11,1	-0,1	326,8	330,7	-1,2
	1.15	373	393	9,2	11,4	2,2	338,7	348,2	-2,8
(broken)	1.16			9,8	11,4	1,6			
	1.17	333	328	13,9	10,6	-3,3	286,7	293,2	-2,3
	1.18	383	393	10,2	11,1	0,9	343,9	349,4	-1,6
	1.19	324	343	10	14,2	4,2	291,6	294,3	-0,9
	1.20	291	326	10,6	12,0	1,4	260,2	286,9	-10,3
	1.21	347	366	10,9	12,4	1,5	309,2	320,6	-3,7
	1.22	372	390	11,8	13,4	1,6	328,1	337,7	-2,9
	1.23	408	436	9,4	14,1	4,7	369,6	374,5	-1,3
	1.24	316	359	9,6	12,6	3,0	285,7	313,8	-9,8
	Mean value	**362,2**	**376,2**	**10,9**	**12,5**	**1,6**	**306,2**	**312,1**	**-2,0**
	Std	**34,3**	**35,5**	**1,3**	**1,7**	**2,3**	**77,8**	**78,7**	**4,0**

Table A2.2, Dry matter loss determination of the partially covered large recovered wood pile in campaign 1 (summer storage)

Campaign 1									
Recvered wood									
Partially covered large pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
	2.1	254	282	11,2	13,4	2,2	225,6	244,2	-8,3
	2.2	228	233	12,3	8,9	-3,4	200,0	212,3	-6,2
(not found)	2.3								
	2.4	230	232	12,1	10,6	-1,5	202,2	207,4	-2,6
	2.5	324	338	11,0	9,4	-1,6	288,4	306,2	-6,2
	2.6	281	323	11,3	12,9	1,6	249,2	281,3	-12,9
	2.7	228	234	11,4	11,5	0,1	202,0	207,1	-2,5
	2.8	338	340	11,0	10,5	-0,5	300,8	304,3	-1,2
	2.9	320	305	11,6	10,9	-0,7	282,9	271,8	3,9
	2.10	376	364	12,5	10,2	-2,3	329,0	326,9	0,6
	2.11	373	425	11,6	10,3	-1,3	329,7	381,2	-15,6
	2.12	252	232	15,3	10,4	-4,9	213,4	207,9	2,6
(broken)	2.13			15,5	12,4	-3,1			
	2.14	425	431	13,2	13,2	0,0	368,9	374,1	-1,4
	2.15	427	420	12,7	11,5	-1,2	372,8	371,7	0,3
	2.16	450	453	10,8	11,3	0,5	401,4	401,8	-0,1
	2.17	370	365	11,4	11,3	-0,1	327,8	323,8	1,2
	2.18	410	395	13,3	11,5	-1,8	355,5	349,6	1,7
	2.19	366	375	14,2	12,9	-1,3	314,0	326,6	-4,0
	2.20	409	416	10,0	10,0	0,0	368,1	374,4	-1,7
	2.21	496	502	12,4	12,9	0,5	434,5	437,2	-0,6
	2.22	324	323	14,2	11,5	-2,7	278,0	285,9	-2,8
	2.23	428	445	15,2	16,3	1,1	362,9	372,5	-2,6
(error in measurement)	2.24								
	Mean value	**348,0**	**354,0**	**12,5**	**11,5**	**-0,9**	**305,1**	**312,8**	**-2,8**
	Std	**80,0**	**80,7**	**1,6**	**1,6**	**1,7**	**70,0**	**69,3**	**4,8**

Table A2.3, Dry matter loss determination of the small bark pile in campaign 1 (summer storage)

Campaign 1									
Bark									
Small pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
	3.1	658	655	63,3	62,6	-0,7	241,5	245,0	-1,4
	3.2	752	710	64,2	59,2	-5,0	269,2	289,7	-7,6
	3.3	518	594	55,4	60,9	5,5	231,0	232,3	-0,5
	3.4	635	677	57,5	61,1	3,6	269,9	263,4	2,4
	3.5	774	777	60,5	61,3	0,8	305,7	300,7	1,6
	Mean value	**667,4**	**682,6**	**60,2**	**61,0**	**0,8**	**263,5**	**266,2**	**-1,1**
	Std	**102,4**	**67,6**	**3,7**	**1,2**	**4,1**	**29,1**	**29,0**	**4,0**

Table A2.4, Dry matter loss determination of the uncovered large bark pile in campaign 1 (summer storage)

Campaign 1									
Bark									
Uncovered large pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
(not found)	4.1								
	4.2	558	445	36,8	24,2	-12,6	352,7	337,3	4,4
	4.3	476	386	33,6	26,9	-6,7	316,1	282,2	10,7
(not found)	4.4								
(not found)	4.5								
	4.6	549	441	44,3	34,2	-10,1	305,8	290,2	5,1
	4.7	484	474	41,3	35,1	-6,2	284,1	307,6	-8,3
	4.8	507	451	41,1	32,5	-8,6	298,6	304,4	-1,9
	4.9	568	428	38,1	27,2	-10,9	351,6	311,6	11,4
	4.10	524	374	38,3	27,4	-10,9	323,3	271,5	16,0
	4.11	621	537	42,3	33,7	-8,6	358,3	356,0	0,6
	4.12	482	338	39,9	28,9	-11,0	289,7	240,3	17,0
	4.13	532	425	34,7	23,7	-11,0	347,4	324,3	6,7
	4.14	424	372	40,3	34,0	-6,3	253,1	245,5	3,0
	4.15	474	686	34,9	50,6	15,7	308,6	338,9	-9,8
	4.16	521	416	36,2	29,5	-6,7	332,4	293,3	11,8
	4.17	524	406	36,3	26,9	-9,4	333,8	296,8	11,1
	4.18	648	542	38,8	28,3	-10,5	396,6	388,6	2,0
	4.19	524	570	29,9	42,8	12,9	367,3	326,0	11,2
	4.20	610	638	40	48,9	8,9	366,0	326,0	10,9
	4.21	766	796	53,4	59,0	5,6	357,0	326,4	8,6
	4.22	615	614	57,7	59,4	1,7	260,1	249,3	4,2
(error in measurement)	4.23								
(broken)	4.24			66,9	59,7	-7,2			
	Mean value	**547,7**	**491,5**	**41,2**	**36,6**	**-4,6**	**326,4**	**306,1**	**6,0**
	Std	**78,4**	**122,2**	**8,8**	**12,2**	**8,6**	**38,4**	**38,3**	**7,3**

Table A2.5, Dry matter loss determination of the partially covered large bark pile in campaign 1 (summer storage)

Campaign 1 Bark Partially covered large pile	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
	5.1	677	673	43,7	39,3	-4,4	381,2	408,5	-7,2
	5.2	583	504	44,1	40,1	-4,0	325,9	301,9	7,4
(broken)	5.3			48,6	43,2	-5,4			
	5.4	597	566	47,6	40,5	-7,1	312,8	336,8	-7,7
	5.5	493	492	43,4	41,2	-2,2	279,0	289,3	-3,7
	5.6	579	612	48,5	51,8	3,3	298,2	295,0	1,1
	5.7	535	536	45,5	46,9	1,4	291,6	284,6	2,4
	5.8	570	561	45,5	44,5	-1,0	310,7	311,4	-0,2
	5.9	571	517	47,9	42,0	-5,9	297,5	299,9	-0,8
(not found)	5.10								
	5.11	666	578	46,4	42,1	-4,3	357,0	334,7	6,3
	5.12	653	521	47,7	37,6	-10,1	341,5	325,1	4,8
	5.13	753	675	46,3	41,6	-4,7	404,4	394,2	2,5
	5.14	448	414	48,1	38,1	-10,0	232,5	256,3	-10,2
(not found)	5.15								
	5.16	639	537	48,8	37,8	-11,0	327,2	334,0	-2,1
	5.17	520	454	40,8	35,8	-5,0	307,8	291,5	5,3
	5.18	509	397	47,7	37,4	-10,3	266,2	248,5	6,6
	5.19	532	531	46,1	44,5	-1,6	286,7	294,7	-2,8
(broken)	5.20			44,4	38,0	-6,4			
	5.21	620	611	46,9	46,3	-0,6	329,2	328,1	0,3
	5.22	648	557	44,3	39,7	-4,6	360,9	335,9	6,9
(broken)	5.23			48,6	37,5	-11,1			
(broken)	5.24			49,5	36,7	-12,8			
	Mean value	**588,5**	**540,9**	**46,4**	**41,0**	**-5,4**	**317,2**	**315,0**	**0,5**
	Std	**76,3**	**75,7**	**2,2**	**3,9**	**4,3**	**41,9**	**40,7**	**5,3**

Table A2.6, Dry matter loss determination of the uncovered large recovered wood pile in campaign 2 (autumn storage)

Campaign 2									
Recvered wood									
Uncovered large pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
	1.1	472	471	27,7	21,2	-6,4	341,4	371,0	-8,6
	1.2	393	399	30,1	21,9	-8,2	274,8	311,8	-13,5
	1.3	478	490	24,8	21,2	-3,7	359,3	386,3	-7,5
	1.4	527	550	21,3	25,8	4,5	414,8	408,0	1,6
	1.5	370	448	24,5	36,9	12,5	279,5	282,5	-1,1
(broken)	1.6			24,5	19,4	-5,1			
	1.7	435	454	21,7	22,0	0,3	340,8	354,2	-3,9
	1.8	519	522	20,0	20,6	0,6	415,2	414,5	0,2
	1.9	408	457	25,6	28,6	3,0	303,6	326,4	-7,5
	1.10	451	500	24,3	27,8	3,5	341,4	361,0	-5,7
	1.11	535	523	20,4	21,1	0,6	425,8	412,9	3,0
	1.12	464	463	21,7	21,4	-0,4	363,2	364,1	-0,3
(not found)	1.13								
	1.14	490	488	22,5	22,5	0,0	379,8	378,1	0,4
	1.15	469	487	22,1	19,5	-2,6	365,5	392,2	-7,3
	1.16	421	425	26,2	21,4	-4,7	310,9	333,9	-7,4
	1.17	426	508	18,6	26,0	7,4	346,7	375,9	-8,4
	1.18	451	450	22,1	21,8	-0,3	351,5	352,0	-0,1
	1.19	423	427	24,7	19,9	-4,8	318,6	342,1	-7,3
	1.20	500	497	28,8	21,8	-7,0	356,0	388,4	-9,1
	1.21	416	419	18,6	19,6	1,0	338,7	336,9	0,5
(broken)	1.22			23,3	19,2	-4,1			
	1.23	457	534	23,3	33,0	9,8	350,7	357,5	-2,0
	1.24	538	544	23,1	21,3	-1,8	413,8	428,0	-3,4
	Mean value	**459,2**	**478,9**	**23,5**	**23,2**	**-0,2**	**352,0**	**365,6**	**-4,2**
	Std	**47,33**	**42,89**	**2,96**	**4,55**	**5,29**	**42,0**	**36,3**	**4,5**

Table A2.7, Dry matter loss determination of the partially covered large recovered wood pile in campaign 2 (autumn storage

Campaign 2									
Recvered wood									
Uncovered large pile									
	Net bag number	Net bag, before storage (g)	Net bag, after storage (g)	Moisture content, before storage (GW%)	Moisture content, after storage (GW%)	Moisture content Increase/ decrease (GW%)	Dry weight before storage (g)	Dry weight after storage (g)	Dry matter losses after storage (DM%)
(not found)	2.1								
	2.2	483	492	18,8	17,9	-0,9	392,1	403,9	-3,0
	2.3	416	429	17,0	17,9		345,1	352,3	-2,1
	2.4	453	463	23,9	15,5	-8,4	344,6	391,3	-13,5
	2.5	441	445	18,4	18,0	-0,4	359,8	364,7	-1,4
	2.6	470	476	19,0	17,1	-1,9	380,5	394,5	-3,7
	2.7	426	487	20,1	24,2	4,1	340,5	369,1	-8,4
	2.8	419	419	17,3	16,9	-0,4	346,4	348,0	-0,5
	2.9	392	405	16,4	16,9	0,4	327,6	336,7	-2,8
	2.10	409	411	17,9	17,6	-0,3	335,7	338,6	-0,9
	2.11	463	467	19,0	15,9	-3,1	375,0	392,6	-4,7
	2.12	482	489	18,1	19,1	1,0	394,6	395,4	-0,2
(not found)	2.13								
(not found)	2.14								
(not found)	2.15								
	2.16	405	424	22,0	18,6	-3,4	316,1	345,3	-9,2
	2.17	482	490	18,3	17,5	-0,8	393,8	404,4	-2,7
	2.18	466	469	18,9	18,3	-0,6	377,8	383,0	-1,4
	2.19	474	467	18,5	17,4	-1,1	386,3	385,8	0,1
	2.20	395	449	16,4	27,7	11,3	330,3	324,7	1,7
	2.21	402	403	20,2	16,6	-3,6	320,8	336,2	-4,8
	2.22	360	351	20,3	18,0	-2,3	286,9	287,7	-0,3
	2.23	371	381	19,6	18,3	-1,4	298,1	311,4	-4,4
	2.24	349	506	17,7	40,3	22,6	287,3	302,3	-5,2
	Mean value	**427,9**	**446,2**	**18,9**	**19,5**	**0,6**	**347,0**	**358,4**	**-3,4**
	Std	**42,61**	**41,86**	**1,81**	**5,63**	**6,54**	**34,9**	**35,4**	**3,7**

Appendix 3 Literature survey

This literature survey deals with the state-of-knowledge of biomass losses during storage of biomass fuels in piles. Examples how to try to reduce degradations losses and improve the fuel quality are also included.

Biomass losses and changes in biomass properties during storage in piles

Storage of bark in piles

In a study in northern Sweden [24] a bark pile, 12 m long and 4 meter high, of coniferous bark was built up. Almost half of the bark material had a particle size distribution exceeding 22 mm. The amount of fine fraction, which has a diameter below 5 mm, was about 7 wt%. One half of the pile was covered with a tarpaulin with a ventilation opening at the top. The storage time was 2 months. The temperature went up to about 65ºC after three days and remained in those regions through the whole time of storage.

The initial moisture content of the bark material was very inhomogeneous and varied between 42.1 % and 58.3 % in different parts of the pile. The average moisture content decreased from 48.4 % to 38.1 % in the covered part of the pile and from 49.5 % to 43.0 % in the uncovered pile.

The changes in ash content during storage were small with changes ≤0.6 %DM, which could only be coupled to natural variations in the bark material. The change in heating value was low and could not either be coupled to the storage process. For the covered part of the pile, the change in net heating value was 2.4 % and 4.3 % after 1 and 2 months respectively. The change in net heating value was 2.4 % and 1.2 % after 1 and 2 months respectively for the uncovered part of the pile

The dry matter losses were measured after 1 and 2 months of storage. The results indicate that the dry matter losses were higher in the covered part than the uncovered part of the pile, Table A3.1. The dry matter losses were highest during the first month of storage. Despite the high dry matter losses overall, some sampling points showed an increased dry matter content, which was connected to errors in the determination of the moisture content. However, roughly it could be verified that the dry matter losses were at least 10 %DM, seen to the whole pile. Since the biomass losses come from the dry matter losses and the changes in the heating value, the biomass losses are almost solely out of the dry matter losses.

Table A3.1, Dry matter losses (%DM) of bark after 1 and 2 months of storage. The total number of samples at each sample point is shown within brackets.

Sample point	Dry matter loss* 1 month		Dry matter loss* 2 months	
	Covered	Uncovered	Covered	Uncovered
1	25.9 (5)	18.5 (5)	17.5 (4)	-5.7 (3)
2	26.1 (4)	9.6 (2)	21.7 (2)	1.7 (5)
3	12.4 (5)	21.8 (5)	20.7 (5)	8.0 (5)
4	-8.3 (5)	-1.9 (4)	2.5 (4)	-5.6 (5)
5	8.2 (5)	0.7 (5)	-10.0 (5)	9.7 (5)

*Given as %DM

It was concluded that the dry matter losses were higher in the covered pile than the uncovered. To prevent condensate at the surface of the covered pile, beneath the tarpaulin, the covering should be achieved to release the moist heat. This could be done with certain ventilation holes. However, the ventilation holes should not be of such extent that precipitation could penetrate the holes and saturate the pile. Storing under roof, instead of a tarpaulin, could solve the condensate problems [24].

Storage of wood chips in piles

Two wood chip piles were built up in a study [24], one under roof and one outdoor without roof. The piles were identical in size, 12 meters long and 6 meters high. Almost half of the wood chips had a particle size distribution between 7 and 16 mm. About 20 wt% of the wood chips was fine fraction. The storage time was 8 months, from October to May. The piles were analyzed after 1, 2 and 8 months of storage. The temperature development in the piles was similar. The initial temperature of the wood chips was 10ºC and stayed there for the first three months. The temperatures followed the ambient temperature during storage and started to decrease when the ambient temperature went below 0ºC.

The average value of the initial moisture content was 22 % as well as 26 % for the roof covered pile and the pile without roof respectively. The initial moisture content, when the piles were built, was also very homogenous. The moisture content decreased gradually in the pile stored under roof during the whole time of storage. In the pile stored without roof, the average value of the moisture content was marginally changed during the first two months of storage, while it was increased at the end of storage. The moisture content decreased in all sampling points in the pile stored under roof. In the pile stored without roof the moisture content decreased in all sampling points in the pile except the point at the top where it was heavily increased from 24 % to 43 %.

Only marginal changes were seen for the ash contents and the heating values during storage. The changes were between 0.25 and 0.4 %DM for the ash content. The net heating value showed variations between 0.1 % and 1 %.

The dry matter losses are showed in Table A3.2. The dry matter losses were similar and marginal through the whole storage time in the pile stored under roof. The pile that was stored without roof had increased dry matter losses after 8 months of storage in sample points 4 and 5, which were in the middle of the pile and probably had the biggest heat development in the pile. Despite that the temperatures were low, it was enough for degradation of the material to happen.

Table A3.2, Dry matter losses (%DM) of wood chips after 1, 2 and 8 months of storage. The total number of samples at each sample point is shown within brackets.

Sample point	Dry matter loss* 1 month		Dry matter loss* 2 months		Dry matter loss* 8 months	
	Under roof	Without roof	Under roof	Without roof	Under roof	Without roof
1	-2.0 (4)	1.4 (4)	1.6 (3)	1.5 (4)	-1.5 (3)	-1.8 (4)
2	-3.0 (4)	3.7 (4)	**	1.0 (2)	-0.1 (4)	-5.3 (4)
3	-1.0 (3)	-0.2 (3)	0.3 (4)	-0.7(3)	0.1 (3)	0.8 (4)
4	1.5 (3)	0.3 (4)	-0.2 (4)	-0.2 (2)	1.5 (5)	8.9 (5)
5	0.9 (3)	4.0 (4)	0.7 (4)	-2.1 (4)	-0.9 (5)	7.3 (5)
6	2.5 (4)	1.6 (4)	0.3 (4)	3.5 (4)	0.2 (5)	1.8 (5)

*Given as %DM, **All samples were destroyed

The moisture content decreased in the piles stored under roof while it was the opposite for the piles outdoors. The dry matter losses were also lower in the roof-covered pile, primarily because of the lower moisture content. It was also concluded that storage of wood chips under roof could be further advantageous in storage regions with higher levels of precipitation [24].

Storage of residue fuel chips in piles

A storage study of chipped clear-cut residues in piles [4] dealt with changes in fuel chips when stored in large piles. The pile that was built up was 90 m long, 14 m wide and 7 m high. Along the pile, 12 section numbers (6 m apart from each other) were used where sampling bags were placed. The fuel chips consisted of 46 wt% wood, 16 wt% branches and tops, 21 wt% needles, 11 wt% bark and 6 wt% of an inseparable fine fraction. The bark and the needles are the components that are most nitrogenous. More than half of the fuel chips, 56 wt%, had a particle size distribution between 3 and 7 mm and the amount of fine fraction was 16 wt%. The storage time was 7 months with start in May. The temperature in the pile increased during storage and stabilized itself at 70-75ºC in many places in the pile after a couple of weeks, with only small variations. The initial moisture content varied between 33 and 50 % within the pile. During storage, the moisture content decreased in all parts of the pile. In the first few weeks the change in moisture content was marginal, although the pile started to dry considerable after circa 4-5 weeks. After storage the moisture content varied between 28 and 40 % within the pile.

The ash content showed marginal changes after storage of 0.2 %DM. The gross heating value was unchanged while the average net heating value had increased with 2.8 % after storage from 17.6 to 18.1 MJ/kg DM.

The dry matter losses were largest in the beginning of storage, Table A3.3. After the first week, the dry matter losses were as high as 3.6 %DM. The dry matter losses then gradually declined for the rest of the storage period. Between 12 and 16 weeks of storage the dry matter losses increased from 0.4 to 0.7 %DM per week. This difference could be explained by variations in moisture content, where the average moisture content was higher in the last four sections (9-12) than the first eight. The dry matter losses during the first weeks would probably have been a lot higher, maybe as high as 10 %DM, if the moisture content had been as high as it was in the last sections, revised at the end of storage. The total dry matter losses were over 11 %DM at the end of storage.

During the first week of storage, the energy losses that depended on the dry matter losses and the change of the net heating value were almost 3 %, Table A3.3. The energy losses then gradually decreased as the dry matter losses were reduced and the pile dried out. At the end of storage the energy losses were almost 8 %.

Table A3.3, Dry matter losses [%DM] and Energy losses [%] of clear-cut residue fuel chips during 7 months of storage

Section number	Initial moisture content*	Weeks of storage	Dry matter loss**		Energy loss***	
			during storage	per week	during storage	per week
1	38.8	1	3.6	3.6	2.9	2.9
2	42.9	2	4.5	2.3	2.6	1.3
3	40.3	3	5.2	1.7	2.3	0.8
4	32.8	4	3.6	0.9	2.9	0.7
5	38.8	6	6.0	1.0	4.0	0.7
6	35.7	8	5.6	0.7	4.7	0.6
7	40.1	10	5.9	0.6	5.1	0.5
8	38.2	12	4.6	0.4	2.0	0.2
9	49.7	16	11.8	0.7	6.4	0.4
10	50.6	20	12.2	0.6	6.7	0.3
11	45.9	24	11.9	0.5	8.9	0.4
12	48.8	28	11.3	0.4	7.9	0.3

*Given as %GW, **Given as %DM, *** Given as %

It was concluded that during storage of fuel chips, the moisture content has a massive impact on degradation losses. The dry matter losses and the energy losses follows the same curve, they are largest at the beginning of storage and then gradually decrease [4].

Change in energy content through different storage alternatives

Following numbers are expected changes in energy content with different storage alternatives, which are based on different sub-projects [28].

Table A3.4, Dry matter losses (DML) and change in energy content (CEC) of comminuted residue fuel chips during different storage alternatives

Material	Storage time (months)	Moisture content* (%)	Pile Size (m3)	DML (%DM) Total	CEC (%)	
					Total	Per month
Comminuted fresh logging residues						
– Under roof	7	20 (55)	55	18	-7.1	-1.0
– Not covered	7	50 (55)	55	20	-17.6	-2.5
– Under roof	9	55 (55)	55	23	-23.0	-2.6
Comminuted older logging residues						
– Not covered	6	45 (30)	55	11	-14.3	-2.4
– Not covered	6	30 (25)	55	5	-6.0	-1.0
Comminuted fresh logging residues**						
– Not covered	5	55 (55)	400	8	-8.0	-1.6
– Not covered	6	50 (55)	400	16	-13.5	-2.3
– Tarpaulin covered	6	55 (55)	400	20	-20.0	-3.3
– Tarpaulin covered	6	40 (40)	400	7	-7.0	-1.1

*Moisture content at the end of storage. Numbers in brackets are initial moisture content
**Explanation (from top to bottom): finely comminuted material, crudely comminuted material, crudely comminuted material, crudely comminuted material stored on the logging area 1 year before comminution

Storing of chipped logging residues and chipped oak stemwood in big piles

Storage of chipped logging residues and chipped oak in big was investigated [15]. Two piles were built up, one of each materials. Four storage alternatives were studied for each pile:

- Compacted, indoors
- Compacted, outdoors
- Uncompacted, indoors
- Uncompacted, outdoors

The piles were 60 m long, 14 m wide and 7 m high with a volume about 5000 m^3 each. The storage time was 7 months (June-January).

The temperature in the piles of chipped residues was varied during storage. The uncompacted piles reached a maximum temperature of 60ºC but were only 20-30ºC at the end of storage. The compacted pile stored outdoors reached a maximum of 55ºC and remained there for the rest of the storage period. However, the temperature in the compacted pile stored indoors rose first slowly to about 50ºC and then increased explosively to about 300ºC after 4.5 months. The temperature then decreased to about 100ºC at the end of storage.

The temperature in the piles of chipped oak stemwood was more even during storage. The uncompacted piles had a temperature of 20-30ºC in the beginning of storage and then adapted to the ambient temperature. The compacted piles reached a temperature of 55ºC but then decreased to temperatures slightly above the ambient temperature.

The ash content showed mostly minimal changes after storage. The largest changes were seen for the chipped logging residues stored indoors. The ash content increased by 1.1 and 1.5 %DM for the uncompacted and the compacted section respectively. The gross heating and the net heating values were unchanged for most sections with the biggest change for the compacted pile of logging residues stored indoors. The gross heating value increased with 1.9 % from 20.2 to 21.2 MJ/kg DM after storage while the same for the net heating value was 2.2 % from 19.4 to 19.8 MJ/kg DM.

The moisture content, the dry matter losses and the changes in energy content for the different storage alternatives could be viewed in Table A3.5. The moisture content decreased in all piles except for the compacted piles stored outdoors. The dry matter losses in all piles of oak stemwood were very small, below 5 %DM. The piles stored outdoors showed slightly higher dry matter losses. Larger dry matter losses were seen in the piles of logging residues, between 6.8 to 12.0 %. The highest losses was seen in the in the compacted pile stored outdoors and the smallest losses in the uncompacted pile stored indoors.

Table A3.5, Moisture content (MC), dry matter losses (DML) and change in energy content (CEC) of chipped logging residues and chipped oak stemwood in large piles during storage of 7 months

Material	Type of storage	MC before storage (%)	MC after storage (%)	DML (%DM)	CEC (%)
Logging residues	compacted*	46.6	38.5	9.8	-4.8
Oak stemwood	compacted*	36.2	27.7	3.1	0
Oak stemwood	uncompacted*	35.9	24.3	1.4	2.6
Logging residues	uncompacted*	42.2	23.3	6.8	-0.9
Logging residues	uncompacted**	40.5	27.5	8.1	-4.1
Oak stemwood	uncompacted**	36.6	33.3	4.1	-2.8
Oak stemwood	compacted**	35.1	33.1	4.9	-4.9
Logging residues	compacted**	44.1	46.9	12.0	-12.0

*Stored under roof, **Stored outdoors

The conclusions of the study were that chipped logging residues had higher dry matter losses than chipped oak stemwood, mainly because of the higher contents of nutritious needles and fine fraction which were desirable for microbes. I was also concluded that storage of compacted biomass and storage without roof gives higher dry matter losses [15].

Seasonal storage of bark from wet stored logs

This study reflects storage of really wet bark [23]. Four uncompacted piles were built up, two indoors and two outdoors. The total volume of all piles was approximately 2350 m^3. The four piles were 4 and 7 m high with a width of 8 and 14 m respectively. The length of each pile was 15 m. The storage time was 6 months (September-February)

The temperature in all piles, both stored indoors and outdoors was similar. The temperature reached 60-70ºC after a couple of weeks and then decreased to about 50-60ºC at the end of storage.

The ash content increased marginally in the piles stored indoors while the piles stored outdoors had a marginal decrease. Both the gross heating value and the net heating value were unchanged after storage. The moisture content, the dry matter losses and the changes in energy content could be viewed in Table A3.6. Despite the relatively high temperatures the material had not changed appreciably. The dry matter losses were highest in the piles stored outdoors. The 4 m pile had higher losses than the 7 m pile. Even in the piles stored indoors, the dry matter losses were higher in the 4 m pile.

Table A3.6, Moisture content (MC), dry matter losses (DML) and change in energy content (CEC) wet bark during 6 months of storage

Material	Type of storage	MC before storage (%)	MC after storage (%)	DML (%DM)		CEC (%)
				Total	Per week	Total
Bark, 4 m high	indoors	64.9	65.3	16.5	4.1	-16.6
Bark, 7 m high	indoors	66.9	67.5	14.3	3.6	-14.3
Bark, 4 m high	outdoors	68.0	71.2	25.8	6.4	-29.9
Bark, 7 m high	outdoors	69.0	69.0	18.4	4.6	-19.6

The conclusions of the study were that during storage of very wet bark, the moisture content of the bark was not changed despite considerable heat development in the piles. The dry matter losses were higher in piles of less height (4 m), than in higher ones (7 m) [23].

Examples of measures how to reduce degradation losses during storage and improve the biomass fuel quality

Mixture of wood fuels

With the purpose of improving the fuel quality before storage, a study was made that contained storage of a mixture of two fuels [7]. The mixture was constituted of bark and shavings with the initial moisture contents of 46.3 % and 11.2 % respectively, which was stored in an outdoor pile. A plain bark pile was also stored for comparison reasons. Mixing a very wet fuel with a more dry fuel is often done before the fuel is combusted since the combustion process of a very wet fuel can be highly ineffective because a lot of energy is required to vaporize the moisture in the fuel. Since different storage problems, like self-ignition, are more likely to fall upon an inhomogeneous fuel, the mixing process of the fuel is preferably done short before the fuel is utilized. The results showed that the dry matter losses as well as the moisture content after six months of storage were lower in mixture fuel pile than the bark pile. The decreased moisture content of the mixture fuel did not just affect the dry matter losses but also led to an increased net heating value of the fuel after storage. [7]

Active and passive ventilation of piles

Ventilation of piles can lower the pile temperature as well as the moisture content of the stored wood fuels. Ventilation can either be passive or active. No external energy is used as an input in passive ventilation, which is the case with active ventilation. Passive ventilation can be utilized by digging a tunnel in the bottom of a pile. This method has been shown effective at lowering pile temperatures and thereby reduces risks for self-ignition. On the other hand, by lowering the temperature to circa 25-45°C and by letting in free oxygen, this could provide a favorable environment for different types of fungi. The cooling should therefore be below 20°C. [7]

Storage of freshly harvested Salix chips equipped with active ventilation has shown to be an effective storage method [7]. Three different alternatives were investigated, namely one uncovered unventilated pile and one continuously ventilated pile, where one half of the ventilated pile were built under roof. The storage time was five months, from January to May. The results showed significant growth of fungi in the unventilated pile and the temperature stabilized itself at 60ºC after about six weeks of storage. In the ventilated pile, the temperature was close to ambient temperature during the whole time of storage. The dry matter losses was around 9 %DM for the unventilated pile while they were 6.5 and 7 %DM for the covered and uncovered parts respectively [7].

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