Dissertationes Forestales 167

Moisture content, weight loss and potential of energy wood in South and Central Ostrobothnia regions in western Finland

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Academic dissertation

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ABSTRACT

The aim of this thesis was to improve the quality of energy wood and therefore increase the potential of forest energy. The role of moisture content in energy wood was crucial in this study and the data concerning it was collected at various stages in the operational energy wood supply chain.

About half of the mass of a freshly-felled tree consists of water. From the point of view of energy generation this water is unwelcome. There are two main ways to dry energy wood; these are artificial drying and drying naturally. The Norway spruce (*Picea abies* L. Karst.) stump wood dries fairly quickly in favourable natural conditions. The average moisture content (wet basis) of a stump was about 31 % one month after stump harvesting. Spruce stump wood also retains its dryness well in storage all year round; providing the stumps are dried well one time after harvesting. Small-sized whole trees did not dry well at roadside storage sites under natural conditions. About one year after harvesting the moisture content of a small-sized whole tree was still about 43 %. However, during storing a remarkable weight loss of 37 % was detected between the forest and the heating plant.

The most effective and the fastest drying method found in this study was the continuous compression drying method. The lowest moisture content of 30 % was achieved for Downy birch (*Betula pubescens* Ehrh.) by continuous pressing using 38 MPa and with a pressing time of 30 seconds. Correspondingly, the moisture content of softwood was about 35 % under the same pressing conditions. The energy consumption for compression drying is very low compared to the energy required to vaporise water in thermal drying.

The techno-economic forest energy potential of the study area was 1.6 TWh/y and it could be even greater (2.7 TWh/y) if the Scots pine (*Pinus sylvestris* L.) stumps were also fully utilised for energy recovery. The forest energy potential calculations were made using the heating value of fresh wood and therefore the real potential will be greater when using dried energy wood. For absolutely dry wood the potential was about 1.9 TWh/y.

The properties of energy wood vary widely depending on its assortment, storage conditions, as well as the weather conditions and the origin of the energy wood. However, a better understanding of energy wood properties will increase forest energy's potential and the use of renewable energy and thus help mitigate climate change globally.

Keywords: bioenergy, energy wood, forest energy, measuring, stump, whole tree

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Lapua, June 2013

Jussi Laurila

LIST OF ORIGINAL ARTICLES

The dissertation consists of a summary and the following studies, referred to in the text by Roman numerals **I-IV**. The articles are reprinted with the permission of the respective publishers.

I Laurila, J., Tasanen, T. & Lauhanen, R. 2010. Metsäenergiapotentiaali ja energiapuun korjuun resurssitarpeet Etelä-Pohjanmaan metsäkeskuksen alueella. Metsätieteen aikakauskirja 4/2010: 355-365. Available at: http://www.metla.fi/aikakauskirja/full/ff10/ff104355.pdf (in Finnish.)

II Laurila, J. & Lauhanen, R. 2010. Moisture Content of Norway Spruce Stump Wood at Clear Cutting Areas and Roadside Storage Sites. Silva Fennica. Vol. 44(3), 2010: 427-434. Available at: http://www.metla.fi/silvafennica/full/sf44/sf443427.pdf

III Laurila, J. & Lauhanen, R. 2012. Weight and volume of small-sized whole trees at different phases of the supply chain. Scandinavian Journal of Forest Research, 2012; 27: 46-55. Available at: http://dx.doi.org/10.1080/02827581.2011.629621

IV Laurila, J., Havimo, M. & Lauhanen, R. 2012. Compression drying of energy wood. Manuscript Submitted (Fuel Processing Technology).

The planning of the studies was carried out by the authors of the articles. The data for papers II and III was collected by Laurila and Lauhanen. Laurila collected the data of papers I and IV by himself. The main author had the main responsibility for all calculations and data analyses of papers I, II and III. He also carried out the moisture content analysis in papers II and IV. Laurila wrote the first draft of papers I, II and III, which was commented on by the other authors. Havimo wrote the literature review for the Introduction chapter in paper IV and was involved in the calculations and writing of the Results and Discussion chapter of paper IV, whereas Laurila wrote the rest of the paper. Lauhanen improved paper IV by commenting on the manuscript.

“Where no wood is, there the fire goeth out”

Proverbs 26:20

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1 INTRODUCTION

1.1 Background

Population growth and rising living standards are increasing world energy consumption. In 2008, the world's primary energy demand was 12,271 Mtoe (142,712 TWh) and demand is increasing every year, from 2008 to 2035, by between 0.7 - 1.4 % depending on the scenario used (World Energy Outlook 2010). Most of the energy, 80 % (Figure 1), is generated with fossil fuels and the share of renewable energy sources is only slightly more than 10 % (World Energy Outlook 2010). However, there are five strong driving forces (climate change, high price of fossil fuels, reduction of fossil fuel deposits, energy security and rural development) which strongly promote the use of renewable energy sources globally. The most important driver is global climate change (United Nations Framework… 1992, Kyoto Protocol to… 1998, Hakkila 2004, Directive 2009).

The on-going anthropogenic climate change is due to greenhouse gas emissions which have increased during the last century (Solomon et al. 2007, Ilmasto-opas.fi 2012). Increases in the carbon dioxide content of the atmosphere have especially promoted the greenhouse effect (Ilmasto-opas.fi 2012). Other remarkable greenhouse gases are methane and nitrous oxide (Solomon et al. 2007). The atmosphere's carbon dioxide content rose, from the 18th century to the present time, from 208 ppm to 390 ppm (Pimenoff et al. 2008, Recent Mauna Loa… 2012). The use of fossil fuels is the main cause for the increased carbon dioxide (CO_2) content in the atmosphere (Le Treut et al. 2007).

The greenhouse gas emission will result in an increase in the global mean temperature (Ilmasto-opas.fi 2012). For example the mean temperature of the globe has risen by about 0.8 °C compared to the period before industrialisation (Solomon et al. 2007). It has been estimated that the Greenland ice sheet will melt if the temperature rises by 1 - 2 degrees from the present level (Lenton et al. 2008). If the Greenland ice sheet totally melted, the sea level would raise by as much as 7 metres (Lenton et al. 2008). Global warming also causes other serious changes on the planet, such as: the melting of the West Antarctic ice sheet, the melting of Artic sea ice, the melting of permafrost, the disappearance of Boreal forests and the decreasing of the Indian summer monsoon etc. (Lenton et al. 2008). The impacts might be catastrophic for mankind. Therefore it is a fact that greenhouse gas emissions must be reduced so that global warming can be prevented. Energy efficiency and renewable energy has an essential role to play in fighting climate change.

Higher prices for fossil fuels promote the use of renewable energy. A variety of geopolitical and economic events directly affect the price of crude oil. In the early 70's the price of crude oil was under 20 dollars per barrel, but the price rose quite rapidly in the 70's to almost 50 dollars per barrel at the time of the oil crisis in 1973. The rise in the oil price continued until the highest point was reached at slightly over 80 dollars per barrel in 1982 after which the price began to fall temporarily. The price was about 30 dollars per barrel for almost the whole of the 90's. However, the price began to rise again in the new millennium and it was over 120 dollars per barrel before the global financial collapse in 2008. (What drives crude... 2012). In the autumn of 2012 the price of crude oil was about 90 dollars per barrel (Petroleum & other liquids 2012). Crude oil sets the price of petroleum and also other forms of energy (What drives crude... 2012). The interest in biofuels will increase when the price of oil is high and fluctuations in fossil fuel prices affect the use of forest energy (Hakkila 2006a, Thorsén et al. 2010, Mikkola 2012).

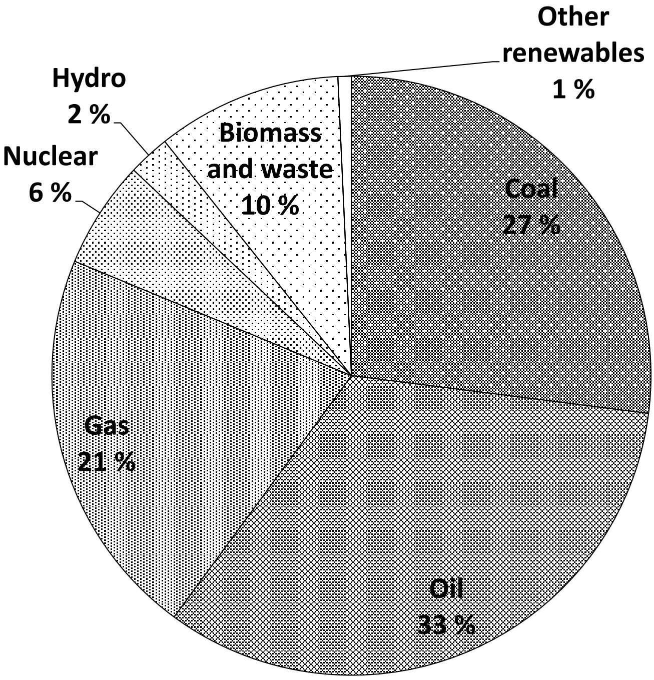

Figure 1. World primary energy demand by fuel in 2008 (Drawn by Jussi Laurila according to World Energy Outlook 2010).

Other important driving forces are the reduction of fossil fuel deposits as well as energy security. Energy security is increased in that the use of renewable energy contributes significantly to local energy independence (Lunnan et al. 2008). Moreover, rural development drives the use of renewable energy, because it promotes development and employment in rural areas, which is desirable (Lunnan et al. 2008). The lack of fossil fuel deposits, the great forest energy potential and high energy demands promote the development and use of bioenergy (Röser 2012). The strong rise in the world market price of fossil fuel and the high cost of emission trading has changed the price relationship between fossil and renewable energy. The competitiveness of renewable energy in the current situation is better now than during the time of cheap oil (Pitkän aikavälin ilmasto… 2008).

There are versatile renewable energy sources in the world. There is hydropower, solar energy, wind energy and bioenergy forms of renewable energy. Bioenergy is also divided into several different sources, such as: field crop energy, forest energy and algae energy. However, currently forest energy is probably the most important source of bioenergy in many countries (Riala & Asikainen 2012). Also forest energy is divided into different sources according to its origin. The main sources in Finland are, for example: small-size trees from young stand thinning sites, logging residues and stump wood from clear cutting areas.

The use of wood as fuel has a long tradition in many Nordic countries, especially in Finland and Sweden where the development of the utilization of forest energy is the most progressive in Europe (Asikainen et al. 2008, Röser 2012). Also, the share of mechanization in wood harvesting is high in Finland and Sweden compared to other European countries (Asikainen et al. 2008). However, the present large scale use of forest energy is also a relatively new phenomenon in these countries.

According to the Finnish long-term climate and energy strategy wood fuel has an important role to play in increasing the use of renewable energy (Pitkän aikavälin ilmasto… 2008). The aim of the European Union Commission is to substantially increase renewable energy usage by the year 2020 (Directive 2009). In 2012, the amount of forest wood chips used for heat energy production in Finland was 8.3 million m^3 solid, while the techno-economical potential of forest energy was about 15 million m^3 solid per year (Ylitalo 2013, Hakkila 2004, Laitila et al. 2008). Accordingly, forest energy is a limited resource despite its renewability (Hakkila 2004). The use of forest wood chips for heat energy production has increased quite rapidly over the past 10 years in Finland (Figure 2). As a comparison, the use of wood fuel for district heating in Sweden was 32 TWh (circa 16 million m^3 solid) in 2010 (Wigrup 2012). The total wood consumption for energy generation in the EU's 27 member states was 346 million m^3 in 2010 (Mantau et al. 2010). The aim of the Finnish Ministry of Employment and Economy is to increase the use of forest wood chips up to 13.5 million m^3 solid per year by the year 2020; based on the European Union Commission's target (Directive 2009, Työ- ja elinkeinoministeriö 2010). The target is very challenging and new innovations, research and development work is needed so that the goal can be met.

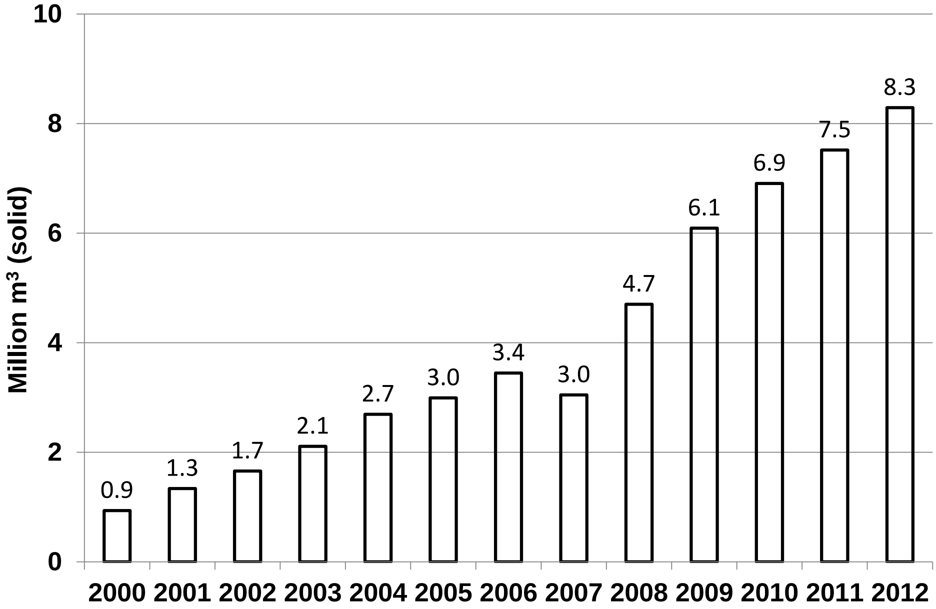

Figure 2. Consumption of forest wood chips from 2000 to 2012 in Finland (Drawn by Jussi Laurila according to Ylitalo 2013).

1.2 Moisture content of wood

About half of the biomass of a living tree consists of water (Hakkila 1989, Haygreen & Bowyer 1996, Kärkkäinen 2007). It is well known that the moisture content range (wet basis), in Finland, of freshly-felled small-sized Scots pine and Norway spruce trees varies between 50 - 60 % and birch trees 40 - 50 % (Hakkila 1989, Kärkkäinen 2007). The share of water varies both between the separate parts of the tree and between trees. In the outermost growth ring of spruce the moisture content is even as high as 60 % whereas the moisture of the heartwood is only about 30 %. With the pine tree the corresponding values are a little lower (Saranpää & Tuimala 1997, Kärkkäinen 2007). The variation of moisture content can be explained partly by, among other things, the density of the wood and by the age of the tree (Kärkkäinen 2007). In general the denser the wood is, the lower the moisture content of the wood. The age of the tree significantly affects the proportion of heartwood in a tree (Haygreen & Bowyer 1996). For example the heartwood of pine and spruce is substantially drier than sapwood (Haygreen & Bowyer 1996, Kärkkäinen 2003). It has also been shown that the moisture of the tree is partly determined by its hereditary (Kärkkäinen 2003). The moisture varies significantly according to the season and also a little bit according to the time of day. The moisture of a living conifer will be at its highest in the winter season (Saranpää & Tuimala 1997). The moisture is also at its lowest in the commercial part (log and pulp wood) of the tree. The exception to this may be stump wood where the moisture can be relatively low due to the high density of the stump. Usually the moisture increases from the middle of the stump moving towards the root points (Kärkkäinen 2007).

Wood has a cellular structure, mostly formed of dead cells, which have stiff cell walls and a void inner cavity called the lumen (Gibson & Ashby 1999, Kärkkäinen 2007). There is water retained in the wood cell in two ways (Figure 3). Part of it is free water in the cell lumens and part is bound to the cell walls (Haygreen & Bowyer 1996). Also, there is saturated water vapour in the lumen. In a living tree water is transported from the roots to the crown through these hollow lumens. Therefore, in freshly-felled trees the lumens are also filled with water as well as the cell walls (Kärkkäinen 2007).

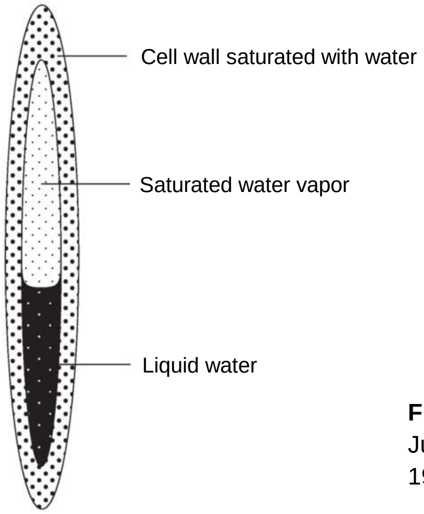

Figure 3. Water in a green wood cell (Re-drawn by Jussi Laurila according to Haygreen & Bowyer 1996).

Wood is a hygroscopic material because it tends to absorb water from the surrounding air (Kärkkäinen 2007). Wood also has equilibrium moisture content (EMC) which depends on the temperature and the relative air humidity (Haygreen & Bowyer 1996, Kärkkäinen 2007). The amount of water vapour which is entering the wood in the equilibrium moisture content and leaving it is equal (Kärkkäinen 2007). The equilibrium moisture content of wood is different dependent on whether the moisture of the wood is decreasing or increasing. When moisture increases, the equilibrium moisture content will be lower than when the moisture content is decreasing (Kärkkäinen 2007). The reaction of untreated wood to moisture changes is moderately quick (Kärkkäinen 2007). According to Time (2002) the new equilibrium moisture content point of thin (10 mm) spruce samples was reached within a day in a temperature of 25 °C when the relative air humidity varied between 75 and 94 %.

The amount of water in the wood can be described using different methods and concepts (Kärkkäinen 2007). When speaking about the moisture of wood, some of the general concepts used are moisture ratio (dry basis) and moisture content (wet basis). The moisture content (MC) is the relation of the mass of the water and the total mass of the fresh wood, Equation 1. The moisture ratio (MR) is the relation of the mass of the water and the mass of the dry wood, Equation 2. (Saranpää & Tuimala 1997, Kärkkäinen 2003).

$$\mathrm{MC} = \frac{(\mathrm{m_g} - \mathrm{m_0})}{\mathrm{m_g}} \times 100\% \tag{1}$$

$$\mathrm{MR} = \frac{(\mathrm{m_g} - \mathrm{m_0})}{\mathrm{m_0}} \times 100\% \tag{2}$$

where:
MC = moisture content (wet basis)
MR = moisture ratio (dry basis)
$\mathrm{m_g}$ = the mass of the sample before drying
$\mathrm{m_0}$ = the mass of the sample after drying

According to the recommendation, the moisture content and the moisture ratio are usually shown in per cent (Kärkkäinen 2007). The conversion between moisture content and moisture ratio can be easily calculated using equations 3 and 4 (Saranpää & Tuimala 1997, Kärkkäinen 2003). However, in practice the terms of moisture content and moisture ratio have not been totally established and this might cause confusion (Kärkkäinen 2007).

$$\mathrm{MR} = \frac{100 * MC}{100 - MC} \tag{3}$$

$$\mathrm{MC} = \frac{100 * MR}{100 + MR} \tag{4}$$

There are several methods for the measurement of wood moisture. The methods can be divided into two main types: one phase methods and two-phase methods (Kärkkäinen 2007). In a one phase measuring method the mass of the water and the mass of the wood is not measured separately. In this method the moisture of the wood is directly determined with one measuring based on, for example: the electrical conductivity, micro waves, infrared waves or nuclear magnetic resonance (Kärkkäinen 2007).

In the two-phase methods the mass of the water and the mass of the wood is determined separately. The simple laboratory method is to weigh the mass of fresh wood and then the mass of the wood absolutely dry. Thus, the mass of the water, which the wood contained, is obtained as a result of subtracting the one from the other. The drying can be carried out in an oven at 85 to 120 ˚C depending on the standard used (Kärkkäinen 2007). Usually a drying time of 24 hours is sufficient, but longer times can also be used. The drying time can be shortened by raising the temperature of the oven (Kärkkäinen 2007). However, the result will not be as exact as that obtained using lower temperatures (Kärkkäinen 2007).

There are several standards for the determination of the moisture of wood which differ from each other (Kärkkäinen 2007). The variation is found in the drying times and temperatures used and also the ventilation definitions might be incomplete (Kärkkäinen 2007). In addition, too long a drying time and too high a temperature in the oven causes loss of volatile wood compounds. This directly reduces the mass of the wood and gives incorrect results. Moreover, in practice it is impossible to know exactly when the wood is absolutely dry (Kärkkäinen 2007). Due to the above mentioned factors the two-phase oven methods also have inaccuracy factors. However, the two-phase method is more accurate than the one phase method which is based on electrical conductivity. Especially above the fibre saturation point the one phase method (electrical conductivity) is imprecise.

1.3 Drying of energy wood

From the point of view of logistics and energy generation the moisture in wood is unwelcome and it causes extra costs in the energy wood supply chain (Nurmi 2000, Hakkila 2004). When wood is burnt, water evaporates before the wood begins to chemically decompose. The warming of the water, the vaporising of the water and the rising of the vapour’s temperature requires thermal energy. This causes a reduction in the wood’s heating value and the temperature at which the fuel is burning. The decline in the burning temperature also slows down the speed at which the burning happens (Kärkkäinen 1981, Pietilä 2005).

Energy generated from wood fuel can be increased by improving the wood quality. The moisture content of the wood is an important quality factor in energy wood (Jahkonen et al. 2012, Routa et al. 2012). The lower the wood fuel’s moisture content, the better its quality. The heating value (5.3 MWh/ton) of dry wood is significantly higher than the heating value (2.2 MWh/ton) of fresh wood (Alakangas 2000, Nurmi 2000, Kärkkäinen 2007). It is therefore economically reasonable to dry energy wood before transportation and utilization (Routa et al. 2012). The drying of energy wood can be done either by using artificial drying (thermal drying, cold-air drying, compression drying) or by using natural conditions (solar radiation and wind).

The moisture qualification of energy wood depends on what the fuel is going to be used for: in general the dryer the wood the better the fuel. The moisture content of wood fuel which is used in household fireplaces should be 15 - 20 %. From the point of view of the durability of wood chips in storage, the moisture content should not exceed 25 %. The moisture content of wood fuel which is to be used in a heating plant of less than 1 MW should not be more than 40 %. Large heating plants can use fairly moist fuel although it lowers the energy content of the fuel (Alakangas 2000).

The disadvantage of energy wood drying at the road side storage under natural conditions is its slowness and the dryness achieved. Typically the moisture content of small-size trees varies between 35 - 40 % after a period of road side storage in Finland (Hakkila 1989, Hillebrand & Nurmi 2004). Because of the disadvantages of natural drying artificial drying methods like thermal drying are also used. However, the energy consumption of thermal drying is quite high and therefore the method is not so cost effective. When wood dries, for example in thermal drying, the free water in the lumen leaves first (Haygreen & Bowyer 1996). The moisture content at which lumen is free of water, but the cell walls are still fully saturated, is called the fibre saturation point (Skaar 1972). The fibre saturation point differs between tree species, usually being between 20 - 25 % (Skaar 1972, Koponen 1985). The wood contains hydroxyl groups, which can form strong intermolecular hydrogen bonds with water molecules (Skaar 1972). Therefore, water can bind tightly to the cell wall and the energy required when vaporizing water using thermal drying is quite high (2300 kJ/kg).

Other artificial drying methods are cold-air drying and compression drying. The latter one is not used much for wood drying in practise. However, compression drying has been used for decades for bark drying in the plywood, pulp and sawmills industry (Isomäki 1974, Alakangas 2000, Ahtila 2010, Siitonen 2010). Bark is a softer material than wood and therefore it is presumably more suitable for compression drying than wood (Kärkkäinen 2007). However, the moisture content of bark might still be above 60 % after compression drying, especially in conifers (Alakangas 2000). The idea of compressing drying for wood has been tested in a few studies. The first studies were in North America at the beginning of the 1980s (Haygreen 1981, 1982). Liu & Haygreen (1985) continued the studies later and determined the optimal pressure and compression times for some of the North American tree species. Yoshida et al. (2010) introduced a roller compression dryer in Japan. The dryer contains two rollers that are positioned closely together leaving a narrow gap. Wood chips are fed into the gap, and the compression of the rollers removes the water. However, the lowest moisture content achieved by the roller press was fairly modest being just 46 %. Referring to the above-mentioned drying results: research, development and new innovations are needed for the drying of energy wood. The moisture content could be taken into consideration in the pricing of the energy wood, because one is able to pay more for dry fuel than for fresh.

1.4 Measurement of energy wood

The measurement of energy wood is an important part of its procurement (Hakkila 2006b, Lauhanen & Laurila 2007a). The measurement results set the price of the energy wood between the buyers and the sellers as well as what the machine entrepreneur’s remuneration will be (Nurmi 1992). However, there is no legal act regarding energy wood measurement; unlike timber measurement in Finland (Puutavaranmittausasetus 1991, Puutavaranmittauslaki 1991). There is a measurement agreement which contains guidelines and it gives the principles on how to measure the weight, volume and energy content of energy wood (Lindblad et al. 2010). The measurement agreement is generally used in the forest energy sector and several organisations are behind this agreement in Finland

(Lindblad et al. 2010). However, an energy wood measuring act is coming (Hakkila 2006b, Työryhmä esittää energiapuun… 2012).

The energy wood measurement methods commonly used in Finland are: the measurement of the frame volume of energy wood stacks, the measurement of the energy wood's weight using a crane scale, the measurement of the volume of the energy wood chips and the measurement of the energy content of the energy wood (Lindblad et al. 2010). The weighing results can be converted into volume by using the fresh density number from the measurement agreement. The bulk volume of the chips can be changed into the solid volume by using a coefficient. The factor that is normally used in practise when changing solid volume to bulk volume is 2.5 and from bulk volume to solid volume the factor is 0.4 (Lindblad et al. 2010). The frame volume of an energy wood stack can also be converted into a solid volume by using the solid volume factor based on the measurement agreement (Lindblad et al. 2010). Energy content can also be converted into volume. Timber and energy wood measuring always happens with bark on the trees in Finland.

Unfortunately, exact wood energy measuring is challenging and there are many problems, when measuring biomass (Rosillo-Calle et al. 2007). First of all, the shape of the energy wood is challenging when measuring it. Small-sized whole trees, which contain: a stem, branches and leaves, are especially difficult to measure. However, the yield of energy wood is 15 - 35 % higher when harvesting whole-trees compared to delimbed stems (Hakkila 2001, Laitila 2012). Secondly, there are several units (weight [kg], volume [m^3] or energy content [MWh]) which can be used when measuring energy wood. Also, the conversion from one unit to another unit can be unreliable and inaccurate. And thirdly, the change in moisture content makes the situation even more complex, because it should be known when the result is based on fresh or dry weight (Hakkila & Parikka 2002).

1.5 Weight loss of energy wood

After harvesting, the energy wood is at the roadside storage sites for a longer or shorter time, usually from ½ year up to 2 years (Hakkila 1989, Hillebrand & Nurmi 2004). There is some weight loss in the energy wood supply chain from the forest to the heating plant; especially during storage (Hakkila 2006b). However, there are not many surveys concerning it (Jirjis & Norden 2005, Pettersson & Nordfjell 2007, Anerud & Jirjis 2011). The weight loss comes from many different sources such as: harvesting, storing, chipping and transportation (Figure 4). Probably, the drying of the energy wood in storage is the most important source of weight loss. However, the drying of the energy wood is desirable and it improves the quality of the wood fuel. There are also other sources of weight loss which are totally unwelcome, such as: storage and transportation loss and the dry matter loss of wood (Jirjis & Norden 2005, Hakkila 2004, Pettersson & Nordfjell 2007, Anerud & Jirjis 2011).

According to Jirjis & Norden (2005) the dry matter loss for composite residue logs can even be as high as 11.5 % after a storage period of 8 months. Pettersson & Nordfjell (2007) reported similar observations for composite residue logs after 9 months of storage. A lower dry matter loss of 8.3 % is reported for stump wood after a storage period of 13 months (Anerud & Jirjis 2011).

Figure 4. Energy wood supply chain from the forest to the heating plant consists of many phases where losses might exist (Picture: Jussi Laurila).

According to Erkkilä (2010) the average weight loss (storage and chipping) in storage was 3 - 4 %. Tyynismaa (2012) got similar results in the Seinäjoki region. Despite unwelcome weight loss, storing is an important part of the forest energy supply chain, because it decreases the moisture content of the energy wood and secures the availability of wood fuel around the entire year (Hakkila 1989, Ranta 2002, Laitila 2012).

1.6 Theoretical framework of the thesis

The aim of the European Union Commission is to increase renewable energy usage substantially in every member state as well as in Finland (Directive 2009). The study area of this thesis consists of 6 % of the total area of Finnish forest land (Ylitalo 2011). Within this area there is a lot of primary production in both agriculture and forestry. Also, there is lively heating entrepreneurial activity in the area (Sauvula-Seppälä 2010). Usually the heating entrepreneur is a small-business and they do not have sufficient resources for research and development work. However, the use of energy wood by heating entrepreneurs is significant. In addition there are large-scale energy operators which have a remarkable effect on the usage of forest energy.

The use of forest energy has been growing rapidly in recent years. However, there is not enough research-based information in this sector to support decision-making, although there is an acute need for it. The availability and quality of energy wood are critical factors for both heating entrepreneurs and large-scale energy operators. In this work the forest energy potential of the study area and the effect of moisture content and weight loss on this potential are clarified. Also, the moisture and drying of the energy wood in natural conditions are examined. Because of the poor drying results obtained from natural conditions, the possibilities of the artificial drying method compression drying were also examined.

1.7 Aim of the thesis

The primary aim of this study was to examine the quality of energy wood and especially the moisture content and drying of energy wood. Moisture content is an important factor because it directly affects the transportation costs and heating value of energy wood. From the point of view of combustion moisture is unwelcome and small heating plants are especially affected by the use of moist wood fuel. The drying of energy wood was studied both under natural conditions as well as artificial ones in the laboratory. The latter one was studied because the drying of energy wood under natural conditions is limited. The aim was also to examine the forest energy potential in the study area (Figure 6) and clarify how moisture content affects it. The new information can be used to improve the quality of energy wood and increase the potential of forest energy by decreasing the moisture content of wood fuel. More specifically the aims of the study were:

- To study the municipality’s forest energy potential in South and Central Ostrobothnia (**Study I**).
- To examine the moisture content of Norway spruce stump wood at the clear cutting areas and at the roadside storage sites (**Study II**).
- To clarify the correlation between moisture content and other factors such as drying time (**Study II, III & IV**).
- To examine weight loss of small-sized whole trees at various stages in the energy wood supply chain (**Study III**).
- To examine the possibilities of energy wood compression drying (**Study IV**).
- To study the effect of moisture content on energy wood potential and fuel properties (**Study I, II, III & IV**).
- To develop the profitability of energy wood procurement and improve the properties of energy wood (**Study I, II, III, IV**).

2 MATERIAL AND METHODS

Study I is based on the National Forest Inventory (NFI-10) data produced by The Finnish Forest Research Institute (Metla). **Studies II & III** were field studies under real energy wood harvesting conditions in South Ostrobothnia. **Study IV** was a laboratory test which was carried out on three commercially important tree species in Finland. In each of the studies either one or more of the three primary data sources from forest to heating plant were used (Figure 5). Each study was carried out in western Finland in the same 1.25 million hectares of forest that the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre (previous organisation name before 2012: "the Forest Centre of South Ostrobothnia") covers (Figure 6).

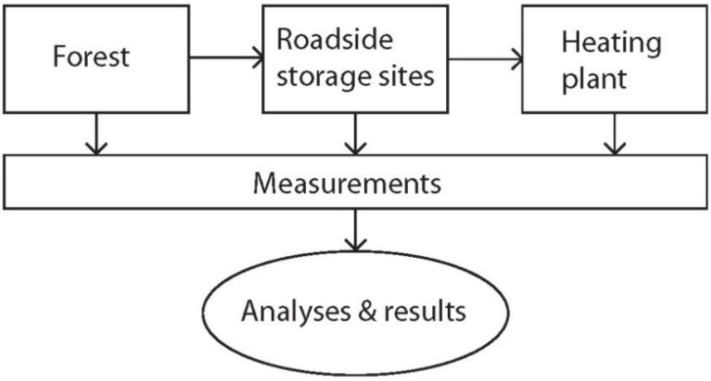

Figure 5. The three primary data sources for measurements, analyses and results.

Figure 6. Each study was made in the area (grey) that the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre covers.

2.1 Study sites (Study II & III)

There were four Norway spruce (*Picea abies* L. Karst.) stump harvesting sites in **study II** and the data was collected between June 2006 and May 2009 in western Finland. Spruce stumps are usually harvested for energy production because they are loosely anchored in the ground and therefore easier to harvest than pine (Hakkila 1972, Laitila et al. 2008). In general, the sites represented typical stump harvesting sites in Finland. The soil types were fertile or semi fertile mineral soil except for one site which was fertile peat soil. The total study area was 19.9 hectares. The stumps were harvested by excavators which lifted and split the stumps. At first, the stumps were in small piles on the clear cut areas and then, after some weeks, the stumps were moved to the roadside storage sites with a forwarder.

The small-sized whole tree data (Study III) was collected from energy wood thinning sites from young stands in western Finland. Tree species was Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies*) and Downy birch (*Betula pubescens* Ehrh.). The data was collected from the real worksites where energy wood was harvested mechanically using the whole tree method. In total 12.7 million kg of energy wood was collected from 75 worksites. The collection period was from November 2004 to October 2009.

2.2 Sampling and samples (Study II & IV)

The stump wood moisture content samples were collected from both the clear cut areas and the roadside storage sites randomly (Study II). In every case the samples were taken from the top surface layer of the piles. The sampling point was midway between the stump and the end of the root (Figure 7). The shape of the samples was a circular slice of wood, the length of which was 4 - 11 cm with an average diameter of 7 cm. Eight samples per worksite (4 sites) were taken at each sampling time and the total number of samples was 333.

The compression drying of energy wood study (Study IV) was made on sawdust from small-sized freshly-felled: Scots pine (*Pinus silvestris*), Norway spruce (*Picea abies*) and Downy birch (*Betula pubescens*). The samples were collected from western Finland and it consisted of chain-saw sawdust from the freshly-felled trees. The particle size of the sawdust varied from 0.5 mm to 4.0 mm. The samples were taken in March 2012. The initial moisture content of Scots pine was 60 %, Norway spruce was 63 % and Downy birch was 45 %.

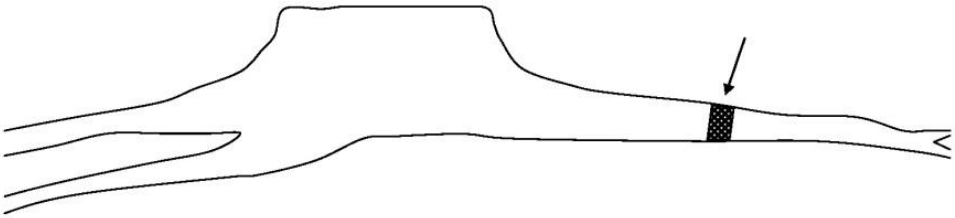

Figure 7. The sampling point of Norway spruce stump wood for moisture content analysis.

2.3 Measurements at different phases of the supply chain (Study III)

In **Study III** there were three different stages in the energy wood supply chain where energy wood was measured (Figure 5). The first measuring (kg) was carried out at the forest work sites using a crane scale. Two Ponsse Loadoptimizers and one TB 3000 crane scale was used in this study. Additional information on logging, forest haulage, trees and stands was also recorded in the first stage.

The second measuring was carried out at the roadside storage sites where the frame volume of the energy wood stacks was measured based on the length, width and height of the stack. The levelled out measuring method (Figure 8) was used. The frame volume was converted to a solid volume using the solid volume factor from the official guide for the measurement of energy wood (Lindblad et al. 2008). Additionally, measuring time, tree species information and whether the stack was covered or not was recorded.

The third measuring was carried out at the heating plant by the heating entrepreneurs or the receiver of the energy wood. The receiving time, the loose volume of the chips (m^3), the wood’s weight (kg), the energy content of the chips (MWh), the energy density of the chips (MWh/m^3) and the moisture content (%) of the wood was collected from five different energy organisations in the study area.

Figure 8. The width of a stack was measured at both ends of the stack and was based on the levelled out width as well as length of the stack (Picture: Jussi Laurila).

2.4 Potential data and analysis (Study I)

The potential of forest energy and the resource requirements for energy wood procurement were calculated for the different municipality's forest land wood production in South and Central Ostrobothnia. There were 31 municipalities in this area and 12,500 km^2 of forest land. The potential was calculated for three different development classes based on Tapio's classification; the advanced seedling stands, young thinning stands and mature stands (Saarenmaa 2002). The average hectare-specific logging outturns were used as felling accumulations (Sirén et al. 2001, Vesisenaho 2003, Hakkila 2004, Maa- ja metsätalousministeriö 2006).

Both theoretical and techno-economic potential was calculated. Theoretical potential refers to the total amount which can be utilised for energy generation when limitations are not taken into account. It was estimated that the techno-economic potential was 50 % of the theoretical potential (Hakkila 2004, Maa- ja metsätalousministeriö 2006, Lauhanen & Laurila 2007b, Maidell ym. 2008). In the calculations the energy content of 2 MWh/m^3 for freshly felled wood with bark was used (Alakangas 2000, Maa- ja metsätalousministeriö 2006).

The techno-economic potential was calculated using equation number 5. The resource requirements for the energy wood procurement were calculated for the type of machine used. In the calculation the numbers used were the yearly output of the machines and vehicles determined by Asikainen (2004).

$$P_{tt} = A_{hak}/5 * E_{\bar{x}} * 0.5 \tag{5}$$

where:

P_{tt} = Techno-economic potential, MWh/y

A_{hak} = Felling plan area according to NFI-10 (5-year period), ha

$E_{\bar{x}}$ = The average energy wood yield per hectare, MWh/ha

2.5 Laboratory measurements (Study IV)

The compression drying tests were made at room temperature (20°C) using a Lloyds EZ 50 materials testing machine with a pressing cylinder and piston (Figure 9). The diameter of the steel piston was 20 mm and the piston fitted the cylinder precisely. The height of the cylinder was 118 mm. There were little holes (diameter of 5 mm) near the bottom of the cylinder for the water to run-off. Also, there was another route for water run-off in the joint between the bottom plate and the cylinder. The compression force was generated by the material testing machine and the pressing data and piston positions were collected to a log file for further analysis. For each compression drying test about 14 g of freshly-felled sawdust was used.

Figure 9. Doctor Mikko Havimo shows how the material testing machine Lloyds EZ 50 works (Picture: Jussi Laurila).

Two pressing methods (momentary and continuous) were used in the wood compression dying tests. The momentary pressing tests were made using six pressing forces (6 MPa, 13 MPa, 19 MPa, 26 MPa, 32 MPa and 38 MPa). With this method the pressure was relieved immediately when the maximum force was reached. In the first continuous test holding times of 30 and 60 seconds was used with a pressure of 13 MPa and in the second test a holding time of 30 seconds was used with a pressure of 38 MPa. Every testing value was used with each tree species. In total 81 tests were carried out.

2.6 Moisture content and heating value analysis (Study II, III & IV)

The moisture content analysis was made based on standard (ISO 589:2003) “Hard coal - Determination of total moisture”. The mass of the samples were weighed both fresh and absolutely dry using a laboratory scale (Figure 10). The drying temperature was 105 ºC, and a drying time of 24 h was used. Weather data was obtained from the Finnish Meteorological Institute and from Finland’s environmental administration. The moisture content (wet basis) of the wood was calculated using equation 1 (Kärkkäinen 2007). The heating value analysis was made according to standard (CEN/TS 14918:2005) “Solid Biofuels - Method for the determination of calorific value”.

Figure 10. Moisture content analysis based on the weighing of fresh and absolutely dry samples based on standard ISO 589:2003 (Picture: Jyrki Foudila).

2.7 Effect of moisture content and weight loss on forest energy potential

The effect of the moisture content and weight loss on the forest energy potential was calculated for the study area (Figure 6). The techno-economic potential 1.6 TWh/y (0.82 million m^3 solid) from **Study I** was used as primary data. The effect of weight loss on potential was calculated based on data from **Study III**. The heating value as received ($Q_{net,ar}$) was based on equation 6 (Alakangas 2000). The weight based heating value (MWh/ton) was converted to a volume based heating value (MWh/ton) using a wood density of 427 kg/m^3. The average wood densities are: for pine (420 kg/m^3), spruce (380 kg/m^3) and birch (480 kg/m^3) (Fagerstedt et al. 2004). Moreover, the average heating value (pine, spruce and birch) for dry matter ($Q_{net,d}$) 5.4 MWh/ton was used (Alakangas 2000, Nurmi 2000). The calculations produced a moisture content range of 0 - 60 %.

$$Q_{net,ar} = Q_{net,d} \times \frac{100-MC_{ar}}{100} - 0.006781 \times MC_{ar} \tag{6}$$

where:
$Q_{net,ar}$ = heating value as received, kWh/kg
$Q_{net,d}$ = heating value of dry matter, kWh/kg
MC_{ar} = moisture content as received, %
0.006781 kWh/kg = latent heat for vaporization of water (+25 °C)

3 RESULTS

3.1 Forest energy potential (Study I)

The techno-economic forest energy potential in the area (Figure 6) of the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre was 1.6 TWh/y (0.82 million m^3 of solid wood). Therefore, the average hectare-specific potential for forest land for wood production was 1.4 MWh/ha/y. If the pine stumps were also fully utilised for energy generation then the techno-economic potential of the area would be as much as 2.7 TWh/y. Municipality-specific techno-economic potentials are shown in Table 1.

The greatest techno-economic potential 709 GWh/y (354,603 m^3/y) was obtained from the first thinning sites as an integrated harvest (Figure 11). The second greatest potential 387 GWh/y (193,485 m^3/y) was obtained from the improvement of young stands. The rest of the potential was obtained from the spruce-dominated clear cutting areas as logging residues 251 GWh/y (125,708 m^3/y) and stumps 297 GWh/y (148,564 m^3/y). The greatest municipality-specific potentials were in the western parts of the study area and in Vähäkyrö, Isokyrö and Laihia. Higher than average potentials were also found in Himanka, Kokkola, Evijärvi and Veteli. For full utilisation of the potential of forest energy in the area 185 harvest machines per year, and twice that number of drivers to operate them in two shifts, would be needed.

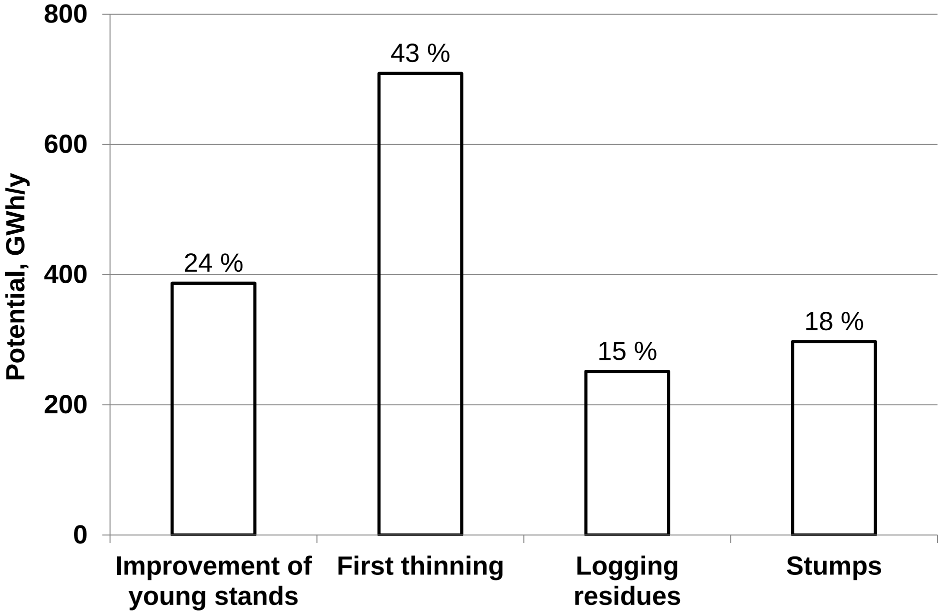

Figure 11. Potential annual techno-economic forest wood energy sources in the area of the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre.

Table 1. Techno-economic forest energy potential in the study area (Figure 6) by municipality from four energy wood sources.

Municipality	Improvement of young stands			First thinning			Logging residues			Stumps			Total		
	GWh/y			GWh/y			GWh/y			GWh/y			GWh/y		
	-20%	**±0%**	+20%	-20%	**±0%**	+20%	-20%	**±0%**	+20%	-20%	**±0%**	+20%	-20%	**±0%**	+20%
Alajärvi	15	**19**	23	30	**37**	44	7	**9**	11	9	**11**	13	61	**76**	91
Alavus	11	**13**	16	18	**22**	27	4	**4**	5	4	**5**	6	36	**45**	54
Evijärvi	7	**8**	10	13	**17**	20	4	**4**	5	4	**5**	6	28	**35**	41
Halsua	9	**11**	13	11	**14**	16	1	**1**	1	1	**1**	1	21	**26**	32
Himanka	7	**8**	10	12	**15**	18	4	**4**	5	4	**5**	6	27	**33**	40
Ilmajoki	6	**7**	8	14	**18**	21	10	**13**	15	12	**15**	18	42	**53**	63
Isojoki	9	**12**	14	20	**25**	30	11	**14**	16	13	**16**	19	53	**67**	80
Isokyrö	4	**6**	7	9	**12**	14	5	**7**	8	6	**8**	9	25	**32**	38
Jalasjärvi	13	**16**	19	16	**20**	24	7	**8**	10	8	**10**	12	43	**54**	65
Kannus	12	**15**	18	18	**22**	27	3	**4**	5	4	**5**	6	37	**46**	55
Karijoki	2	**3**	4	5	**7**	8	4	**5**	7	5	**6**	8	17	**22**	26
Kauhajoki	23	**29**	34	28	**36**	43	14	**18**	22	17	**21**	26	83	**104**	124
Kauhava	17	**22**	26	40	**50**	60	8	**10**	13	10	**12**	15	76	**95**	114
Kaustinen	8	**10**	12	13	**16**	20	2	**3**	3	3	**3**	4	26	**33**	39
Kokkola	25	**31**	37	42	**53**	63	9	**11**	14	11	**13**	16	87	**109**	130
Kuortane	7	**8**	10	13	**17**	20	3	**4**	5	4	**5**	6	27	**34**	40
Kurikka	11	**13**	16	24	**30**	36	18	**23**	27	21	**27**	32	74	**93**	111
Laihia	7	**9**	10	18	**22**	27	12	**15**	18	14	**17**	21	50	**63**	75
Lappajärvi	7	**9**	11	16	**20**	24	4	**5**	5	4	**5**	6	31	**39**	46
Lapua	9	**11**	14	23	**29**	35	7	**9**	10	8	**10**	12	47	**59**	71
Lestijärvi	10	**12**	14	17	**21**	25	3	**4**	5	4	**5**	6	33	**41**	49
Perho	13	**16**	20	20	**25**	30	3	**4**	5	4	**5**	5	40	**50**	60
Seinäjoki	18	**23**	27	31	**39**	47	12	**15**	18	14	**17**	21	75	**94**	113
Soini	7	**9**	11	18	**23**	28	6	**7**	9	7	**9**	11	39	**49**	58
Teuva	7	**9**	10	15	**19**	22	12	**16**	19	15	**18**	22	49	**61**	74
Toholampi	12	**15**	18	17	**21**	25	4	**5**	6	5	**6**	7	38	**47**	57
Töysä	4	**5**	6	7	**9**	10	3	**4**	4	3	**4**	5	18	**22**	26
Veteli	10	**13**	15	17	**21**	26	4	**5**	6	5	**6**	7	36	**45**	55
Vimpeli	5	**6**	7	9	**11**	14	3	**4**	4	3	**4**	5	20	**25**	30
Vähäkyrö	2	**3**	3	5	**7**	8	2	**3**	4	3	**4**	4	13	**16**	19
Ähtäri	12	**15**	17	27	**33**	40	11	**14**	17	13	**17**	20	63	**79**	95
Total	310	**387**	464	567	**709**	851	201	**251**	302	238	**297**	357	1316	**1645**	1974

3.2 Moisture content of stump wood (Study II)

The average initial moisture content of stump wood was 53 % immediately after harvesting at four stump harvesting sites in western Finland. After stump harvesting the moisture content decreased fairly quickly at the storage site, and about one month after harvesting the average moisture content was 31 % in the summer of 2006. The lowest recorded moisture content for stumps in this study was just 13 %.

During the autumn the moisture content increased a little bit while raining and decreased during the following spring to a lower level than the previous autumn (Figure 12). The same phenomenon was repeated each year during this study. The moisture content of stump wood was at its highest point at the beginning and at the end of the year. On average the lowest annual moisture content was at the beginning of July. At the end of the study, three years after harvesting, the moisture content of the stump wood was about 14 % and the heating value was 5.24 MWh/ton.

In the study a correlation between the moisture content of stump wood and other factors was detected. There was a weak (R^2=0.31) non-linear correlation between stump wood moisture content and relative air humidity. Also, there was a weak (R^2=0.40) non-linear correlation between stump wood moisture content and absolute air humidity. Moreover, there was a non-linear correlation (R^2=0.44) between stump wood moisture content and temperature. Furthermore, a non-linear correlation (R^2=0.51) between the stump wood moisture content and time was observed. The highest coefficient of determination (R^2=0.63) in this study was obtained using a four variable moisture content model (Equation 7). However, there was no correlation between moisture content and the diameter of the sample and precipitation in the long term.

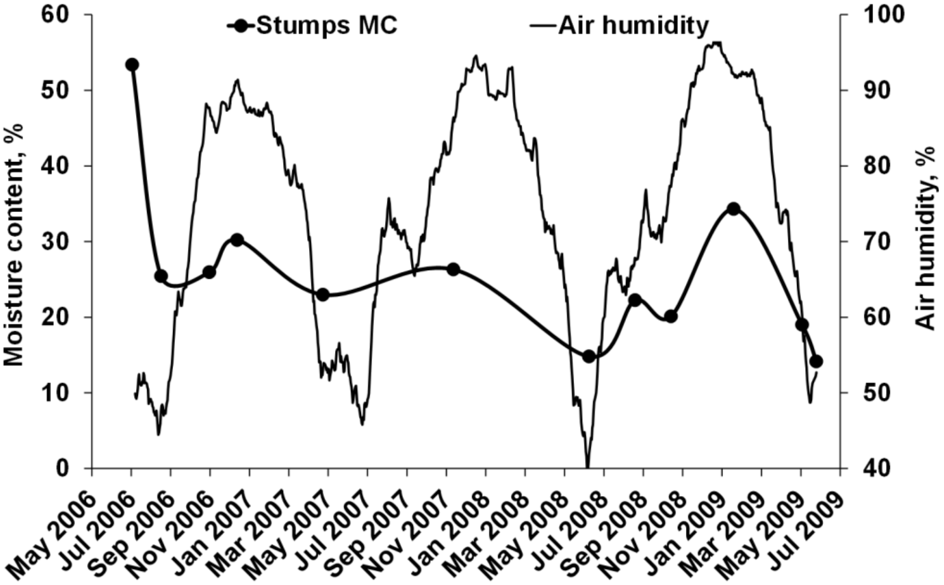

Figure 12. Average moisture content of Norway spruce stump wood and relative air humidity as a function of time.

$$MC = 0.0189t_{wn}^2 - 1.0694t_{wn} - 0.0021AH_a^2 + 0.2499AH_a + 0.0375T_a^2 - 0.7260T_a - 0.0340t_d + 32.747 \quad (7)$$

where:

MC	=	moisture content (wet basis)
t_{wn}	=	calendar week number
AH_a	=	relative air humidity (weekly average)
T_a	=	temperature (weekly average)
t_d	=	drying time in weeks

3.3 Weight loss and moisture content of small-sized whole trees (Study III)

The average storage time for small-size energy wood at the road side storage was 11 months. After the storage period a remarkable average weight loss of 37 % was detected between the forest and the heating plant (Figure 13). However, part of the weight loss comes from the drying of the energy wood at the storage site.

The average moisture content measured at the heating plant 11 months after harvesting was about 43 %. There was a difference, over the years, in the moisture content measured. In 2007 the average moisture content was 38 %, in 2008 it was 45 % and in 2009 it was 42 %. Most of the stacks (85 %) were covered with waterproof paper. There was no correlation between the moisture content and the time from the harvesting.

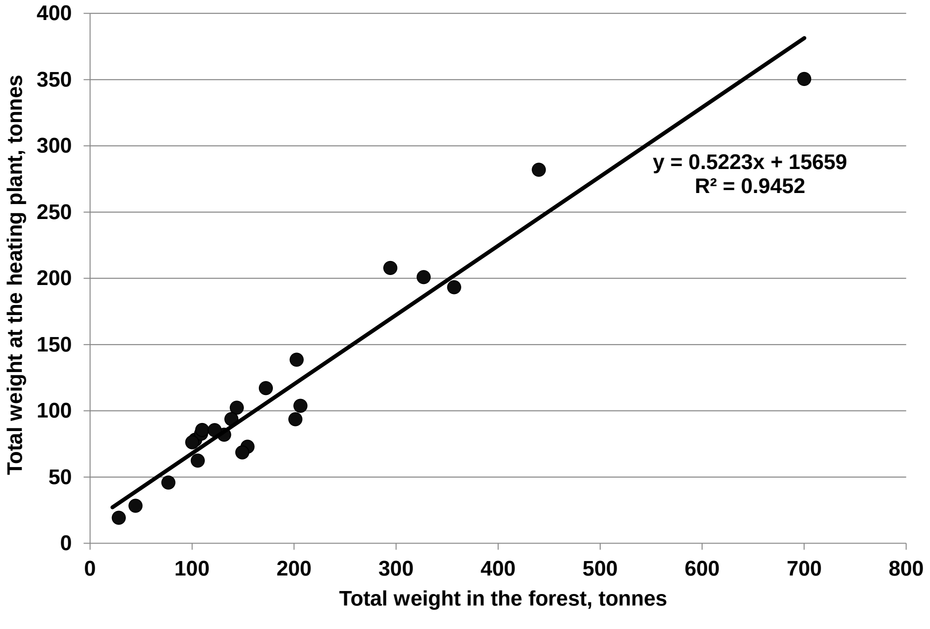

Figure 13. The weight loss of small-size whole trees between the forest and the heating plant during storage.

3.4 Wood moisture reduction by compression drying (Study IV)

3.4.1 Moisture content with momentary pressing

In the momentary pressing test the sample was compressed until a defined maximum pressure was reached, after which the compression was immediately released. In this method a lowest moisture content of 33 % was reached for birch at a pressure of 38 MPa (Figure 14, Table 3). The pressure of 19 MPa had reduced the moisture content of birch by 10 percentage points from its initial moisture content (45 %). However, the softwood's drying rate was higher than hardwood in this study. The highest drying rate of 25 percentage points was achieved for spruce and the second highest 24 percentage points for pine at a pressure of 38 MPa. Even 19 MPa was enough to decrease the moisture content of softwood by 20 percentage points, which was double that of birch at the same pressure. The moisture content of spruce and pine were almost at the same level at each pressure level.

Figure 14's curves illustrate the effect of compression pressure on the moisture content of wood. Three parameter exponential decay regression equations (Equation 8) were fitted to the measured values. The parameter values were presented in Table 2 for each tree species.

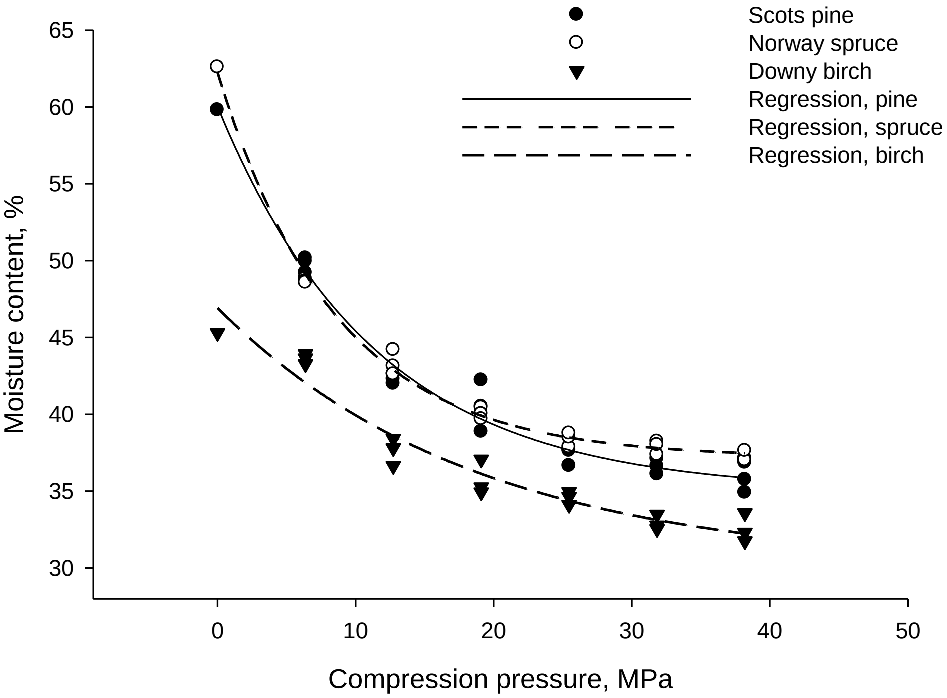

Figure 14. Effect of the compression pressure on the moisture content of Scots pine, Norway spruce and Downy birch.

$$MC = y_0 + ae^{-bp} \tag{8}$$

where:

MC = moisture content, % (wet basis)

p = maximum compression pressure, MPa

y_0 = model parameter (Table 2)

a = model parameter (Table 2)

b = model parameters (Table 2)

Table 2. Parameter values and coefficient of determination for regression equations 8 for each tree species.

	Scots pine	Norway spruce	Downy birch
y_0	35	37	30
a	25	25	17
b	0.088	0.12	0.053
R^2	0.98	0.99	0.93

3.4.2 Moisture content with continuous pressing

In the continuous pressing method a holding time (30 or 60 seconds) was used after the maximum pressure was achieved. With this method the drying results were a little bit better than when using the momentary pressing method with the same pressure. In general, when the pressure was 13 MPa, and a pressing time of 30 seconds instead of 0 seconds was used, continuous pressing increased the drying effect on the wood by 1 - 2 percentage points. However, there was only a small additional effect on the moisture content of wood when the pressing time was doubled from 30 to 60 seconds with 13 MPa.

Accordingly the continuous pressing method using 13 MPa with a holding time of 30 seconds resulted in, for example, 37 % moisture content for birch, while momentary pressing gave 38 %. However, under a pressure of 38 MPa the disparity was a little bit greater (Table 3). The lowest moisture content in this study (birch 30 %, pine 34 % and spruce 35 %) was achieved by using the continuous pressing method with a pressure of 38 MPa with 30 seconds holding time (Table 3). The pressing time of 60 seconds with 38 MPa was not examined completely in this study, because of the limited extra drying effect when compared to the holding time of 30 seconds.

3.4.3 Energy consumption of compression drying

Energy consumption for the compression drying of water (kJ/kg) was 11.0 kJ/kg for pine, 9.7 kJ/kg for spruce and 41.0 kJ/kg for birch. The energy required was much lower than the energy required for vaporizing water in thermal drying, because latent heat for the vaporization of water is 2300 kJ/kg. The compression drying of wood, depending on tree species, therefore requires only 0.4 - 1.8 % of the energy required for the vaporization of water.

Table 3. Moisture content of Scots pine, Norway spruce and Downy birch before and after momentary and continuous pressing with a pressure of 38 MPa.

Tree species	Moisture content		
	Initial	0 second	30 seconds
Scots pine	60	36	34
Norway spruce	63	37	35
Downy birch	45	33	30

3.5 Effect of moisture content and weight loss on forest energy potential

Potential techno-economic forest energy in the study area (Figure 6) was about 1.6 TWh/y (0.82 million m^3 solid) for fresh wood (50 %) according to **Study I**. Figure 15 illustrates the effect of moisture content on the forest energy potential in the study area. The range of potential was about 1500 - 1900 GWh/y. For absolutely dry wood the potential was about 1900 GWh/y. Based on the average moisture content (43 %) of small-size whole trees after 11 months storage (Study III) the potential was 1710 GWh/y. According to the moisture content (31 %) of stump wood one month after harvesting (Study II) the potential was 1780 GWh/y. Similar potential was also achieved by using the lowest moisture content (30 %) from the compression drying test (Study IV).

There was a 37 % weight loss on average between the forest and the heating plant according to **Study III**. Furthermore, based on **Study III** the average moisture content of small-sized whole trees was 43 % at the end of storage. Taking into account the above mentioned factors the techno economic-forest energy potential was 1.2 TWh/y in the study area.

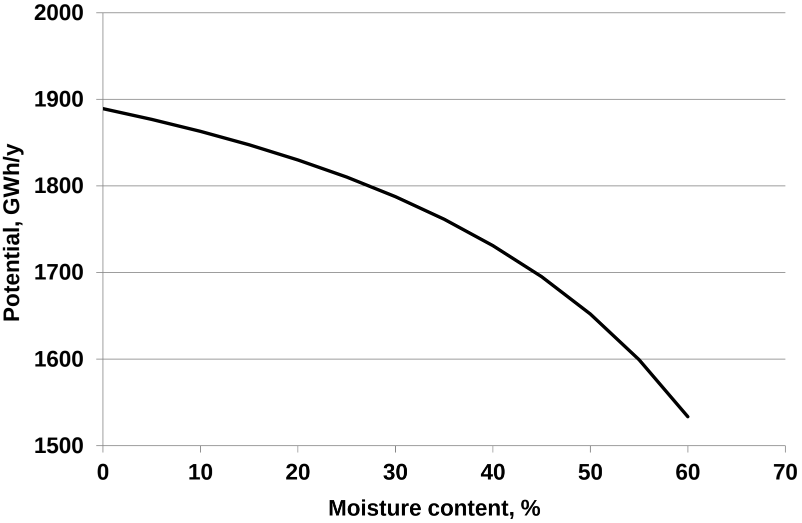

Figure 15. The effect of moisture content on the forest energy potential in the study area based on 0.82 million m^3 of solid energy wood.

4 DISCUSSION

4.1 Forest energy potential (Study I)

A completely exact potential for forest energy cannot be presented here because there are always many factors causing inaccuracies in the potential calculations. Some assumptions have to be made. Ultimately the forest owner’s willingness to supply wood to the market might be a key factor, but it was not taken into account in this study (Maidell et al. 2008). Hectare-specific yields of energy wood, which are based on the literature, were used in the calculations. However, many factors (structure, habitat, silvicultural state, harvesting method etc.) affect the yields. For example, the integrated harvest method does not always come about in practice, because it is possible that the whole yield is utilised in heat energy production instead of for both industrial and energy usage. When large areas are dealt with using calculations for hectare-specific yields, then mistakes of a few cubic metres will already affect the final result significantly.

The yield of logging residues and stumps are directly tied up to the amount of harvested industrial round wood in the area. Also, the fertility of the stump, logging residue and whole tree harvesting sites should at least be at the level of sub-xeric forest or even more fertile. According to recommendations the stumps, logging residues and whole trees from low fertile soils should not be harvested, because the nutrient economy of the forest can suffer because of it (Koistinen & Äijälä 2005, Äijälä et al. 2010).

On the basis of the earlier potential calculations it was supposed that the techno-economic potential was half of the theoretical potential (Hakkila 2004, Maa- ja metsätalousministeriö 2006, Lauhanen & Laurila 2007b, Maidell et al. 2008). However, it is difficult to present the exact relation between a theoretical and techno-economic potential.

At the Forest Centre Regional Unit level the comparison of results with earlier studies is difficult because of different divisions in regions and potential definitions. The range of the techno-economic potentials that have been calculated in earlier studies for the area was 1.1 - 2.1 TWh/y, whereas in this study the result was 1.6 TWh/y (Lauhanen & Laurila 2007b, Maa- ja metsätalousministeriö 2006, Maidell et al. 2008, Anttila et al. 2013). The forest energy potential (1.6 TWh/y) of the area consisted of small-sized whole tree from the improvement of young stands (24 %), small-sized whole tree from first thinnings (43 %), logging residues (15 %) and stumps (18 %) from clear cutting areas. It is remarkable that the energy potential of logging residues is fully utilised in the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre area (Anttila et al. 2013). Furthermore, the stump potential is almost fully utilised as well (Anttila et al. 2013). According to Anttila et al. (2013) there is about 0.4 TWh/y of unutilized energy potential of small-sized trees when using the whole tree harvesting method and only 0.2 TWh/y when harvesting delimbed stems. Thus, increasing the use of forest energy is rather limited in the area. However, the utilization of large-sized trees for energy generation might be a solution for the growing renewable energy needs.

The advantage of the calculation method that has been used in this study was the novel use of municipality specific data and the latest NFI 10 material. Moreover, the results were published under energy wood sources (improvement of young stands, first thinning, logging residues and stumps) and by municipality instead of by province, which have usually been used in potential calculations. The method which was used in this study can also be duplicated in other Finnish Forest Centre Regional Unit areas.

4.2 Moisture content of stump wood (Study II)

The most favourable time for stump harvesting is in the spring and early summer. In the dry summer the moisture content of harvested stump wood decreases relatively rapidly, and about one month after stump harvesting the moisture content was level of 30 %. During the late autumn the moisture content increases again, but not significantly. If stumps were dried well in the summer the water absorption was very slow in the autumn. Every subsequent spring and summer the moisture content was at a lower level compared to the previous year. Overall the stumps were combustible at any point during the three year storage period; excluding the one month drying period immediately after harvesting.

There were many different factors which affected the moisture content and drying of stump wood. Probably the weather is the most important factor. According to Erber et al. (2012) meteorological data with site specific drying models can predict the moisture content of naturally dried logwood. However, good topography of storage sites is also essential. For example: ditches, hillocks, pit sites and the geographical location can result in different moisture contents. In addition, the structure of the storage causes variations in the stump wood moisture content. Moreover, the stump splitting methods used in harvesting can affect the moisture content; sometimes more sometimes less. The spruce stump’s wood moisture content model (Equation 6) was significant (p-value < 0.001) and the model is the first one which has ever been presented for Norway spruce stump wood in the study area conditions. However, there were still some residual values in the model. Therefore more data is needed to construct a more reliable and better model. Routa et al. (2012) found that net evaporation could be a good determining variable for the modelling of energy wood drying. Finnish Forest Research Institute, University of Eastern Finland and Finnish Meteorological Institute are to develop presently different calculating models to forecast the moisture content of energy wood (Routa et al. 2012).

There was almost no deterioration in the heating value of the stump wood during the three year storage period. The energy content (5.24 MWh/ton) for the dry mass of stump wood was almost the same after the three year storage period than the fresh wood (5.37 MWh/ton) immediately after harvesting (Nurmi 2000). The ash content of the stump wood was however lower than normal. Normally stumps include some soil remnants which increase the ash content, it is probable that rain and frost cleaned the stumps at the storage site during the long storage period.

The samples were collected from the surface layer of the stump piles at the forest or at the roadside storage sites. Inside the piles the moisture content of the energy wood might have been different than on the surface of the pile (Jirjis 2005). The moisture content might be either higher or lower depending on, for example, the weather conditions and the season. However, the moisture content of stump wood on the surface layer of the pile was quite stable; excluding the one moth drying period at the beginning. Further studies about moisture content in different parts of a pile and in different kinds of piles is needed. Also, studies about Scots pine stump wood are needed.

4.3 Weight loss and moisture content of small-sized whole trees (Study III)

There was a strong correlation between the different measurement methods in this study; although a remarkable weight loss between the forest and the heating plant was detected. Part of the weight loss comes from the loss of water and therefore it is desirable. However, the average moisture content in this study was 43 % at the heating plant after, on average, 11 months of storage time. The result was only 10 percentage points lower than the moisture content of freshly-felled small-sized trees. Therefore the dry matter loss was about one third of the total weight loss in this study. However, previous studies of the moisture content of energy wood were 35 - 42 % after various storage periods (Hakkila 1989, Hillebrand & Nurmi 2004).

The loss of water cannot be the only explanation for the entire weight loss. There has to be also other unknown factors such as dry matter loss. According to a Swedish study the dry matter loss of energy wood can be 8 - 12 % after an 8 - 13 month storage period, depending on energy wood assortment (Anerud & Jirjis 2011, Jirjis & Norden 2005, Pettersson & Nordfjell 2007. However, neither dry matter loss nor the loss of volatile compounds was examined in this study.

Even dry matter and water loss together cannot account for the total loss of weight in this study. However, it is impossible to know exactly where all of the weight loss came from; because there is no absolute value measured in this study. It might be possible that the crane scale had a positive systematic measurement error. Loss of foliage and needle mass might also be a part of the explanation as well as wood degradation. Moreover, loss of wood chips is also possible during roadside chipping and transportation. The data was collected mainly from different forest energy sector organisation's databases. Every organisation has their own data system and privacy protection might be infringed if the whole of the data was given to a third party. A mistake might be possible when manually picking up the information from the database. Measurements of the stacks at the roadside storage were carried out by the authors and every time the same measurement methods and instruments were used. However, systematic measurement error of frame volume might be possible in this study.

The measurement of the amount of energy wood is an important stage for energy wood sellers and buyers. The amount of energy wood sets the price paid for the energy wood. Thus, it is essential that the measurement result is reliable and accurate. Further studies about measurement of energy wood are needed. It is important to clarify where weight loss between the forest and the heating plant comes from.

4.4 Wood moisture reduction by compression drying (Study IV)

Compression drying was a fast and an effective method for wood drying on a laboratory scale. The drying rate of softwood was higher than hardwood. Obviously, the initial moisture content of wood and tree species had a direct effect on the drying rate of the wood. The drying results for the pressing depended strongly on the pressing force used.

Scots pine and Norway spruce behaved similarly in the compression tests, and their energy consumption per unit of removed water was at the same level. Downy birch required more energy for removing the same amount of water. However, in all cases the required energy was only a fractional part of the energy required in thermal drying. In reality the energy consumption of compression drying might be a little bit higher than the theoretical values which were presented in this study because the energy requirement calculations did not take into account the efficiency of the electrical motor driving the compression piston.

The higher energy required by birch was probably due to its higher density compared to the softwoods. More energy is needed to crush the denser and stronger birch wood than the softer pine and spruce. Similar results were obtained by Yoshida et al. (2010) who found that in the roller compression of several tree species hardwoods consumed more energy than softwoods.

According to this study the usable range for the compression drying of wood was about 10 - 30 MPa. Using a holding time of 30 seconds (continuous pressing) instead of 0 seconds (momentary pressing) resulted in the wood being a little bit dryer when using the same pressure. However, the increasing of the pressing time from 30 to 60 seconds does not significantly improve the drying results.

The experiment presented here did not support the hypothesis that the fibre saturation point can be reached using only compression drying. The lowest moisture content measured for pine, spruce and birch were 7 - 12 percentage points over the fibre saturation point of 23 % (Koponen 1985).

In this study the compression drying results for pine, spruce and birch wood were ascertained with different pressing forces and time. Previous results for Finnish tree species have not been published using a similar method. The compression drying test of the energy wood was made using sawdust in this study. The results might be different for different wood particle sizes and different drying cylinder sizes, but, sawdust was chosen because its particle size was more homogenous than wood chips, for example, and therefore it was easier to control and study under laboratory conditions. However, further studies about large scale compression drying for wood chips are needed. The compression drying method must be capable of being integrated into the energy wood supply chain and plant technology before the method can be introduced.

4.5 Effect of moisture content and weight loss on forest energy potential

It is well known that the moisture content of wood will specifically affect the wood’s energy content. However, the energy content (2 MWh/m^3) of fresh wood is usually used in potential calculations. The energy wood, however, is used drier than freshly felled wood in practice, in which case the energy content is greater than 2 MWh/m^3. Due to this the real techno-economic potential is probably higher than the numbers that have been presented (1.6 TWh/y); for example in **Study I**. The disparity in potential between absolutely dry wood and freshly-felled trees was 400 GWh/y. However, in the study area the potential of 1900 GWh/y for absolutely dry forest energy is theoretical and impossible to reach in practice. Probably, the most realistic potential is 1710 GWh/y which was based on the moisture content (43 %) of small-size whole trees 11 months after harvesting; according to **Study III**. However, the same level of moisture content and potential (1780 GWh/y) could be achieved in the future using compression drying. The weight loss reduces the potential substantially.

4.6 Final remarks

Moisture content of energy wood is one of the most important quality factors for heat energy production. It directly affects transportation costs and the heating value of wood. Also, the moisture affects wood durability in storage, moreover, the dryer the wood the greater the forest energy potential. However, nowadays many heating plants still use quite moist fuel and there are many reasons for that. Firstly, the drying of energy wood in natural conditions is a slow and limited process. Secondly, the traditional artificial drying (cold or hot air drying) of energy wood requires a lot of energy. Therefore new drying methods and innovations are needed. Forest energy is a limited resource, despite its renewability. There is no reason to waste energy to combust fresh wood.

5 CONCLUSIONS

- The techno-economic potential of forest energy in the Regional Unit of South and Central Ostrobothnia of the Finnish Forest Centre was 1.6 TWh/y and it would be significantly higher (2.7 TWh/y) if the pine stumps in the area were also fully utilised for energy generation (**Study I**).
- The techno-economic forest energy potential would also be much higher in the area, if the wood is utilised dry instead of fresh, which is usually used in potential calculations (**Study I, II, III & IV**).
- Norway spruce stump wood keeps its dryness and energy content well at roadside storage sites all year round providing that the stumps are dried well at the beginning during the first summer (**Study II**).
- Part of the energy wood weight loss is desirable (removing of water) and part is undesirable (dry matter loss, storage loss, transportation loss and wood degradation) in different phases of the energy wood supply chain (**Study III**).
- The loss caused by measuring errors must be eliminated by developing the measuring methods to be more reliable and accurate (**Study III**).
- Compression drying is a potential method for wood drying according to the laboratory tests and the required energy is very low compared to the thermal vaporization of water (**Study IV**).
- The moisture content of the wood is the sum of many factors of which the most significant factors are the weather during natural drying conditions and the pressure used during compression drying (**Study II, III and IV**).
- The properties of energy wood are varying quite widely depending on the energy wood assortment and the origin of the wood (**Study I, II, III and IV**).
- The new information obtained in these studies can be used to improve the profitability of energy wood procurement and utilization (**Study I, II, III and IV**).

REFERENCES

Ahtila O. (2010). Biomassan energia-arvon nostaminen sekundäärilämmöllä kuivaamalla [Increase of biomass energy content by utilisation of secondary heat in drying]. Master thesis. 68 p. (in Finnish.) https://helda.helsinki.fi/bitstream/handle/10138/26479/Ahtila.pdf?sequence=1 [Cited 29 Apr 2013].

Äijälä O., Kuusinen M., Koistinen A. (eds.) (2010). Hyvän metsänhoidon suositukset energiapuun korjuuseen ja kasvatukseen [Forest management recommendations for energy wood harvesting and silviculture]. Metsätalouden kehittämiskeskus Tapio. 31 p. (in Finnish.)

Alakangas E. (2000). Suomessa käytettävien polttoaineiden ominaisuuksia [Properties of fuels used in Finland]. VTT tiedotteita 2045. 172 p. + appendices 17 p. (in Finnish.)

Anerud E. & Jirjis R. (2011). Fuel quality of Norway spruce stumps - influence of harvesting technique and storage method. Scandinavian Journal of Forest Research 26: 257-266. http://dx.doi.org/10.1080/02827581.2011.561807

Anttila P., Nivala M., Laitila J., Korhonen K.T. (2013). Metsähakkeen alueellinen korjuupotentiaali ja käyttö. Metlan työraportteja / Working Papers of the Finnish Forest Research Institute 267. 24 p. (in Finnish.) http://www.metla.fi/julkaisut/workingpapers/2013/mwp267.htm [Cited 18 May 2013].

Asikainen A. (2004). Puunkorjuu ja kuljetus [Timber harvesting and transportation]. In: Harstela P. (ed.) Metsähake ja metsätalous [Forest chips and silviculture]. Metsäntutkimuslaitoksen tiedonantoja 913: 26 - 36. (in Finnish.)

Asikainen A., Liiri H., Peltola S., Karjalainen T., Laitila J. (2008). Forest energy potential in Europe (EU27). Working Papers of the Finnish Forest Research Institute 69. 33 p. http://www.metla.fi/julkaisut/workingpapers/2008/mwp069.htm

CEN/TS 14918:2005 Solid biofuels - Method for the determination of calorific value. 62 p.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. 47 p.

Erber G., Kanzian C., Stampfer K. (2012). Predicting Moisture Content in a Pine Logwood Pile for Energy Purposes. Silva Fennica 46 (4): 555-567.

Erkkilä A. (2010). Teknologiset mahdollisuudet biomassan tuotantoketjuissa [Technological possibilities in the biomass production chains]. Biomassa 2010 - seminaari. Sibeliustalo, Lahti 2.12.2010. VTT. 28 p. (in Finnish.)

Fagerstedt K., Pellinen K., Saranpää P., Timonen T. (2004). Mikä puu - mistä puusta [Which tree - from which wood]. Yliopistopaino, Helsinki. 184 p.

Gibson L.J. & Ashby M.F. (1999). Cellular solids. Structure and properties. Second edition. Cambridge University Press. 532 p.

Hakkila P. (1972). Mechanized harvesting of stumps and roots. A sub-project of the joint Nordic research programme for the utilization of logging residues. Communicationes Instituti Forestalis Fenniae 77. 71p.

Hakkila P. (1989). Utilization of Residual Forest Biomass. Springer Series in Wood Science. Springer-Verlag. 568 p.
http://dx.doi.org/10.1007/978-3-642-74072-5

Hakkila P. (2001). Wood Energy in the Nordic Countries. In: Pelkonen P., Hakkila P., Karjalainen T., Schlamadinger B. (eds.) Woody Biomass as an Energy Source - Challenges in Europe. Joensuu, Finland 25-28 September 2000. EFI Proceedings No. 39, p. 7-19.

Hakkila P. (2004). Puuenergian teknologiaohjelma 1999-2003 [Wood energy technology programme 1999-2003]. Metsähakkeen tuotantoteknologia [Forest chips production technology]. Loppuraportti [Final report]. Tekes. Teknologiaohjelmaraportti 5. 135 p. (in Finnish.)

Hakkila P. (2006a). Factors Driving the Development of Forest Energy in Finland. Biomass and Bioenergy. 30:281-288.
http://dx.doi.org/10.1016/j.biombioe.2005.07.003

Hakkila P. (2006 b). Selvitys energiapuun mittauksen järjestämisestä ja kehittämisestä [Report from arranging and developing of the measuring of the energy wood]. Helsinki 2006. Työryhmämuistio MMM 2006:8. 30 p. (in Finnish.)
http://wwwb.mmm.fi/julkaisut/tyoryhmamuistiot/2006/trm2006_8.pdf [Cited 31 Oct 2012].

Hakkila P. & Parikka M. (2002). Fuel Resources from the Forest. In: Richardson J., Björheden R., Hakkila P., Lowe A.T., Smith C.T. (eds.) Bioenergy from Sustainable Forestry: Guiding Principles and Practice. Kluwer Academic Publisher, Netherlands. p. 19-48.
http://dx.doi.org/10.1007/0-306-47519-7_2

Haygreen J.G. (1981). Potential for compression drying of green wood chip fuel. Forest Products Journal 31(8): 43-54.

Haygreen J.G. (1982). Mechanics of compression drying solid wood cubes and chip mats. Forest Products Journal 32(10): 30-38.

Haygreen J.G. & Bowyer J.L. (1996). Forest Products and Wood Science. An Introduction. Third edition. Iowa State University. 576 p.

Hillebrand K. & Nurmi J. (2004). Nuorista metsistä korjattavan energiapuun kuivatus ja varastointi -osaprojekti [Drying and storing of harvested energy wood from young stands -subproject]. In: Hillebrand K. (ed.) Metsähakkeen tuotannon kehittäminen nuorista metsistä. Hankekokonaisuus 2001 - 2004. Osaprojektien loppuraportit [Development of production of forest chips from young stands. Project portfolio 2001 - 2004. Final reports of subprojects]. VTT, 17 p. (In Finnish.)

Ilmasto-opas.fi (2012). Finnish meteorological institute. http://ilmasto-opas.fi/fi/ [Cited 17 Oct 2012].

ISO 589:2003(E). Hard coal - Determination of total moisture. International Standard. 7 p.

Isomäki O. (1974). Sahateollisuuden kuorintajätteiden käyttömahdollisuudet. Erityisesti käyttö maanparannusaineena ja kasvualustana [Using possibilities of barking waste in sawmill industry. Specially using as a soil improver and substrate for plants]. Acta Forestalia Fennica 140. 81 p. (in Finnish.)

Jahkonen M., Lindblad J., Sirkiä S., Laurén A. (2012). Energiapuun kosteuden ennustaminen [Moisture content predicting of energy wood]. Metlan työraportteja / Working Papers of the Finnish Forest Research Institute 241. 35 p. (in Finnish.) http://www.metla.fi/julkaisut/workingpapers/2012/mwp241.htm. [Cited 23 Apr 2013].

Jirjis R. (2005). Effects of particle size and pile height on storage and fuel quality of comminuted Salix viminalis. Biomass and Bioenergy 28 (2): 193-201. http://dx.doi.org/10.1016/j.biombioe.2004.08.014

Jirjis R. & Norden B. (2005). Fuel quality and working environment during storage and handling of composite residue logs. Report no 7. Department of Bioenergy, Swedish University of Agricultural Sciences, Uppsala, Sweden. 41 p. (in Swedish with English summary.)

Kärkkäinen M. (1981). Polttopuun rasiinkaadon ja muiden kuivausmenetelmien perusteet [The basis of leaf seasoning and other methods for drying fuelwood]. Folia Forestalia 459. 15 p. (in Finnish.)

Kärkkäinen M. (2007). Puun rakenne ja ominaisuudet [Wood structure and properties]. Metsälehti kustannus. Hämeenlinna. 468 p. (in Finnish.)

Koistinen A. & Äijälä O. (2005). Energiapuun korjuu [Energy wood harvesting]. Metsätalouden kehittämiskeskus Tapio. 40 p. (in Finnish.)

Koponen H. (1985). Sorption isotherms of Finnish birch, pine and spruce. Paperi ja Puu. Paper and Timber (2): 70-77.

Kyoto Protocol to the United Nations Framework Convention on Climate Change (1998). 21 p. United Nations. http://www.kyotoprotocol.com/resource/kpeng.pdf [Cited 9 Oct 2012].

Laitila J. (2012). Methodology for choice of harvesting system for energy wood from early thinning. Doctoral dissertation. University of Eastern Finland. Dissertationes Forestales 143. 68 p. http://www.metla.fi/dissertationes/df143.htm

Laitila J., Asikainen A., Anttila P. (2008). Energiapuuvarat [Energy wood resources]. In: Kuusinen M. & Ilvesniemi H. (eds.) Energiapuunkorjuun ympäristövaikutukset, tutkimusraportti [Environmental effect of energy wood harvesting, research report]. Publications of Tapio and Metla. p. 6-12. (in Finnish.)

Laitila J., Ranta T., Asikainen A. (2008). Productivity of stump harvesting for fuel. International Journal of Forest Engineering 19(2): 37-47.

Lauhanen R. & Laurila J. (2007a). Bioenergian tuotannon haasteet ja tutkimustarpeet. Working Papers of the Finnish Forest Research Institute 42. 58 p. (in Finnish.) http://www.metla.fi/julkaisut/workingpapers/2007/mwp042.htm [Cited 27 Nov 2012].

Lauhanen R. & Laurila J. (2007b). Etelä-Pohjanmaan tavoite 2 -alueen metsäenergiapotentiaali [Forest energy potential of South Ostrobothnia's target 2 area]. In: Lauhanen R. & Laurila J. (eds.) Bioenergian hankintalogistiikka. Tapaustutkimuksia Etelä-Pohjanmaalta [Procurement logistics of bioenergy. Case studies from South Ostrobothnia]. University of Applied Sciences. Seinäjoki p. 11 - 25. (in Finnish.)

Laurila J., Havimo M., Lauhanen R. (2012). Compression drying of energy wood. Manuscript Submitted (Fuel Processing Technology).

Laurila J. & Lauhanen R. (2010). Moisture Content of Norway Spruce Stump Wood at Clear Cutting Areas and Roadside Storage Sites. Silva Fennica 44(3): 427-434. http://www.metla.fi/silvafennica/full/sf44/sf443427.pdf

Laurila J. & Lauhanen R. (2012). Weight and volume of small-sized whole trees at different phases of the supply chain. Scandinavian Journal of Forest Research 27:46-55. http://dx.doi.org/10.1080/02827581.2011.629621

Laurila J., Tasanen T., Lauhanen R. (2010). Metsäenergiapotentiaali ja energiapuun korjuun resurssitarpeet Etelä-Pohjanmaan metsäkeskuksen alueella. [Forest energy potential and resource needs of energy wood harvesting in area of Forest Centre of South Ostrobothnia]. Metsätieteen aikakauskirja 4/2010: 355-365. (in Finnish.) http://www.metla.fi/aikakauskirja/full/ff10/ff104355.pdf

Lenton T.M., Held H., Kriegler E., Hall J.W., Lucht W., Rahmstorf S., Schellnhuber H.J. (2008). Tipping Elements in the Earth's Climate System. Proceedings of the National Academy of Sciences USA. 105 (6), 1786-1793. http://dx.doi.org/10.1073/pnas.0705414105

Le Treut H., Somerville R., Cubasch U., Ding Y., Mauritzen C., Mokssit A., Peterson T., Prather M. (2007). Historical Overview of Climate Change. In: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge. United Kingdom and New York, NY, USA. p. 93-127.

Lindblad J., Äijälä O., Koistinen A. (2010). Energiapuun mittaus [Measurement of energy wood]. Tapio and Finnish Forest Research Institute. 31 p. (in Finnish.)

Liu Z. & Haygreen J.G. (1985). Drying rates of wood chips during compression drying. Wood and Fiber Science 17(2): 214-227.

Lunnan A., Vilkriste L., Wilhelmsen G., Mizaraite D., Asikainen A., Röser D. (2008). Policy and Economic Aspects of Forest Energy Utilisation. In: Röser D., Asikainen A., Raulund-Rasmussen K., Stupak I. (eds.) Sustainable Use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic region. Managing Forest Ecosystems, Vol. 12. Published by Springer. Dordrecht. The Netherlands. 262 p. http://dx.doi.org/10.1007/978-1-4020-5054-1_8

Maa- ja metsätalousministeriö (2006). Metsäenergian tuotannon, korjuun ja käytön kustannustehokkuus sekä tukijärjestelmien vaikuttavuus päästökaupan olosuhteissa [Cost efficiency of the production, harvesting and use of the forest energy and effectiveness of support systems in the conditions of the emission trade]. Pöyry Forest Industry Consulting Oy. 52A07161-Ejpc-1. 9.8.2006. Loppuraportti. 47 p. (in Finnish.)

Maidell M., Pyykkönen P., Toivonen R. (2008). Metsäenergiapotentiaalit Suomen maakunnissa [Forest energy potential in Finnish provinces]. Pellervon taloudellisen tutkimuslaitoksen työpapereita 106. 42 p. (in Finnish.)

Mantau U., Saal U., Prins K., Steierer F., Lindner M., Verkerk H., Eggers J., Leek N., Oldenburger J., Asikainen A., Anttila P. (2010). Real potential for changes in growth and use of EU forests. Final report. EUwood. Hamburg. June 2010. 160 p.

Mikkola H. (2012). Peltobioenergian tuotanto Suomessa. Potentiaali, energiasuhteet ja nettoenergia [Field crop production in Finland. Energy potential, energy ratios and amount of net energy]. Väitöskirja. Helsingin yliopisto. Maataloustieteiden laitos. Julkaisuja 10. Helsinki 2012. 93 p. (in Finnish.)

Nurmi J. (1992). Measurement and Evaluation of Wood Fuel. Biomass and Bioenergy 2 (1-66):157-171.

Nurmi J. (2000). Characteristics and storage of whole-tree biomass for energy. Doctoral dissertation. The Finnish Forest Research Institute. Research Papers 758. 42 p.

Nurmi J. & Hillebrand K. (2007). The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. Biomass & Bioenergy 31(6): 381-392. http://dx.doi.org/10.1016/j.biombioe.2007.01.010

Petroleum & other liquids (2012). Independent Statistics & Analysis. U.S. Energy Information Administration. http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm [Cited 22 Sep 2012].

Pettersson M. & Nordfjell T. (2007). Fuel quality changes during seasonal storage of compacted logging residues and young trees. Biomass and Bioenergy 31: 782-792. http://dx.doi.org/10.1016/j.biombioe.2007.01.009

Pietilä K. (2005). Puun panospolton identifiointi ja säätö tulisijassa [Identification and control of batch combustion of wood in a fireplace]. Thesis. Oulun yliopisto. 91 p. (in Finnish.)

Pimenoff N., Venäläinen A., Pilli-Sihvola K., Tuomenvirta H., Järvinen H., Ruosteenoja K., Haapala J., Räisänen J. (2008). Epälineaariset ja äärimmäiset ilmaston muutokset [Nonlinear and extreme climate changes]. Selvitys Vanhasen II hallituksen tulevaisuusselontekoa varten. Valtioneuvoston kanslian julkaisusarja 14/2008. 57 p.

Pitkän aikavälin ilmasto- ja energiastrategia [Long term climate and energy strategy] (2008). Valtioneuvoston selonteko eduskunnalle 6. päivänä marraskuuta 2008. 130 p. (in Finnish.) https://www.tem.fi/files/20585/Selontekoehdotus_311008.pdf [Cited 11 Oct 2012].

Puutavaranmittausasetus [Timber measuring statute] (1991). Asetus N:o 365/1991. Annettu Helsingissä 22 päivänä helmikuuta 1991. (in Finnish.) http://www.metla.fi/metinfo/tietopaketit/mittaus/mittausasetus1991.htm [Cited 25 Oct 2012].

Puutavaranmittauslaki [Timber measuring law]. (1991). Laki N:o 364/1991. Annettu Helsingissä 22 päivänä helmikuuta 1991. (in Finnish.) http://www.metla.fi/metinfo/tietopaketit/mittaus/mittauslaki1991.htm [Cited 25 Oct 2012].

Ranta T. (2002). Logging residues from regeneration fellings for biofuel production - a GIS- based availability and supply cost analysis. Doctoral dissertation. Lappeenranta University of Technology. Finland. Acta Universitatis Lappeenrantaensis 128. 182 p.

Recent Mauna Loa CO_2 (2012). Earth System Research Laboratory. http://www.esrl.noaa.gov/gmd/ccgg/trends/ [Cited 22 Oct 2012].

Riala M. & Asikainen A. (2012). Future of forest energy in Europe in 2030. Working Papers of the Finnish Forest Research Institute 244. 47 p. http://www.metla.fi/julkaisut/workingpapers/2012/mwp244.pdf [Cited 22 Oct 2012].

Röser R. (2012). Operational efficiency of forest energy supply chains in different operational environments. Doctoral dissertation. University of Eastern Finland. Dissertationes Forestales 146. 83 p.
http://www.metla.fi/dissertationes/df146.htm

Rosillo-Calle F., Groot P., Hemstock S.L. (2007). General Introduction to the Basis of Biomass Assessment Methodology. In: Rosillo-Calle F., Groot P., Hemstock S.L., Woods J. (eds.) The Biomass Assessment Handbook - Bioenergy for a Sustainable Environment. Earthscan. p. 27-68.

Routa J., Kolström M., Ruotsalainen J., Sikanen, L. (2012). Forecasting moisture changes of energy wood as a part of logistic management. In: Special issue. Abstracts for international conferences organized by LSFRI Silava in cooperation with SNS and IUFRO. Mezzinatne 25(58): 33-35.

Saarenmaa L. (2002). Metsien luokitus [Classification of forests]. In: Hyvämäki T. (ed.) Tapion taskukirja [Tapio's pocket book]. Metsätalouden kehittämiskeskus Tapio. p. 311- 322. (in Finnish.)

Saranpää P. & Tuimala A. (1997). Kosteus puussa [Moisture in wood]. Työtehoseuran metsätiedote 9 (577). (in Finnish.)

Sauvula-Seppälä T. (2010). Lämpöyrittäjyyden kannattavuus lämmönostajan ja -myyjän sekä metsänomistajan näkökulmasta [Profitability of Heating Entrepreneurship from the Viewpoint of Heating Energy Buyer, Heating Energy Seller and Energy Wood Seller]. Maataloustieteen päivät 2010. 7 p. (in Finnish.)
http://www.smts.fi/jul2010/poste2010/001.pdf [Cited 9 May 2013].

Siitonen K. (2010). Vaneritehtaan sivutuotteet energiantuotannossa [Secondary products of plywood factory in power production]. Bachelor's thesis and seminar. Lappeenrannan Teknillinen Yliopisto. 44 p. (in Finnish.)
http://www.doria.fi/bitstream/handle/10024/66280/nbnfife201011253036.pdf?sequence=3 [Cited 29 Apr 2013].

Sirén M., Tanttu V., Aaltio H. (2001). Metsähakkeen korjuuolot ja niiden parantamismahdollisuudet ensiharvennuksissa - PUUT04 [Harvest conditions of forest chips and their improving possibilities in first thinning - PUUT04]. In: Alakangas E. (ed.) Puuenergian teknologiaohjelman vuosikirja 2001 [Yearbook of the technology programme of the wood energy 2001]. VTT Symposium 216. p. 77 - 93. (in Finnish.)

Skaar C. (1972). Water in wood. Syracuse Wood Science Series. Syracuse University Press. 218p.

Solomon S., Gin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds) (2007). Climate Change 2007: The Physical Science basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental panel on Climate Change. Cambridge University press. Cambridge, United Kingdom and New York, NY, USA. 996 p.

Thorsén Å., Björheden R., Eliasson L. (eds.) (2010). Efficient forest fuel supply systems. Composite report from a four year R&D programme 2007-2010. Skogforsk. Sweden. 113 p.

Time B. (2002). Studies on hygroscopic moisture transport in Norway spruce (Picea abies). Part 1: Sorption measurements of spruce exposed to cyclic step changes in relative humidity. Holz als Roh- und Werkstoff 60: 271-276. http://dx.doi.org/10.1007/s00107-002-0303-3

Työ- ja elinkeinoministeriö (2010). Suomen kansallinen toimintasuunnitelma uusiutuvista lähteistä peräisin olevan energian edistämisestä direktiivin 2009/28/EY mukaisesti [Finland's national action plan for promotion of renewable energy according to directive of 2009/28/EC]. 10 p. (in Finnish.)

Työryhmä esittää energiapuun mittausta lain piiriin [The work group presents the energy wood measuring within the sphere of the law] (2012). Maa- ja metsätalousministeriö. (in Finnish.) http://www.mmm.fi/fi/index/etusivu/tiedotteet/120905_puutavaranmittauslaki.html [Cited 31 Oct 2012].

Tyynismaa V. (2012). Energiapuun hävikki varastopaikalla Metsäliitto Osuuskunnan Seinäjoen hankintapiirin alueella [The loss of energy wood at roadside storage sites in the Metsäliitto Seinäjoki area]. Final thesis. Seinäjoki University of Applied Sciences. School of Agriculture and Forestry. 36 p. (in Finnish.)

United Nations Framework Convention on Climate Change (1992). United Nations. 25 p. http://unfccc.int/resource/docs/convkp/conveng.pdf [Cited 9 Oct 2012].

Vesisenaho T. (2003). Puuperäiset polttoaineet - metsähakkeet [Wood based fuels - forest chips]. In: Knuuttila K. (ed.) Puuenergia [Wood energy]. Jyväskylä 2003. p. 37 - 40. (in Finnish.)

What drives crude oil prices? (2012). An analysis of 7 factors that influence oil markets, with chart data updated monthly and quarterly. September 11, 2012. U.S. Energy Information Administration. Washington, DC. 22 p. http://www.eia.gov/finance/markets/reports_presentations/eia_what_drives_crude_oil_prices.pdf [Cited 9 Oct 2012].

Wigrup I. (ed.) (2012). Swedish statistical yearbook of forestry 2012. Official statistics of Sweden. Skogsstyrelsen. Jönköping: Swedish Forest Agency. 380 p.

World Energy Outlook (2010). OECD/IEA. International Energy Agent. Paris. 731 p.

Ylitalo E. (ed.) (2011) Finnish statistical yearbook of forestry 2011. Official Statistics of Finland. Agriculture, forestry and fishery. Finnish Forest Research Institute. 470 p.

Ylitalo E. (2013). Puun energiakäyttö 2012 [Wood energy usage 2012]. Metsätilastotiedote 15/2013. Finnish Forest Research Institute. 6 p. (in Finnish.) http://www.metla.fi/metinfo/tilasto/julkaisut/mtt/2013/puupolttoaine2012.pdf [Cited 18 Apr 2013].

Yoshida T., Sasaki H., Takano T., Sawabe O. (2010). Dewatering of high-moisture wood chips by roller compression method. Biomass & Bioenergy 34(7): 1053 - 1058. http://dx.doi.org/10.1016/j.biombioe.2010.02.013