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skog + landskap
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PREFACE

Biomass from forestry sector is able to provide an important contribution for increasing bioenergy use. The amount of wood of adequate quality for industry is continually decreasing. Therefore, it is necessary to use it more efficiently. The complete tree concept offers a tremendous opportunity for forestry to meet the future industrial demands. Besides stem wood also branch wood with bark, and unmerchantable part of trees, i.e. logging residues, could be used to ensure the forest balance and re-open the possibilities of industrial expansion.

The Norwegian forest and landscape institute was chosen to direct the “Solid biofuels from forest - Fuel specification and quality assurance” project. A project council subordinated to the Bioenergy Innovation Center (CenBio) was set up to supervise the work. The study is being conducted within the framework program approved by The Research Council of Norway.

The right knowledge about the forest biomass quality can improve the forest-based bioenergy sector and will result in its increased and more efficient use. To analyze Norway spruce fuel-wood production there is a need to determine the difference in qualitative properties of raw material. This study concerns the geographical variation of selected properties of Norway spruce (*Picea abies* (L.) Karst.) forest biomass in South Norway, the most valuable tree species from the viewpoint of bioenergy use in Norway. The most important fuel qualitative properties of stemwood, bark, branches and tree tops were investigated in order to know the potential of raw material properties available for bioenergy use in Norway.

The material was collected from three geographical locations in South Norway, specifically from Hobøl and Seljord stads in 2011 under the direction of Simen Gjølsjø, Kjell Vadla, Olav Høibø, Georg Behr and from Vindafjord site in 2011 under the direction of Gitte Halvorsen and Tore Filbakk. Most of the laboratory work and calculations was done by Kari Hollung, Eva Grodås and Monica Fongen from the Norwegian forest and landscape institute. Valuable help and counsel in the course of the research work were received from many other persons.

My best thanks are due to all those mentioned above.

Ås, January 2014

Janka Dibdiakova

SUMMARY

Biomass from forestry sector is able to provide an important contribution to meet the government's targets for increasing bioenergy use. Traditionally it has been stem wood which is used as raw material for energy. For a deeper understanding of trees, knowledge is required not only of the stem wood, but also of the branches and tree tops. The most important fuel qualitative properties of stem wood, bark, branch wood and tree tops were investigated in order to know the potential of Norway spruce biomass available for bioenergy use in Norway.

Considerable variations in qualitative properties between stem wood, stem bark and branch wood of Norway spruce among geographical locations and vertically along the stem were observed. The basic density of stem wood was 382.8-523.5 kg/m^3, of stem bark 273.2-582.0 kg/m^3 and of branch wood 243.5-673.0 kg/m^3. Basic density of stem wood decreased from the roof base till 20 % of the tree height and afterwards increased towards the tree top. The axial dependence of basic density in stem bark was different than the one in stem wood, more regular, decreasing towards the top. The vertical density gradient of stem bark in the base was roughly 5-10 % steeper to that in tree top. Branch density decreased moderately within the axial direction along the crown. Branch wood had higher basic density than stem wood within a difference between these two densities of 80-216 kg/m^3. The basic density of branch wood decreased in the direction from the branch basis to its top. The greatest decrease was found in the first 20 cm of the branch, and then the decrease was minimal. The branch diameter strongly affected the basic density distribution along the branch. There was found relationship between basic density of stem wood, stem bark, branch wood and geographical locations. The highest basic density of all collected biomass samples was observed for the east part of South Norway, Hobøl site. It was also found that the higher site index the higher basic density in this location. The bark proportion and bark thickness were highly linear to the tree height. Spruce bark originated from the middle part of South Norway, Seljord site had considerably higher bark proportion than bark collected from trees from other two geographical sites. The average moisture content of stem wood and stem bark harvested in summer season increased axially from the base toward tree top, within significantly more pronounced variations on the tree base compare to tree top. Stem bark had relatively higher moisture content compare to stem wood. The moisture content in stem wood was 36.0-52.3 %, in stem bark 37.6-62.4 % and in branch wood 29.0-67.9 %. The vertical dependence of moisture content in branch wood, collected in summer season originated from Hobøl site differed more than that in Seljord and Vindafjord site.

Characteristic chemical components of stem bark did differ considerably from that of stem wood. Chemical composition in stem bark had higher percentage of lignin and extractives (17 % and 40 %, respectively, the remaining 43 % is holocellulose), compared to stem wood (10 % and 6 %, respectively, the remaining 84 % is holocellulose). There were indications that calorific value of woody-based material was highly affected by its chemical composition. The effective calorific value of stem wood was 5.27-5.58 kWh/kg, of stem bark 5.49-5.80 kWh/kg and of branch wood 5.68-5.87 kWh/kg. Increased in heating value of Norway spruce stem wood, stem bark and branch wood consequently generated higher content of ash. More ever we found that the ash content of Norway spruce branch wood did vary along the branch whereas the position of branch in crown did not affect the ash content. The ash content in the stem wood was 0.17-0.22 %, in stem bark 1.49-2.63 % and in branch wood 1.11-2.49 %. Applied combustion process of twigs performed under oxidative atmosphere resulted in higher residue mass compare to the branch base. Elevated effective calorific value of stem bark, and branch wood because of their higher amount of extractives and lignin content make these materials a valuable energy source for bioenergy industry in Norway.

Key words: Ash content, basic density, forest biomass, heating value, Norway spruce, site index

CONTENTS

1 INTRODUCTION

1.1 Forest biomass for bioenergy use in Norway

Forest land and forest biomass have been given more focus in recent years as a result of the discussions regarding climate change issues and the understanding of forests as an important factor in mitigating climate change. It is a political goal to replace fossil fuels with renewable energy sources, and the current goal is to have a carbon-neutral energy supply in Norway by 2030 (Miljøverndepartementet, 2010; Trømborg, 2011). To achieve this goal, several sources of renewable energy, such as wind, geothermal, wave, hydro, solar and biomass must be utilised. The target for bioenergy is to increase the Norwegian annual consumption of biomass by 14 TWh by 2020 (LMD, 2009).

About 40 % of the Norwegian main land is covered by forest (Granhus *et al*., 2012). The total forested area in Norway amounts to almost 11 million hectares (ha), of which more than 8 million ha are productive forest (Granhus *et al*., 2012). Approximately 15 % of the productive forest has been estimated as non-profitable areas due to difficult terrain and remoteness, which means that cost-effective forestry, may only be performed in about 60 % of the forested area (Eid *et al*., 2002). Trømborg and Leistad (2009) have reported that there is technically potential for the forestry sector to increase bioenergy use in Norway to 39 TWh per year.

Forest contributes to the reduction of CO_2 content in the atmosphere by sequestering CO_2 from the air and binding it as organic carbon through photosynthesis. When biomass from forest is used for bioenergy production, the bound CO_2 is released back into the atmosphere (Timmermann and Dibdiakova, 2013). When bioenergy is used at sustainable rates, the CO_2 binding in the forest will compensate for the CO_2 released during combustion (Zanchi *et al*., 2010). Establishing new forests can contribute to reducing the CO_2 content in the atmosphere (Parigiani *et al*., 2011).

Conifers dominate in Norwegian forests. About 45 % of the total standing volume consists of the Norway spruce (*Picea abies* (L.) Karst.) as the dominant tree species in most regions in Norway and 30 % of Scots pine (*Pinus silvestris* L.) as the second most important tree species. Birches (*Betula* spp.), the most common hardwood species in mountainous areas and in northern Norway, represent 16 % of the standing volume (Granhus *et al*., 2012).

Biomass from forestry sector is able to provide an important contribution to meet the government's targets for increasing bioenergy use. Traditionally it has been stemwood which is used as raw material for energy. The total amount of stemwood available for bioenergy in Norway is estimated to be 9 TWh per year (NVE, 2010). With the increasing demand for fuel the use of other tree components like branches and tree tops has increased rapidly. The potential amount of energy obtained from logging residues and thinning whole trees is estimated to be approximately 3.5 TWh per year for each source. This can even increase to 1.5 TWh per year if logging residues are utilized at reasonable level (Filbakk, 2012).

For a deeper understanding of trees, knowledge is required not only of the stemwood, but also of the branches and tree tops. The very right knowledge about the forest biomass quality can improve the forest-based bioenergy sector and may result in its increased and more efficient use. To analyze Norway spruce fuel-wood production there is a need to determine the difference in qualitative properties of raw material. This study concerns the geographical variation of selected properties of Norway spruce (*Picea abies* (L.) Karst.) tree species in South Norway. The most important fuel qualitative properties of the stem wood, stem bark, branches and tree tops were investigated in order to evaluate potential raw materials available for bioenergy use in Norway.

1.2 Qualitative properties of tree biomass

The wood properties of a tree are a combination of its genetic make-up and the environment that it is grown in. There is therefore considerable scope to improve the wood properties of Norway spruce, through both tree breeding and forest management (Hubert and Lee, 2005). Because individual wood properties differ in the extent to which they are under environmental or genetic control, climate, soil, slope, forest density, disease, wildlife and other, the approach taken to improve these individual properties also differs (Repola, 2006). Much of the previous work in this area has focused on the relations between site factors and tree growth (Blyth and Macleod, 1981), while Worrell and Malcolm (1990a, b) found that yield class declined with increasing elevation and was associated with indices of temperature and windiness. Trees growing at higher elevation sites and with increased wind exposure also tend to have poorer form. This is probably due to higher level of leader loss and meristem desiccation in more wind exposed locations (Grace, 1989; Baldwin, 1993). Poor stem form not only reduces the yield of timber material that can be obtained from a stand but is also associated with a higher incidence of compression wood and a higher grain angle (Spicer *et al*., 2000).

While it is known that the environment is likely to have a considerable effect on the wood density of Norway spruce, few studies have actually quantified the inter-site variation in wood density. Bryan and Pearson (1955) found that wood density declined by approximately 10 kg/m^3 for every one degree increase in latitude. Based on study by Repola (2006), it was found that latitude alone accounted for approximately 22 % variation in wood density, with a decrease in density of 6 kg/m^3 for every one degree increase in latitude. Interestingly, there is a stronger relationship between wood density and longitude (R^2=0.34), with sites in the east Scotland having higher density than those in the west. Preliminary results presented by Vihermaa (2010) indicate that average density decreases by approximately 6 kg/m^3 for every 100 m increase in elevation.

For the potential industrial utilization of forest biomass are the most important properties basic density, moisture content, chemical composition, heating value and ash content.

1.2.1 STUDY AIM

The aim of this study was to clarify the most important wood properties and quality of Norway spruce (*Picea abies* (L.) Karst.) tree biomass growing in three geographical locations in South Norway. The wood properties – basic density, moisture content, chemical composition, calorific value and ash content of stem wood, stem bark, and branch wood of Norway spruce were examined as well as the differences in quality properties between site indexes and geographical locations of stands. Vertical variations of properties along the stem and along the branch were investigated additionally. This research presents some preliminary results of selected wood properties of Norway spruce tree parts, which mostly affect the usability of raw materials for bioenergy use in Norway as well as characteristics and quality of forest-fuel sources.

1.2.2 BIOMASS COMPONENTS OF TREE

Knowledge of the distribution of biomass into its main components in an individual tree is the basis for quantitative and qualitative evaluation of forest biomass. The merchantable stem of trees is the main product of forestry. However, for a deeper understanding of the behaviour of forest trees, knowledge is required not only of the stem, but also of the crown and root system. The tree components dealt with are stem, merchantable stem, top, foliage, branches, crown, stump and roots. The components may be broken down further to wood, bark, and foliage fractions (Hakkila, 1989).

- *Unmerchantable top* of stem, henceforth usually simply *top*, is defined by local logging practice. The bottom diameter of the tree top may vary from 5 to 20 cm.
- *Branch mass* includes all wood and bark of live and dead branches but is free of leaves, shoots, and reproductive organs of a tree. Branch mass is often divided into size classes by diameter, but class division varies from study to study according to conditions.
- *Foliage* includes all leaves and new shoots of branches. Reproductive organs are normally also included in foliage mass.
- *Crown* is defined as all live and dead branches plus all foliage and reproductive organs. However, in many reference studies dead branches are excluded.
- *Stump* is the unutilized above-ground biomass below the bottom of the merchantable stem, and its under-ground projection, excluding the lateral roots.
- *Roots* include all side or lateral roots but exclude the taproot, which is a part of the stump as a natural elongation of the stem. Like branch mass, root mass may also be divided into subclasses by diameter.

Presented study primary focused into qualitative properties of stemwood, stem bark, tops and branches of Norway spruce. Corresponding properties of stumps and roots biomass were beyond the study’s aim.

The proportion of the branch mass differs considerably between tree species (Hakkila, 1989, 1991). There are also considerable variations in the branch mass between and within stands of the same species (Hakkila, 1991). Therefore, the profitability of utilising forest residues may vary significantly between stands.

The qualitative properties of whole trees and logging residues are less homogenous than are those of wood. This difference is due to the large differences in the chemical composition of wood, bark and foliage and to the fact that the contents of the different tree parts vary considerable between sites.

1.2.3 BASIC DENSITY OF TREE BIOMASS

The density of wood is defined as the dry mass per unit volume, usually in kg/m^3. It is a property that is widely studied because is correlated with a number of other physical and mechanical properties.

A number of different definitions of wood density are possible based on the moisture content at which the mass and the volume of the sample are determined. For wood processing industries, the main interest is usually how much dry material is in a cubic meter of fresh wood. This is given by the basic density. Basic density is calculated on the basis of both the mass and volume of the biomass measured at the same moisture content as received (Hakkila, 1989). The average wood density is affected by a large number of factors such as tree species, geographical location and other environmental factors, site quality, position of the tree in a stand, tree age and size, growth rate and genetic factors (Hakkila, 1966).

Variation within a tree

Wood density varies considerably within a tree in both the radial and longitudinal directions.

- *Radial variation* - the radial variation from pith to bark is of great significance in wood utilization. In the juvenile core, wood density decreases from a maximum close to the pith down to a minimum value at between rings 10 and 20, before increasing again towards a quasi-asymptotic value in the mature wood (Mitchell and Denne, 1997; Simpson and Denne, 1997; McLean, 2008). Elliot (1970) attributes the high density observed in the innermost rings to short, small diameter fibres resulting in an increased number of cell walls per unit volume of wood as well as the increased occurrence of compression wood in this region. This radial variation of wood density causes further variation in the axial direction of the stem.

- *Longitudinal variation* - the longitudinal variation in Norway spruce wood density is not as consistent as the radial variation. Some studies have reported a lock of systematic variation in wood density with height up the stem (Jones, 1957; Elliot, 1966), while others have reported a slight decrease (Harvald and Olese, 1987; Mitchell and Denne 1997). Within a growth sheath (layer of wood formed in the same year or years), Simpson and Denne (1997) found that there was a decrease in wood density from the base of the tree up to approximately eight annual growth units from the top, followed by a large increase in density above this height. This decrease is affected by changes in ring width and, above all, the presence of juvenile wood. Some conifers, especially spruces, show only a slight axial variation in wood density. The longitudinal variation in bark density does not necessarily follow the same pattern as the wood density in the same species. For example, data from Tamminen (1962) show for *Picea abies* bark a constant decrease in density from butt to top. The density range is considerable wider in bark than in wood. The densest bark is often found at the tree top and the difference in the basic density between butt and top barks may exceed 100 kg/m^3.

Wood density also varies in branches biomass. Since conifer branches contain large proportions of compression wood which occurs on the lower side of the cross-section, wood is significantly denser on the lower portion of the branch. Timell (1986) reviewed several studies of within-branch density variation in conifers, the lower branch portion usually having 10-40 % higher wood density than the upper one. A clear variation pattern is apparent in wood density along the branch. The density declines from the branch base outwards first rapidly, then levels, and may even turn to a slight increase toward the tip.

Wood density indicates the quality of biomass fuel. Heating value is directly proportional to the wood density. The energy content of a unit volume of wood, bark or foliage depends principally on its dry mass and moisture content and, to some extent, on the cell wall composition and content of extraneous components.

1.2.4 MOISTURE CONTENT OF TREE BIOMASS

In addition to chemical components (cellulose, hemicelluloses, lignin and extractives), wood contains water. This water can exist as absorbed (or free) water in the cell lumens and intercellular spaces, or as adsorbed (or bound) water within the cell walls. The moisture content of wood is calculated as the ratio of the mass of water to the mass of wood that has been oven-dried and is usually expressed as a percentage. Because of this definition, moisture content values exceeding 100 % can and do occur. The moisture content of Norway spruce sapwood is typically in excess of 120 %, while in heartwood it is typically between 40 and 80 %. The average whole-tree moisture content typically ranges from 100 to 160 % (Jeffers and Dowden, 1964).

The moisture content is the main fuel factor affecting combustion efficiency. Moisture content of biomass varies between species, between trees, within a tree, and during the season. In a live tree, the moisture content increases from stem base to stem top and from branch base to branch top, and is generally highest in foliage. Moisture content of conifers is highest during the dormant season and the moisture of hardwoods is at its highest in the spring just before the leaves appear, then drops below the annual average after bursting into leaf, and rises again in the autumn to the higher winter level (Hakkila, 1989).

On the average, approximately one-half of the total mass of a living tree consists of water. However, moisture content varies widely from species to species, from tree to tree within a species, among tree components within a tree, and from week to week or even day to day depending on season, weather conditions, and storage of biomass. Differences in moisture content between species occur partly due to their differences in the basic density. The moisture content decreases with increasing basic density if the amount of water per unit volume of biomass remains constant (Phillips *et al*., 1976; Hakkila, 1989). The moisture content of Scots pine is significantly higher than that of Norway spruce, partly a result of differences in the basic density of the pine wood. In both species, the moisture content of wood decreases and that of branch bark increases with diameter. Particularly high moisture content in bark is probably because bark is mainly composed of phloem (Hakkila, 1989).

The moisture content of newly-felled trees tends to be too high for efficient combustion and utilization of boiler capacity. Increasing attention is being paid to the moisture content to wood as a cost factor in forest fuels heating plants. In additional to the average moisture content, uniformity of moisture is another crucial quality factor, as irregular variation makes combustion control difficult and results in loss of efficiency (Loo and Koppejan, 2002; Obernberger *et al*., 2006).

1.2.5 CHEMICAL COMPOSITION OF TREE BIOMASS

Tree biomass is composed of three principal elements: carbon (C), oxygen (O) and hydrogen (H). About 50-52 % of the dry mass of wood is carbon, usually more than 40 % oxygen, and 6 % hydrogen. Small and variable amounts of nitrogen (N) and mineral elements or ash are also present in forest biomass (Hakkila, 1989). The fuel value of forest biomass is largely determined by this proportional distribution of elements.

Combination of carbon, oxygen, and hydrogen forms three types of polymers - cellulose, hemicelluloses, and lignin – that are strongly enmeshed and chemically bonded by non-covalent forces and by covalent cross-linkages (Popescu *et al.*, 2010). The carbohydrate portion of biomass comprises cellulose and hemicelluloses which are jointly referred to as holocellulose. Trees also contain smaller amounts of extractives.

Cellulose is a linear polymer of anhydroglucopyranose units linked by ether bonds. Hemicelluloses, as cellulose, are polymers constituted of sugar units. They differ from cellulose by being smaller and branched polymers usually containing more than one sugar type; they are also amorphous polysaccharides. Lignin is a complex, cross-linked, three – dimensional polymer formed with phenypropane units which are of the guaiacyl type. Only hardwood lignin contains additional syringyl units (Bobleter, 1994; Carrier *et al.*, 2011). Cellulose and hemicelluloses have function as structural components in different plant tissues. Also as a structural component in plant cell walls, lignin strengthens wood to make the formation of tree stems possible. A wide variety of compounds are included in extractives. These non-structural compounds serve multiple functions within plants, for instance as defense against insects or other damage (Beall, 1986; Hon and Shiraishi, 2001).

The proportion and composition of chemical constituents varies greatly among tree species. Even greater differences are found among wood, bark, and foliage components of a tree (Sjöström and Álen, 1999). Variation may occur in the chemical composition of biomass from various geographical locations (Hakkila, 1989). The chemical differences between these components directly influence their chemical reactivities. This is why the knowledge of the total amount of each component is crucial to foresee the efficiency of a biomass conversion process (Loppinet-Serani *et al.*, 2008).

Table 1 shows comparison of the chemical composition for softwoods and hardwoods, respectively. Although the cellulose content is more or less the same (43±2 %) for both groups, the hardwoods contain less lignin. The lignin content of hardwoods is usually in the range of 18-25 %, whereas that of softwoods varies between 25 % and 35 %.

Table 1. Chemical composition (in percent of extractive-free wood) of softwoods and hardwoods (Hon and Shiraishi, 2001).

Chemical component	***Scots pine***	***Norway spruce***	***Balsam fir***	***Downy birch***	***Copper beech***	***Quaking aspen***
Cellulose	41	41	42	42	45	48
Hemicelluloses	27	31	27	38	29	27
Lignin	29	27	29	19	22	21
Extractives	3	1	2	1	4	4

Significant abnormalities are found in the chemical composition of branch wood. They result from the occurrence of compression (reaction) wood on the lower side of softwood branches and tension wood on the upper side of hardwood branches (Timell, 1969). As the chemical composition of branch wood is largely a result of the specific properties of reaction wood, so are those of stem tops considerable affected by the presence of juvenile wood, which occurs in a cylindrical column of 5-20 annual rings surrounding the pith (Hakkila, 1989).

The chemical composition of compression wood differs from that of normal wood. Table 2 shows comparison of the average chemical composition of normal and compression wood of many softwoods and hardwoods. Pronounced compression wood contains, on average, 39 % lignin and 30 % cellulose, compared to 30 % and 42 % for normal wood, respectively.

Table 2. Average chemical composition (in percnet of extractive-free wood) of normal and compresion wood of softwoods and hardwoods (Hon and Shiraishi, 2001).

Chemical component	**Softwoods**		**Hardwoods**	
	Normal wood	***Compression wood***	***Normal wood***	***Compression wood***
Cellulose	42	30	44	57
Hemicelluloses	27	30	25	28
Lignin	30	39	30	14
Extractives	1	1	1	1

Thermogravimetric analysis, as analytical method on biomasses, is associated to the simulation of the thermal degradation of samples in order to detect the behaviour of individual components of material under oxidative or inert atmosphere. The thermal decomposition of lingocellulosic materials takes place through a complex series of chemical reactions coupled with heat and mass transfer processes (Grønli, 1996; Reina *et al.*, 1998). Using a thermal analysis may provide more precise and accurate information on wood composition in comparison to traditional wet chemical analysis (Emandi *et al.*, 2011).

Knowing accurately the chemical composition of complex lignocellulosic biomass is getting increasing importance for enabling process commercialization converting biomass into green fuels or valuable.

1.2.6 CALORIFIC VALUE OF TREE BIOMASS

The calorific value (or heating value) of wood is the amount of heat released during the combustion of a specified amount of it and is an important property for assessing the biomass energy resource. For the purpose of the technical specification two different terms apply for the calorific value (CEN-TS 14918:2005).

- *The higher calorific value (gross calorific value)* explicates the total amount of heat released form the fuel during combustion under a constant volume. When determining the higher heating value, all of the combustion products are returned to the pre-combustion temperature. The higher calofiric value is independent of the sample moisture content. This heating value also includes the heat released from the condensed vapour produced from the bound and free water and hydrogen combustion in the wood. The higher calorific value, usually determined using a bomb calorimeter is expressed as the energy units per dry matter units of substances, e.g., MJ/kg (CEN-TS 14918:2005).

- *The lower calorific value (net calorific value/effective calorific value)* is calculated by subtracting the heat of vaporisation of all of the water vapour from the hight calorific value (CEN-TS 14918:2005).

From the practical point of view, in many heating plants, the condensation energy from the water vapour is not utilised; therefore it is often more useful to determine the lower calorific value. The moisture content (MC) (%) and the effective calorific value (W_{ea}) (MJ/kg) of the dry biomass affect the effective heating value of the biomass with a given moisture content (W_{em}) (MJ/kg) according to Equetion (1) (Hakkila and Parikka, 2001):

$$Wem = Wea - 2.45\ x\ \left(MC\ /(100 - MC)\right) \qquad (1)$$

The calorific value not only varies with the moisture content but also with the amounts of different chemical compounds and the lement composition of the fuel. In forest fuels, the dry matter consist of 48-52 % carbon, 6-7 % hydrogen, 38-42 % oxygen and 0.5-5 % ash and nitrogen (Hakkila, 1989). Only carbon and hydrogen contribute to the heating value, whereas oxygen, nitrogen and the inorganinc ash elements do not. Energy is released accroding to the following equations (Equation 2 and 3) (Hakkila and Parikka, 2002):

$$C + O_2 \rightarrow CO_2 + 32.8 \text{ MJ/kg of carbon} \qquad (2)$$
$$2H_2 + O_2 \rightarrow 2H_2O + 142.2 \text{ MJ/kg of hydrogen} \qquad (3)$$

Holocellulose (hemicelluloses, cellulose) and lignin are the main chemical compounds in all tree parts. Compared to other compounds of biomass, cellulose and hemicelluloses are richer in oxygen but poorer in carbon and hydrogen. Consequently, they constain less thermal energy (Hakkila, 1989). The calorific values of cellulose and hemicelluloses are approximately 17-18 MJ/kg and 16-17 MJ/kg, respectively (on a dry mass basis). Lignin has a higher calorific value of 25-26 MJ/kg. In addition, trees also contain extractives, which have clarific values of 33-38 MJ/kg (Kollmann and Cote, 1968). Because the propertions of different chemical compounds vary between trees and parts of the tree, the calorific values also vary. The effective heating values of different parts of the tree are given in Table 3.

Table 3. Effective calorific values (MJ/kg dry weight) at 0 % moisture content of the different parts of tree for some tree species (Nurmi, 1993; Nurmi, 1997).

Tree part	***Scots pine***	***Norway spruce***	***Downy birch***	***Silver birch***	***European aspen***
Stem	19.532	19.163	18.571	18.417	18.430
Branches	19.989	19.300	18.644	18.568	18.812
Stumps	22.362	19.175	18.613	18.500	18.319
Roots	19.324	19.334	18.590	18.503	18.298
Foliage	21.004	19.951	19.360	19.761	19.854
Bark	20.302	20.002	21.033	21.422	19.219

Stem wood from conifer trees has higher heating value than does stemwood from broadleaved trees. Stem wood from Scots pines has the highest calorific value (19.5 MJ/kg) of the tree species presented in Table 3. The stem wood from the broadleaved has a calorific value of approximately 18.5 MJ/kg. The higher calorific value found in conifer trees is due to their somewhat higher lignin and extracvite contents. Nurmi (1993, 1997) also found that the differences in the calorific values between the different parts of tree were greater than the differences between species. For example, the branches have higher calorific value than does the stem wood in most tree species investigated. The bark generally has an even higher calorific value due to the high concentration of extractives and lignin.

In Table 3, a moderate differences in the calorific values between the stem wood from different tree species can be seen. In contrast, there is a large difference in the basic density between the tree species and tree parts, and this difference results in large differences in the heating value per unit volume. Among the common Norwegian species, the Downy birch and oak have high densities, whereas the Norway spruce, European aspen and Goat willow have relatively low densities (Treteknisk, 2003). The Norway spruce branches have considerably higher densities than the stem wood, whereas the bark in general has a lower density compared to the stem wood of the Norway spruce and the Scots pine (Hakkila, 1989). There are also considerable density variations within individual trees, both between different trees in the same stand and between trees form different sites (Skovsgaard *et al*., 2011). Because the variations in wood density are coniderably larger than the variations in the calorific values, the energy content per volume is predominantly related to the density and not to the calorific value. The energy content per unit dry weight of wood varies cosiderably less than does the per volume energy content.

1.2.7 ASH CONTENT OF TREE BIOMASS

Ash is the portion of the biomass that is not combustible and thus remains as a waste product after combustion. Although carbon is mostly oxidised and nitrogen is emitted in the form of gaseous compounds during combustion, most other elements present in the biomass material are retained in the ash (Knapp and Insam, 2011). The ash content of stem wood is approximately 0.5 % per unit of dry matter for all Norwegian tree species, whereas bark has a much higher ash content, approximately 2 %, and needles contain approximately 3-5 % ash (Hakkila and Kalaja, 1983), Table 4.

Table 4. Ash content as the percent dry weight in different parts of the tree of some tree species (Hakkila and Kalaja, 1983).

Tree part	***Scots pine***	***Norway spruce***	***Birch***
Stem wood without bark	0.4	0.6	0.4
Stem bark	2.4	3.2	2.2
Branch wood with bark	1.0	1.9	1.2
Foliage	2.4	5.1	5.5

The ash from wood biomasses consists of several different elements. The most important elements (the major elements) are Ca, K, Si, Al, Mg, Fe, Na, P, Mn and Ti. Other elements, i.e., As, Ni, Cr, Pb, Cu, Co, Mo, V, Cd, B and Ba (minor elements) are present only at low concentrations in the ash (Knapp and Insam, 2011). The ash composition varies considerably depending on factors such as site conditions, tree species and part of the tree.

Ash contains nutrienst than can be used as fertiliser. However, ash may aslo contain heavy metals, which are hazardous to the environment, restricting its potential use as a fertilising product. After combustion, the concentration of heavy metals is higher in the ash separated from the flue gas (fly ash) than the ash left at the bottom of the combusion chamber (bottom ash) (Loo and Koppejan, 2002; Obernberger *et al*., 2006). The ash composition also depends on the combustion technology used in the heating plants.

2 MATERIAL AND METHODS

2.1 Study sites

Samples of Norway spruce trees were selected from the three geographical locations in South Norway, one from west (Vindafjord), one from middle (Seljord) and one from east part (Hobøl), Figure 1. The study material was obtained from trees harvested in the summer period 2011 (July-September), carried out by the Norwegian Forest and Landscape Institute.

The material consisted of 9 stands of Norway spruce (*Picea abies* (L.) Karst.) tree species in South Norway, comprising of 3 stands located in Vindafjord (S1), 3 stands located in Seljord (S2), and 3 stands located in Hobøl (S3) site, Figure 1. The selection of geographical locations was based on the specific site altitudes, latitudes and longitudes. Each geographical location was characterized by three site indexes. Site indexes represented the low, middle and high forest quality. These geographical locations are natural growing forest sites corresponding to sites typical for Norway spruce in Norway (Cajander, 1949).

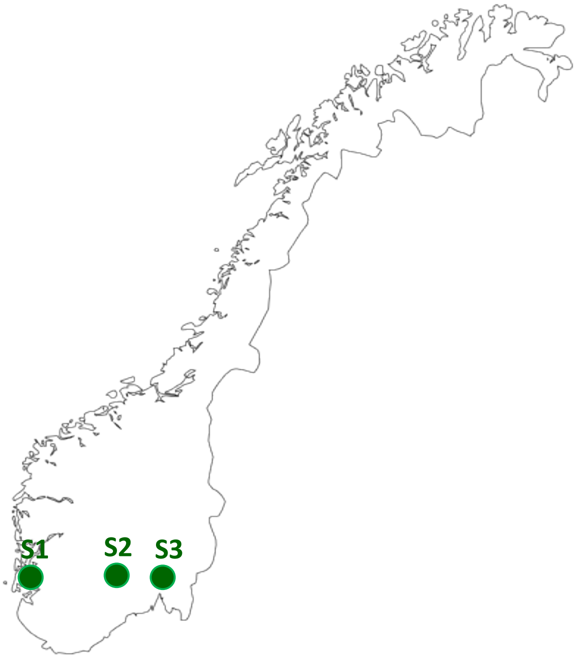

Figure 1. Geographical locations of the collected Norway spruce trees in South Norway (*green dots*).

The site of Norway spruce forest located in the east part of South Norway (S3 Hobøl) illustrates Figure 2, the site located in the middle part (S2 Seljord) presents Figure 3, and the site in the west part of South Norway (S1 Vindafjord) illustrates Figure 4.

Figure 2. Norway spruce forest of the site index 20 located in Hobøl (S3).

Figure 3. Norway spruce forest of the site index 17 located in Seljord (S2).

Figure 4. Norway spruce forest of the site index 17 located in Vindafjord (S1).

2.2 Sampling procedure

After taking into consideration a number of factors (such a site index quality, simplicity and crown level), in order to minimize the sources of errors, sampling was carried out in the same way in all locations. The representative area of each site (radius 12 m) was labelled, and 45 - 50 trees were registered with their diameter at breast height (DBH). Trees were grouped into 5 diameter classes, and one tree was selected for each diameter class. After these trees have been felled their height, DBH and crown ratio were measured. The age was recorded.

Each felled tree was divided into three crown levels (bottom, middle, top), based on the corresponding tree height, Figure 5. The crown base was defined to be the lowest living branch towards to tree top. One branch whirl was selected from the bottom crown level, one from the middle and one branch whirl from the top crown level. From each branch whirl three branches including the needles were randomly cut. The number of branch whirls within each crown level was counted. The diameter of branch was measured as an average in the horizontal direction in bottom, middle and top crown level. The cut branches were weighed fresh in the field.

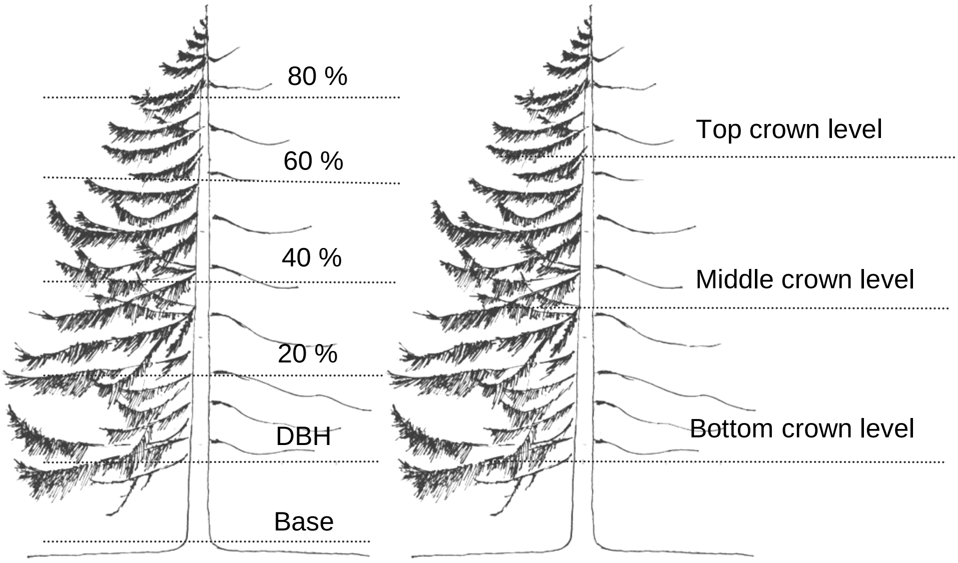

Figure 5. Illustration of the stem level (left) and crown level (right) divisions (Hakkila, 1989).

Cross-sectional discs, 5 cm thick, were cut from each tree in the vertical direction of the stem at given height levels (base, DBH, 20 %, 40 %, 60 %, and 80 %), Figure 6. The stem discs and branches in Hobøl (S3) and Vindafjord (S1) sites were harvested on dry, sunny days in early July 2011 and the study material in Seljord (S2) site was collected on cool, moist, cloudy days in early September 2011. As the samples of stems and branch wood were cut they were placed in sealed plastic bags and kept frozen prior to the measurements in the laboratory.

Figure 6. Cross-sectional discs of Norway spruce.

2.3 Measurements

For the measurements of basic density, moisture content, chemical composition, calorific value and ash content, 5 cm thick wedges were sawn from the sample discs. The wedges were debarked while they were fresh. Branch samples originated from each crown section were cut in 4 segments, one sample being cut at the branch base, in the middle, at the top, and twigs samples including needles, Figure 7. All four branch segments, which were of approximately the same length of 10 cm, were from the same branch, thus all represented the same age range of tissues and were nearly a like anatomically. The wedges were used to define the basic density and moisture content of the wood and bark separately. Collected branches were not debarked, therefore were investigated with their corresponding bark content.

Figure 7. Segments (left) and twigs (right) of the collected Norway spruce branch wood.

2.3.1 BASIC DENSITY

The basic density (ρ_k) of all samples expressed as an oven dry mass of sample divided by its green volume was calculated using the Equation 4:

$$\rho k = \frac{m0}{Vmax} \qquad (4)$$

where:
ρ_k is the basic density, (kg/m^3)
m_0 is the weight of the material at MC = 0 %, (kg)
V_{max} is the maximum volume of material (MC ≥ fibre saturation point), (m^3)

The wood volume determination was made with a modified version of the water displacement method (Olesen, 1971). The samples of stem wood, stem bark, and branch wood separately were first soaked in water for a 48-hour period, Figure 8, and were performed to ensure that the cell lumens were saturated with water and would not soak up water during the ensuing submersion. After placing 10 liters of water in a container, on an electronic balance (1 g) it was tarred. Immersion of a sample just under the water surface was done by hand with a needle, assumed to have negligible volume, attached to the sample. Then samples were dried with filter paper. Dry mass was determined on an electronic balance (1 g) immediately after drying in an oven at 103±2 ˚C to constant weight, which took 1-2 days. Finally the obtained results were processed with standard statistic methods.

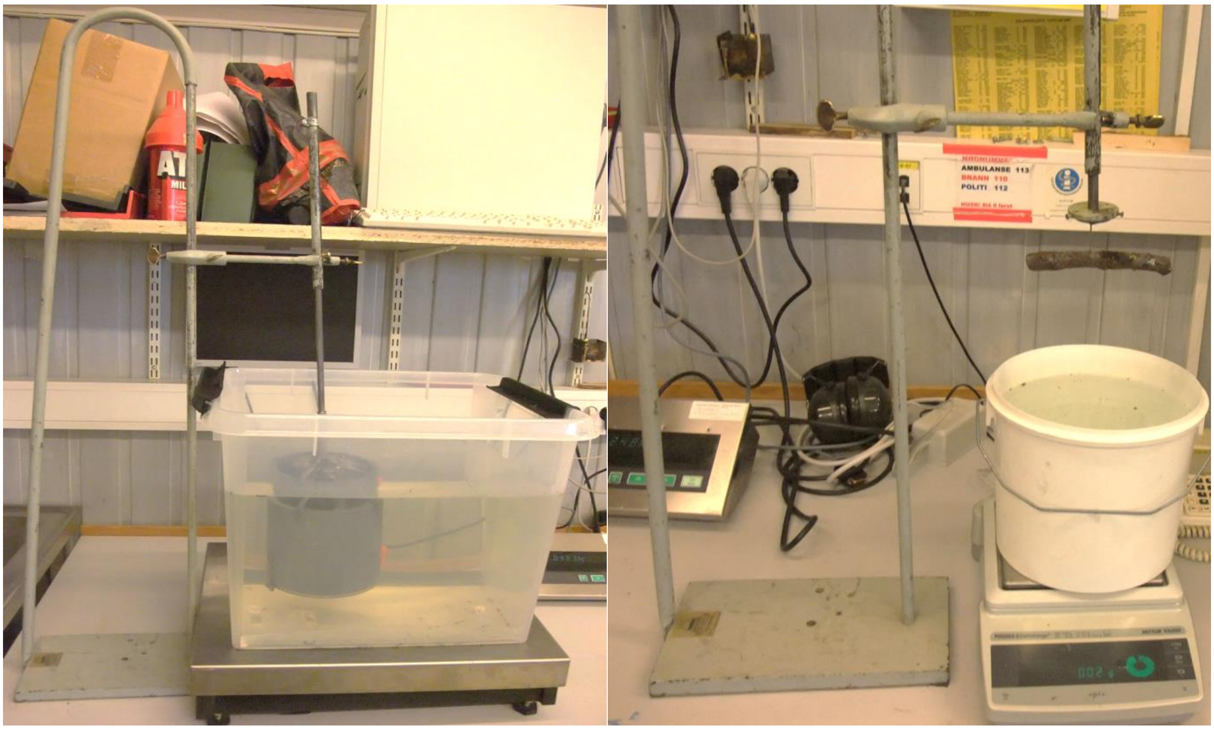

Figure 8. Equipment used for the basic density measurements of the twigs (left) and of the stem wood, stem bark and branch wood (right).

2.3.2 MOISTURE CONTENT

The moisture content M_{ar} in the samples, as received, expressed as a percentage by mass, was calculated according the NS-EN 14774-1:2004 and NS-EN 14961-1:2010 using the Equation 5:

$$Mar = \frac{(m2-m3)+m4}{(m2-m1)} x\ 100 \tag{5}$$

where:
m_1 is the mass of the empty drying container, (g)
m_2 is the mass of the drying container and sample before drying, (g)
m_3 is the mass of the drying container and sample after drying, (g)
m_4 is the mass of the moisture associated with the packing, (g)

The samples of wood, bark and branches separately were dried at a temperature 103±2 °C until constant mass and the percentage moisture was calculated from the loss in mass of the samples, Figure 9.

Figure 9. *Termaks* drying oven used for the moisture content measurements of samples.

2.3.3 BARK PROPORTION AND BARK THICKNESS

Bark was removed from the fresh wood cross-sectional discs using a peeler knife and weighed separately. The thickness of removed bark was measured with a digital caliper *Mitutoyo* 500-181 in five places and the mean thickness was determined. Both wood and bark samples were oven dried until constant weight and then the dry weight was determined. Bark proportion in each sectional disc was calculated as percentage of the total weight of the cylinder for fresh and dry weight. A non-linear regression model was used to study the relationship between the bark percentage and tree height.

2.3.4 CHEMICAL COMPOSITION

The integrated method for assessing chemical compounds within separate tree components (extractives, holocellulose, and lignin) was investigated by simultaneous thermal analysis (STA). In a pre-trial, ground (1.0 mm mesh) stem wood, stem bark and branch samples of Norway spruce were analyzed. Thermogravimetric runs were performed on a Netzsch STA 449 F1 Jupiter simultaneous thermal analyzer coupled to the FT-IR and GC-MS, Figure 10, using an amount of sample of 10 mg. Pyrolysis and combustion runs were carried out under oxidative atmosphere of nitrogen and synthetic air (N_2/O_2 80:20 vol. %) and involved heating from 36 °C to 700 °C at a rate of 5 °C/min, respectively.

Baseline data were obtained by the experimental runs with empty crucibles, and the measured values were subtracted from the values obtained with crucibles containing samples. Each sample was placed into separate Al_2O_3 crucibles without lid and was put into the silicon carbide furnace sample holder. After each single measurement of sample the furnace was cooled down to ambient temperature in order to get ready for the next run. Repeatability of this measurement was confirmed under the same experimental conditions using the same empty crucible.

Figure 10. Simultaneous Thermal Analyzer (STA) device coupled to the Gas Chromatograph Mass Spectrometer (GC-MS) and to the Fourier Transform Infrared Spectrometer (FT-IR) used for the measurements of chemical composition of samples.

2.3.5 CALORIFIC VALUE

The gross calorific value of a solid biofuels at constant volume and at the reference temperature 25 °C in a bomb calorimeter by combustion of certified benzoic acid was determined according the CEN-TS 14918:2005; NS-EN 14961-1:2010.

The samples used for the determination of calorific value were grounded to pass a test sieve with an aperture of 1.0 mm particle size. Due to the low density of solid biofuels they were tested in a pellet form. A pellet of mass 0.7 g was pressed with a suitable force to produce a compact, unbreakable test piece. Produced pellet samples were burned in high-pressure oxygen atmosphere in a bomb calorimeter. The effective heat capacity of the calorimeter was determined in calibration experiments by combustion of certified benzoic acid under similar condition. Water was added to the bomb initially to give a saturated vapour phase prior to the combustion, thereby allowing all the water formed, from the hydrogen and moisture in the sample, to be regarded as liquid water.

The results obtained from the calorimeter, Figure 11, were the gross (higher) calorific value of the analysis samples at constant volume with all the water of the combustion products as liquid water. In practice, biofuels are burned at constant (atmospheric) pressure and the water is either not condensed (removed as vapour with the flue gases) or condensed. Under both conditions, the operative heat of combustion to be used is the net calorific value of the fuel at constant pressure.

The gross calorific value was calculated from the corrected temperature rise and the effective heat capacity of the calorimeter, with allowances made for contributions from ignition energy, combustion of the fuse and for thermal effects from side reactions such as the formation of nitric acid.

The net calorific value at constant volume of samples was obtained by calculation from the gross calorific value at constant volume determined on the analysis sample according the equations stated in CEN-TS 14918:2005. The results were reported as the mean of duplicate determination to the nearest 0.1 %.

Figure 11. Automatic Isoperibol Calorimeter 6300 (left) and its oxygen combustion bomb (right) used for the calorific value measurements.

2.3.6 ASH CONTENT

The ash content was determined by a calculation from the mass of inorganic residue remaining after that samples were heated in air under rigidly controlled conditions of time, heating routine, sample weight (1 g, 1 mm particle size) and equipment specifications to a controlled temperature of 550±10 °C (CEN-TS 14775:2004; NS-EN 14961-1:2010), Figure 12.

The ash content on dry basis, A_d, of samples expressed as a percentage by mass on a dry basis was calculated using the Equation 6:

$$Ad = \frac{(m3-m1)}{(m2-m1)}\ x\ 100\ x\ \frac{100}{100-Mad} \tag{6}$$

where:
m_1 is the mass of empty dish, (g)
m_2 is the mass of the dish plus the test sample, (g)
m_3 is the mass of the dish plus ash, (g)
M_{ad} is the % moisture content of the test sample used for determination

The results were reported as the mean of duplicate determination to the nearest 0.1 %.

Figure 12. Porcelain crucibles filled with grinned samples of stem wood, stem bark, branch wood and twigs used for the ash content measurements.

2.3.7 STATISTICAL ANALYSIS

Both ANOVA and non-linear regressions were performed using JMP version 9.0 software. One-way ANOVA was used to test whether or not there were differences in qualitative properties of Norway spruce biomass vertically in sectional discs and in branches axially towards top crown. Subsequently, differences of investigated properties within geographical locations of sites in South Norway were compared using the same procedure. The results were carried out using the F-test to verify the significant variation to the level of 95 %. In addition Microsoft excel 2003 was used for statistical measurements.

3 RESULTS AND DISCUSSION

The most important part of this research was to investigate the differences in qualitative properties of Norway spruce biomass (stem wood, stem bark, branch wood, twigs and tree tops) originated from three geographical sites in South Norway. It was expected that if significant differences in properties could be observed, it should be possible to link these differences to the origin of the geographical location. The following chapters provide the most important discoveries about the bark proportion and bark thickness, basic density, moisture content, chemical composition, calorific value and ash content in Norway spruce biomass.

3.1 Forest sites characteristics

The total overview about the characteristics of sampled trees is given in Table 5. A striking feature in the material is the high age of the trees in Hobøl sites, more than one hundred years on an average. This was partly because only trees marked for cutting were taken and due to the over-aged trees in this location.

Table 5. Site characteristics of the collected trees of Norway spruce.

Site	Site index H_{40}[a] (m)	Latitude	Longitude	Elevation a.s.l.[b] (m)	No. trees[c]	Height (m)	DBH[d] (cm)	Age	Crown ratio[e] (%)
S3 Hobøl	23	59°43’N	10°52’E	101.9	5	29	30	145	43
S3 Hobøl	20	59°43’N	10°52’E	101.9	5	26	24	134	50
S3 Hobøl	14	59°43’N	10°52’E	101.9	5	18	20	106	61
S2 Seljord	17	59°56’N	08°63’E	761.6	5	16	26	115	79
S2 Seljord	13	59°56’N	08°63’E	761.6	5	16	23	98	86
S2 Seljord	11	59°56’N	08°63’E	761.6	5	14	21	111	92
S1 Vindafjord	23	59°81’N	05°49’E	130.5	5	22	25	78	58
S1 Vindafjord	17	59°81’N	05°49’E	130.5	5	19	23	72	65
S1 Vindafjord	11	59°81’N	05°49’E	130.5	5	16	18	74	64

[a] Dominant height at the age of 40 years
[b] Above sea level
[c] Number of felled trees
[d] Diameter of tree at breast height (1.3 m)
[e] Calculated as the crown length (m) of tree divided by its height (m)

The crown ratio indicates the height of the living crown in percent of the total tree height. The average crown ratio of sampled trees did vary, Table 5. For trees sampled from the Seljord (S2) site, the site with considerable higher elevation than two other sites (S1, S3), was measured the highest crown ratio. Contrary, site S2 with the poorest site index 11 showed to have the highest crown ratio of 92 %. The variation in crown ratio is caused fundamentally by genetic factors and stand density in the different developmental stages of the tree (Hakkila, 1971). It can therefore be explained only fairly inadequately by means of the external tree characteristics. For instance, tree height is not correlated with crown ratio. On the other hand, the height of the lower limit of the living crown from the ground may explain two-thirds of the variation.

The distribution of the breast height diameter (DBH) of sampled trees reports Figure 13 for the Hobøl site (S3), Figure 14 for the Seljord site (S2) and Figure 15 for the Vindafjord site (S1), respectively.

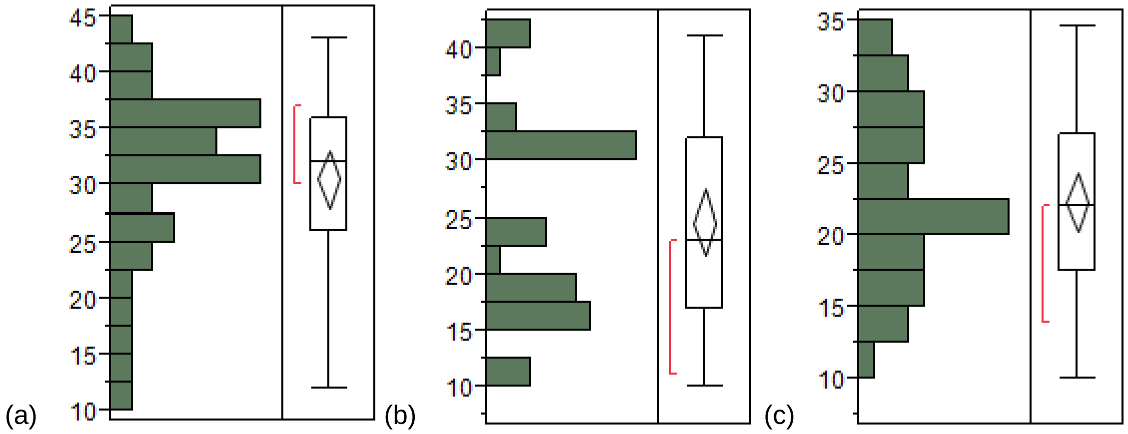

Figure 13. Distribution of Norway spruce DBH (cm) in Hobøl location for site index 23 (a), site index 20 (b), site index 14 (c), (n=45).

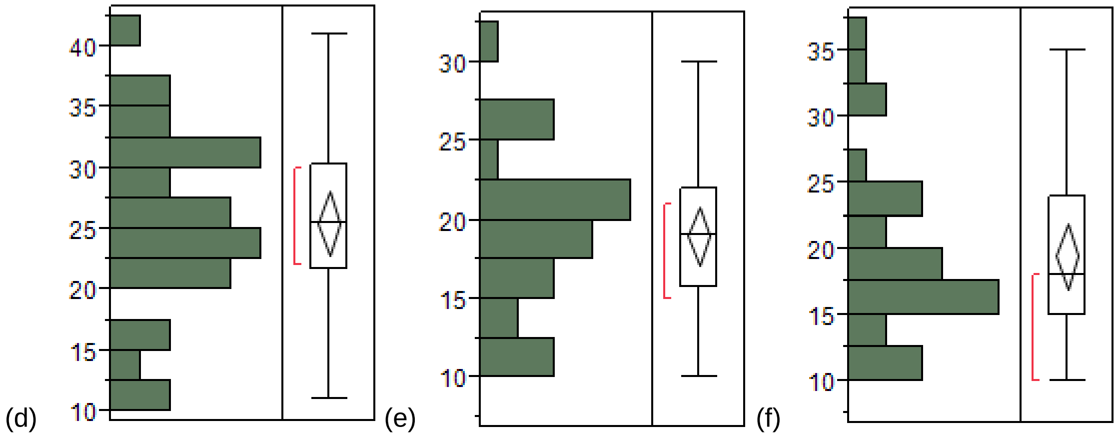

Figure 14. Distribution of Norway spruce DBH (cm) in Seljord location for site index 17 (d), site index 13 (e), site index 11 (f), (n=45).

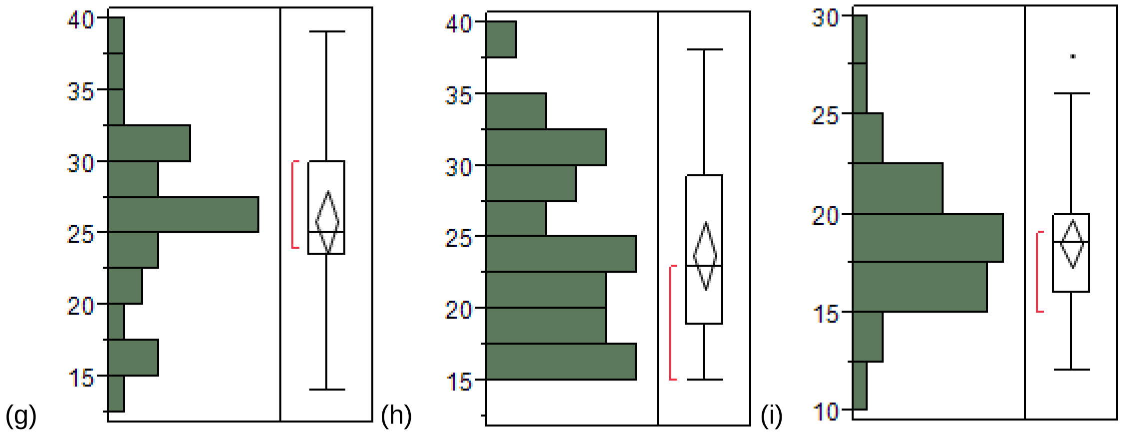

Figure 15. Distribution of Norway spruce DBH (cm) in Vindafjord location for site index 23 (g), site index 17 (h), site index 11 (i), (n=45).

3.2 Bark proportion and bark thickness

For many years, bark had been an unwated byproduct of milling operations, since its disposal, typically through burying or combustion, often incrases the cost of operations (Haygreen and Bowyer, 1996). Bark has been used for centuries, on a small scale, for medicinal purposes, food, baskets, boats, and tannins (Small, 1884). The most basic use of bark is to produce energy and/or heat through combustion. Bark can also be used as a landscape material (Haygreen and Bowyer, 1996).

Bark proportion

Bark proportion has direct impact on the quality of biofuel. Besides the effect of moiture content on the calorific value of fuel, high bark content increases the emissions of pollutants during the combustion process. With age, tree size increases and the proportion of bark decrease (Nygård and Elfving, 2000; Guidi *et al.*, 2008). Furthermore, the existences of substantial differences in bark proportion in percentage for diverse DBH stems indicate the possibility to manage Norway spruce plantation in order to obtain a better quality of biomass. DBHs lower than 4 cm wide may be considered a threshold under which it is not convenient, from a qualitative point of view, to descend (Guidi *et al.*, 2008). Therefore, large DBH sized stems are preferred in order to match the requirements of high quality of feedstock biomass for energy purposes. Differences in bark proportion and bark thickness of Norway spruce stem bark originated from three geographical sites in South Norway within corresponding site indexes are presented in Table 6.

Table 6. Average values and standard deviation of bark proportion and bark thickness of Norway spruce stem bark.

Geographical location	**Site index**	**Bark proportion* (%)**						**Bark thickness (mm)**					
		Tree height (%)						**Tree height (%)**					
		Base	**DBH**	**20**	**40**	**60**	**80**	**Base**	**DBH**	**20**	**40**	**60**	**80**
S1 Vindafjord	23	7.3 (0.49)	9.9 (0.46)	5.6 (0.46)	8.0 (0.46)	10.7 (0.45)	9.4 (0.49)	7.2 (0.25)	5.1 (0.24)	5.4 (0.20)	4.1 (0.20)	4.7 (0.24)	3.1 (0.26)
S1 Vindafjord	17	7.7 (0.48)	5.6 (0.49)	5.9 (0.49)	7.0 (0.46)	8.9 (0.48)	10.0 (0.49)	7.2 (0.24)	5.6 (0.25)	5.0 (0.21)	3.4 (0.25)	3.8 (0,20)	2.4 (0.25)
S1 Vindafjord	11	6.2 (0.49)	6.2 (0.46)	6.4 (0.46)	6.6 (0.49)	9.4 (0.48)	7.5 (0.47)	5.9 (0.24)	5.3 (0.20)	4.5 (0.25)	4.1 (0.25)	4.1 (0.20)	2.9 (0.22)
S2 Seljord	17	15.0 (0.46)	13.2 (0.48)	16.3 (0.48)	15.9 (0.48)	22.0 (0.45)	18.9 (0.48)	13.3 (0.20)	8.0 (0.21)	7.6 (0.25)	6.4 (0.26)	5.3 (0.21)	4.2 (0.22)
S2 Seljord	13	13.9 (0.45)	12.6 (0.47)	14.3 (0.46)	16.7 (0.48)	17.7 (0.49)	22.9 (0.48)	12.1 (0.25)	7.3 (0.24)	6.8 (0.24)	6.9 (0.25)	5.4 (0.22)	3.9 (0.20)
S2 Seljord	11	9.8 (0.46)	10.1 (0.46)	8.3 (0.48)	10.7 (0.46)	15.8 (0.45)	18.1 (0.48)	8.8 (0.26)	5.1 (0.24)	4.4 (0.25)	3.8 (0.24)	4.0 (0.24)	3.4 (0.21)
S3 Hobøl	23	11.0 (0.49)	7.0 (0.48)	7,9 (0,49)	6.4 (0.46)	6.5 (0.49)	11.4 (0.48)	7.1 (0.25)	5.6 (0.20)	5.8 (0.24)	5.3 (0.25)	3.7 (0.26)	3.3 (0.24)
S3 Hobøl	20	11.6 (0.46)	7.6 (0.49)	7.8 (0.46)	10,7 (0.47)	9.9 (0.46)	13.4 (0.49)	6.7 (0.25)	4.7 (0.24)	4.6 (0.26)	4.1 (0.25)	3.2 (0.23)	2.6 (0.25)
S3 Hobøl	14	10.7 (0.49)	11.0 (0.48)	7.1 (0.45)	6.1 (0.49)	8.7 (0.46)	11.2 (0.48)	8.5 (0.25)	6.5 (0.20)	5.3 (0.21)	4.5 (0.20)	4.1 (0.23)	3.5 (0.24)

*Calculated as percentage of the total weight of the disc cylinder for fresh and dry weight.

The vertical dependence of bark proportion was observed. The pattern was similar for all site indexes, higher bark content in the lower part of stem, decreasing approximately to 35 % of the tree height and slightly increasing towards the tree top. The bark proportion of trees did not vary significantly when the site index as an independent variable was added in the model, but did vary vertically at significant level $p<0.0001$*. The variations of bark content are the combined effect of the differing rates of axial variation of bark thickness and wood diameter. Guidi *et al*. (2008) found that as diameter of wood increases total bark amount of stem also increases.

Bark thickness

The vertical dependence of bark thickness of Norway spruce trees showed a decreasing trend towards the top. Bark was significantly thicker at level p<0.005* near the base than near the top, Table 6. Tree-to-tree variations of bark thickness in relation to site index showed insignificant difference at level p>0.05. The bark thickness did vary vertically at significant level p<0.0005*.

Dependencies of bark proportion and bark thickness of Norway spruce trees were well pronounced when the geographical location was added as a variable in the model, at statistically significant level p<0.0001* for bark proportion and at level p<0.005* for bark thickness, respectively. Figure 16 illustrates these variations. Bark samples collected from trees originated from Seljord site (S2) showed the highest bark percentage and thickness among all investigated geographical sites. This observation may be due to grown condition of this site within its considerably high elevation (see chapter 3.1, Table 1).

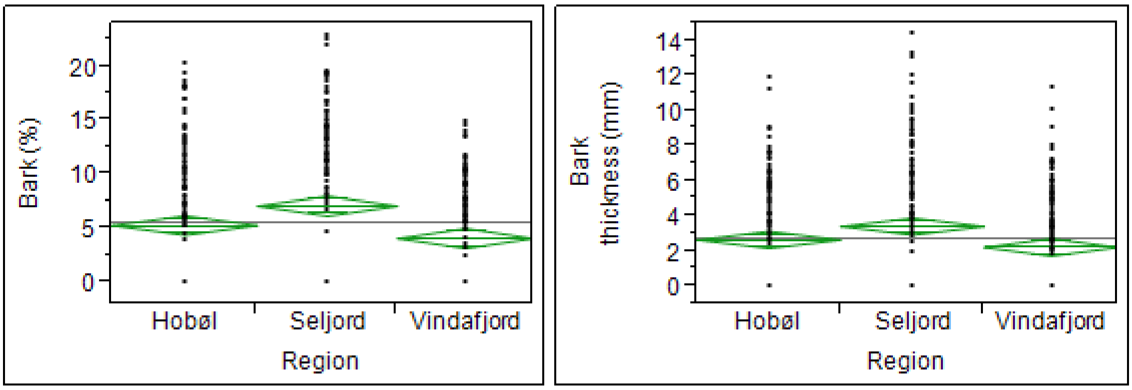

Figure 16. Differences in mean values of bark proportion (left) and bark thickness (right) in relation to the geographical location.

We can conclude that properties such as bark proportion and bark thickness of trees were highly linear to the tree height. Bark proportion may be a relevant aspect for the utilization of Norway spruce raw material as a potential biomass feedstock.

3.3 Basic density

Information on wood basic density variation is a key factor for investigating fuel-wood quality. Next two chapters provide deeper insides about the basic density axial variations in stem wood, stem bark and branch wood of Norway spruce.

3.3.1 BASIC DENSITY OF STEM WOOD AND STEM BARK

The basic density vertical variations were found within specific patterns for the stem wood and stem bark. The results obtained for the vertical dependence of Norway spruce stem wood and stem bark basic density are presented in Table 7.

Table 7. Average values of basic density (kg/m^3) and standard deviations of Norway spruce stem wood and stem bark along the tree trunk towards the top.

Site	Site index	Stem wood						Stem bark					
		Tree height (%)						Tree height (%)					
		Base	**BH**	**20**	**40**	**60**	**80**	**Base**	**BH**	**20**	**40**	**60**	**80**
S3 Hobøl	23	502.3 (61.0)	505.7 (47.3)	482.7 (43.5)	460.1 (35.3)	469.1 (31.3)	523.5 (40.8)	487.7 (31.7)	480.1 (6.5)	466.4 (31.8)	469.7 (67.7)	443.5 (82.4)	421.1 (89.4)
S3 Hobøl	20	480.0 (58.4)	537.0 (34.3)	464.8 (70.5)	451.6 (39.9)	465.7 (31.0)	472.9 (67.0)	460.3 (49.6)	392.5 (55.4)	397.3 (14.3)	391.1 (10.1)	335.2 (48.1)	432.1 (56.0)
S3 Hobøl	14	392.1 (42.1)	417.5 (17.0)	408.6 (32.4)	410.4 (44.3)	418.0 (38.8)	444.0 (52.1)	446.3 (47.0)	393.3 (31.9)	378.3 (12.0)	379.6 (15.2)	409.1 (32.5)	407.6 (21.2)
S2 Seljord	17	429.5 (26.7)	426.2 (38.2)	391.2 (20.8)	389.3 (17.7)	421.7 (22.0)	441.1 (11.8)	582.0 (69.7)	581.6 (77.9)	437.4 (74.6)	366.5 (29.6)	440.8 (67.4)	550.4 (60.8)
S2 Seljord	13	400.6 (11.0)	403.2 (34.2)	359.6 (38.3)	375.6 (11.5)	388.9 (14.5)	417.3 (12.7)	457.3 (42.1)	387.6 (39.1)	343.1 (28.9)	364.1 (19.4)	362.8 (68.0)	394.3 (94.3)
S2 Seljord	11	429.7 (35.1)	418.8 (25.0)	402.5 (9.8)	420.2 (53.9)	405.3 (10.7)	422.7 (5.9)	484.1 (68.1)	382.3 (28.3)	383.8 (40.9)	387.1 (25.4)	419.8 (79.8)	440.4 (84.4)
S1 Vindafjord	23	417.1 (36.0)	442.2 (29.4)	454.1 (34.4)	426.6 (54.3)	459.4 (57.8)	433.5 (72.8)	486.7 (79.7)	414.6 (22.2)	379.7 (47.0)	406.4 (32.6)	363.2 (44.1)	338.0 (23.6)
S1 Vindafjord	17	382.5 (26.4)	390.3 (52.2)	406.3 (29.7)	383.6 (59.8)	402.2 (70.9)	359.2 (20.7)	339.9 (77.1)	254.1 (73.4)	327.6 (67.5)	371.7 (72.2)	310.8 (74.5)	273.2 (77.6)
S1 Vindafjord	11	454.6 (38.5)	425.3 (34.0)	425.5 (21.4)	422.7 (35.6)	403.1 (25.2)	395.5 (29.4)	420.6 (22.2)	342.6 (24.2)	333.6 (10.1)	324.1 (15.4)	342.1 (40.3)	352.2 (50.8)

Basic density of the stem wood was in range 382.8-523.5 kg/m^3 and of the stem bark 273.2-582.0 kg/m^3, respectively. The basic density of stem wood was higher in the lower part of stem, vertically decreasing to approximately 20 % height and then slightly increasing again towards the top, which was agreement with the earlier findings for Norway spruce tree species (Hakkila, 1979; Molteberg and Høibø, 2006; Repola, 2006; Jyske *et al.,* 2008). Lower basic density in stem wood on the tree tops can be partly explained by the presence of juvenile wood. Juvenile wood is characterized by wide growth rings and low proportion of latewood what naturally lowers basic density of raw material (Hakkila, 1989).

An axial dependence of basic density for stem bark was different than the one for stem wood, more regular, decreasing towards the top. Our results proofed lower basic density for stem bark than for stem wood, which confirms previous finding (Fearnside, 1997). The vertical density gradient of stem bark in the base was roughly 5-10 % steeper to that in tree top. Same vertical dependence for Norway spruce trees and other conifers has also been found (Dibdiakova and Vadla, 2012).

Differences in average values of the basic density of examined samples were well pronounced when the geographical location variable was added to the statistical model, at significant level $p<0.0001$* for stem wood and at level $p<0.0001$* for stem bark, respectively. Figure 17 illustrate correspondent variations of basic density for stem wood and stem bark of Norway spruce trees collected from the three sites in South Norway.

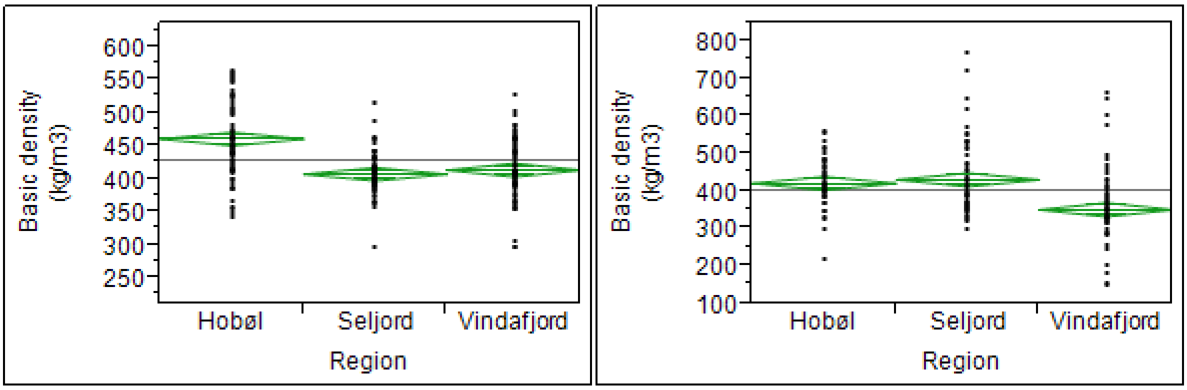

Figure 17. Differences in mean values of basic density for stem wood (left) and stem bark (right) in relation to the geographical location.

For more detailed investigation of axial variations of basic density the site index and tree height variables were taken into account. Table 8 presents the p value of arithmetic mean differences of basic density of Norway spruce stem wood and stem bark in relation to the site index and tree height.

Table 8. p value of arithmetic means differences of basic density for stem wood and stem bark in relation to the site index and tree height.

Geographical location	**Stem wood**		**Stem bark**	
	Site index	**Tree height**	**Site index**	**Tree height**
S1 Vindafjord	p=0.1323	p=0.2078	p=0.1174	p=0.0677
S2 Seljord	p=0.0005*	p=0.4107	p=0.0005*	p=0.4107
S3 Hobøl	p<0.0001*	p=0.1386	p<0.0001*	p=0.1386

Data presented in Table 8 clearly proof that the vertical basic density of stem wood and stem bark did not differ significantly (at level p>0.05) when the tree height was added as a variable in our model. Contrary, the site index variable affected basic density of both raw materials (stem wood and stem bark) significantly at level p<0.0005* for Seljord site (S2) and at level p<0.0001* for Hobøl site (S3). Table 8 shows this variation indicating that the higher site index the higher basic density of stem wood, as well as of stem bark.

In our study the density estimates were based on knot-free stem discs. The wood density in knots and also around them is higher than in knot-free wood. Hakkila (1979) presented a knot correction of +1 % for the dry weight of spruce, pine and birch. This also means that a correction of similar magnitude should be applied to the average wood density in order to obtain realistic values.

3.3.2 BASIC DENSITY OF BRANCH WOOD

Branches possess a high content of reaction wood which is characterized by thick cell walls and narrow lumina (Hakkila, 1989). Compression wood contains less cellulose and more lignin than doe’s normal wood (see chapter 1.2.5). As a consequence of these facts reaction wood is denser than normal wood. This fact should be taken into account in order to understand higher basic density in branch wood compare to stem wood, respectively. The average values of basic density of Norway spruce branch wood are listed in Table 9.

Table 9. Average values of basic density (kg/m^3) and standard deviations of Norway spruce branch wood along the crown and along the branch.

Geographical location	Site index	Bottom crown				Middle crown				Top crown			
		Branch part				Branch part				Branch part			
		Base	Middle	Top	Twigs	Base	Middle	Top	Twigs	Base	Middle	Top	Twigs
S3 Hobøl	23	630.8 (73.3)	495.5 (79.0)	463.3 (68.2)	463.3 (97.1)	461.3 (72.0)	444.2 (92.5)	392.8 (75.2)	328.4 (73.1)	466.9 (93.3)	367.3 (76.8)	295.9 (85.4)	243.5 (75.1)
S3 Hobøl	20	639.8 (47.2)	518.7 (17.1)	527.2 (33.0)	440.6 (12.0)	464.8 (73.0)	426.9 (72.1)	409.4 (90.3)	302.9 (89.9)	485.1 (94.0)	420.9 (88.5)	332.9 (89.0)	331.5 (98.5)
S3 Hobøl	14	577.6 (40.4)	476.2 (83.8)	505.1 (48.2)	400.1 (59.4)	455.0 (90.0)	497.1 (60.9)	464.3 (79.8)	346.4 (74.5)	520.9 (83.0)	466.7 (67.2)	355.2 (78.5)	284.3 (62.9)
S2 Seljord	17	517.7 (23.2)	471.7 (27.9)	434.0 (48.7)	326.7 (28.2)	428.7 (73.3)	388.9 (70.3)	366.6 (72.5)	340.9 (99.3)	407.0 (76.6)	390.6 (70.1)	332.2 (74.6)	308.7 (91.7)
S2 Seljord	13	532.0 (48.5)	506.0 (13.1)	443.1 (46.7)	368.3 (30.6)	461.6 (60.1)	413.8 (71.5)	345.0 (76.3)	299.7 (75.1)	482.1 (27.0)	513.1 (60.0)	412.5 (36.3)	340.7 (75.4)
S2 Seljord	11	511.4 (72.4)	458.8 (74.0)	434.0 (98.6)	361.9 (65.2)	515.6 (28.5)	495.6 (37.0)	453.2 (16.2)	314.4 (63.5)	459.2 (70.4)	437.2 (53.0)	370.9 (55.2)	289.0 (74.5)
S1 Vindafjord	23	673.0 (99.0)	512.5 (49.7)	509.5 (58.8)	373.3 (37.5)	604.3 (50.9)	515.5 (36.9)	456.3 (23.2)	412.5 (21.7)	509.5 (45.1)	450.4 (30.1)	431.6 (23.2)	387.5 (33.7)
S1 Vindafjord	17	641.9 (69.8)	516.9 (19.8)	513.8 (22.3)	344.6 (79.6)	597.1 (25.7)	515.2 (37.1)	484.7 (91.3)	381.8 (66.6)	496.9 (16.4)	447.0 (36.4)	402.9 (21.0)	343.4 (41.9)
S1 Vindafjord	11	586.3 (39.7)	520.6 (12.9)	453.9 (17.8)	408.8 (44.7)	582.9 (40.3)	488.1 (35.2)	480.0 (15.6)	382.2 (51.0)	475.6 (54.2)	431.5 (14.3)	423.0 (14.4)	368.5 (41.8)

Basic density of branch wood was in range 243.5-673.0 kg/m^3, respectively. In average, presented data show a vertically decreasing trend of basic density in branch wood along the crown. Norway spruce branch wood exanimated in this study was denser in the bottom part crown towards less denser branches positioned in the top crown section. More else a clear variation pattern was apparent in basic density variations along the branch. Density declined from the branch base outward first rapidly and then leveled. The highest basic density was found for the branch base, in the part that is embedded in the stem by the natural growth of the tree, i.e., in knots (Hakkila, 1989). The differences in branch wood density are result not only of the presence of compression wood but to a great extent also of a corresponding branch part diameter. Results illustrated in Figure 18 clearly indicate that the higher branch diameter the higher basic density.

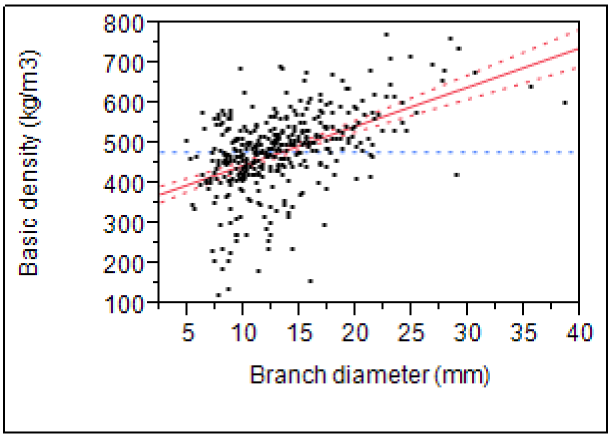

Figure 18. Relationship between branch wood diameter and basic density at statistically significant level p<0.0001*.

Figure 19 illustrates statistical variations of basic density for the branch wood collected from the three sites in South Norway. Differences at significant level p<0.0001* were found for basic density of branch wood in relation to the geographical location.

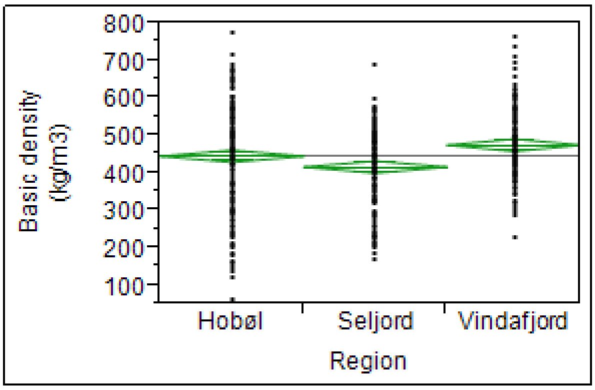

Figure 19. Differences in mean values of basic density of branch wood in relation to the geographical location.

For more precise description of longitudinal variation of basic density in branch wood the site index, crown level and branch part were taken into account. Table 10 shows the p value of arithmetic means differences of basic density for Norway spruce branch wood in relation to the site index, crown level and branch part.

Table 10. p value of arithmetic means differences of basic density for Norway spruce branch wood in relation to the site index, crown level and branch part.

Geographical location	Site index	Crown level	Branch part
S1 Vindafjord	p=0.0796	p<0.0001*	p<0.0001*
S2 Seljord	p=0.0512	p<0.0001*	p<0.0001*
S3 Hobøl	p=0.0631	p<0.0001*	p<0.0001*

Branch wood basic density dependence of site index did not differ significantly (at level p>0.05). On the other hand we found that the basic density varied significantly at level p<0.0001* vertically along the crown and at level p<0.0001* along the branch. Both variations were strongly pronounced in all three geographical locations.

Basic density results obtained for the axial dependence, especially in the upper part of the stem, may be due to how far up the stem the last samples of wood, bark and branches were taken. In general, there is a variability of basic density among individuals of a given species, among geographical locations, with age and along stems (Wieman, 1989; Fearnside, 1997). We found that basic density of stem wood, stem bark and branch wood of Norway spruce trees did vary significantly among three geographical locations investigated in this study, and with position of branch along the crown and along the branch itself. It can be concluded that in average the highest basic density was measured for branch wood, then for stem wood and the lowest one for stem bark.

3.4 Moisture content

3.4.1 MOISTURE CONTENT OF STEM WOOD AND STEM BARK

At a given stem height the proportion of live tissues and sapwood in a tree biomass increases along tree trunk towards tree top, resulting in an increasing moisture content of wood and bark (Hakkila, 1989). The vertical dependence of moisture content of investigated stem wood and stem bark harvested during the summer season is given in Table 11.

Table 11. Average values of moisture content (%) and standard deviations of Norway spruce stem wood and stem bark collected during the summer season along the tree trunk from the base to the tree top.

Site	**Site index**	**Stem wood**						**Stem bark**					
		Tree height (%)						**Tree height (%)**					
		Base	**BH**	**20**	**40**	**60**	**80**	**Base**	**BH**	**20**	**40**	**60**	**80**
S3 Hobøl	23	36.0 (6.9)	37.2 (6.5)	37.2 (7.1)	39.4 (4.0)	44.0 (8.6)	46.1 (4.7)	37.6 (6.2)	42.1 (6.8)	43.2 (12.3)	47.4 (11.7)	46.4 (13.6)	48.4 (7.6)
S3 Hobøl	20	38.3 (5.1)	30.6 (5.3)	40.6 (8.1)	39.4 (1.9)	42.3 (2.6)	48.1 (2.1)	44.9 (3.9)	53.9 (7.4)	54.8 (0.5)	54.5 (2.9)	64.2 (12.0)	58.0 (1.4)
S3 Hobøl	14	45.5 (6.3)	41.3 (4.4)	41.0 (3.4)	41.6 (3.1)	47.6 (3.6)	49.5 (5.4)	45.6 (4.8)	53.4 (5.7)	56.5 (2.9)	56.7 (2.4)	55.9 (2.6)	56.8 (2.3)
S2 Seljord	17	47.3 (5.0)	44.7 (4.0)	46.6 (4.9)	47.3 (3.7)	45.7 (4.5)	45.7 (6.0)	44.5 (7.9)	49.3 (1.7)	51.4 (2.3)	52.9 (3.5)	49.9 (2.4)	51.8 (2.8)
S2 Seljord	13	51.1 (1.3)	46.8 (4.7)	50.2 (5.7)	49.6 (4.8)	52.0 (2.8)	51.7 (4.6)	44.3 (7.7)	54.0 (6.0)	57.5 (4.3)	57.2 (4.9)	59.6 (7.1)	57.2 (5.8)
S2 Seljord	11	44.1 (3.2)	40.4 (3.0)	41.1 (3.8)	43.2 (3.0)	46.7 (3.7)	52.3 (1.1)	45.6 (1.9)	53.1 (4.5)	55.5 (4.7)	55.6 (3.3)	55.0 (7.1)	56.4 (2.9)
S1 Vindafjord	23	44.2 (5.8)	41.2 (6.9)	43.9 (5.1)	46.8 (8.9)	47.6 (4.9)	48.2 (6.6)	49.5 (5.0)	56.5 (5.5)	61.1 (1.3)	58.5 (5.6)	60.4 (1.9)	60.4 (1.8)
S1 Vindafjord	17	44.1 (10.8)	42.4 (8.0)	43.0 (6.8)	45.0 (10.5)	45.5 (11.6)	47.1 (11.1)	48.6 (4.2)	61.5 (3.4)	61.4 (3.5)	60.0 (5.9)	60.7 (5.0)	62.4 (3.7)
S1 Vindafjord	11	42.4 (4.7)	45.7 (2.9)	44.3 (2.1)	47.0 (4.3)	47.5 (2.7)	47.2 (2.7)	50.4 (3.4)	62.3 (2.1)	62.9 (1.9)	63.0 (3.2)	62.3 (4.5)	58.3 (5.7)

Moisture content of stem wood was in range 36.0-52.3 % and of stem bark 37.6-62.4 %, respectively. The vertical dependence of moisture content for stem wood was similar to that for stem bark. The moisture content in both tissues increased axially from the base upwards the top. Results obtained for the vertical variation in the lower part of the stem were significantly more pronounced (at level $p<0.005$*) to that in the top. We measured the higher moisture content for stem bark than for stem wood, which was confirmation with the earlier studies (Adler *et al*., 2005; Dibdiakova and Vadla, 2012). Hakkila (1989) reported that particularly higher moisture content in bark is probably because bark is mainly composed of phloem.

The moisture content of Norway spruce samples did differ when the geographical location was added as a variable in our models, at significant level $p<0.0001$* for the stem wood and at $p<0.0001$* for the stem bark, respectively. Figure 20 illustrate the geographical variations of moisture content for stem wood and stem bark collected from the three sites in South Norway during the summer season 2011.

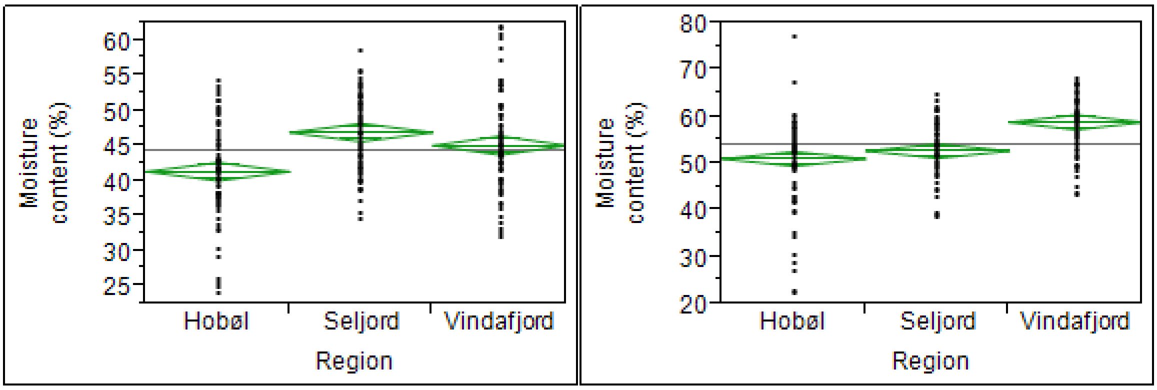

Figure 20. Differences in mean values of moisture content for stem wood (left) and stem bark (right) harvested during the summer season in relation to the geographical location.

In order to investigate more precise knowledge in the vertical variations of moisture content the site index and tree height variables were added in our models. Table 12 shows the p values for the differences of the moisture content for Norway spruce stem wood and stem bark in relation to the site index and tree height variables.

Table 12. p value of arithmetic means differences of moisture content for Norway spruce stem wood and stem bark collected during the summer season in relation to the site index and tree height.

Geographical location	**Stem wood**		**Stem bark**	
	Site index	**Tree height**	**Site index**	**Tree height**
S1 Vindafjord	p=0.8090	p=0.0256*	p=0.1619	p=0.0004*
S2 Seljord	p=0.0993	p<0.0001*	p=0.0993	p<0.0005*
S3 Hobøl	p<0.0001*	p<0.0001*	p<0.0001*	p<0.0001*

We found insignificant relationship between the moisture content for the stem wood and stem bark and the site index for locations S1 and S2, while a significant one (at level p<0.0001*) for the S3 location. To conclude, data presented in previous Table 11 show that the stem wood and stem bark originated from lower site index in S3 location did have slightly elevated moisture content than other two higher site indexes. Earlier study by Oliveira (2003) confirmed that moisture content in wood and bark tends to vary between sites. In addition, the moisture content of stem wood and stem bark did differ vertically at significant level p<0.0001*.

3.4.2 MOISTURE CONTENT IN BRANCH WOOD

Hakkila (1989) reported that the differences in the moisture content of branch wood are partly results of differences in their basic density. The vertical differences of moisture content for branch wood along the crown and along the branch harvested during the summer period 2011 shows Table 13.

Table 13. Average values of moisture content (%) and standard deviations of Norway spruce branch wood along the crown and along the branch harvested during the summer period.

Geographical location	**Site index**	**Bottom crown**				**Middle crown**				**Top crown**			
		Branch part				**Branch part**				**Branch part**			
		Base	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**

S3 Hobøl	23	29.0 (4.2)	42.0 (1.0)	49.5 (6.0)	53.7 (8.7)	37.9 (2.4)	49.5 (4.6)	47.8 (3.4)	54.4 (2.2)	45.6 (3.3)	54.7 (6.3)	55.5 (5.5)	58.0 (5.1)
S3 Hobøl	20	34.2 (1.5)	45.4 (1.8)	48.0 (1.6)	54.0 (1.5)	36.8 (2.2)	49.4 (1.3)	51.6 (3.9)	58.3 (7.9)	47.7 (4.3)	54.0 (3.5)	54.6 (3.7)	54.2 (3.1)
S3 Hobøl	14	38.9 (2.5)	53.1 (3.8)	47.8 (3.3)	45.8 (3.6)	43.0 (3.7)	45.8 (2.4)	50.7 (9.8)	48.8 (4.5)	42.4 (7.5)	49.4 (4.8)	52.0 (6.7)	48.2 (9.0)
S2 Seljord	17	45.3 (4.0)	49.4 (2.6)	54.3 (2.8)	56.5 (2.9)	56.8 (1.7)	51.3 (0.7)	53.7 (3.0)	56.0 (2.4)	54.5 (4.7)	57.0 (2.3)	63.4 (9.3)	63.4 (8.7)
S2 Seljord	13	41.7 (5.1)	47.0 (2.5)	52.3 (4.6)	58.4 (6.8)	42.0 (2.2)	46.0 (1.1)	50.2 (2.7)	53.5 (2.6)	46.8 (3.3)	50.6 (2.0)	53.1 (2.2)	53.3 (2.8)
S2 Seljord	11	45.5 (2.6)	49.1 (3.3)	46.0 (6.9)	53.2 (6.2)	46.5 (8.9)	48.7 (1.1)	51.1 (4.5)	39.3 (9.5)	50.6 (6.0)	47.1 (9.4)	55.1 (6.8)	60.5 (12.2)
S1 Vindafjord	23	33.5 (6.2)	47.5 (4.0)	46.0 (6.3)	59.2 (3.7)	37.0 (4.8)	45.2 (3.6)	48.3 (2.2)	54.5 (1.3)	44.9 (5.0)	51.0 (3.8)	51.7 (2,2)	58.3 (1.6)
S1 Vindafjord	17	56.1 (17.0)	53.6 (17.9)	54.4 (21.9)	60.2 (19.6)	49.9 (27.2)	50.4 (24.8)	42.6 (20.1)	51.0 (32.8)	46.2 (24.0)	54.3 (20.2)	60.5 (13.1)	67.9 (12.3)
S1 Vindafjord	11	45.4 (18.1)	41.2 (10.9)	40.3 (22.2)	39.3 (22.2)	45.3 (14.2)	40.6 (16.8)	30.4 (20.6)	72.3 (36.3)	32.6 (26.6)	34.8 (30.9)	36.1 (28.1)	51.1 (29.2)

Moisture content of branch wood was in range 29.0-67.9 %, respectively. The vertical dependence of moisture content of branch wood had increasing pattern towards the crown top and the branch top. Results obtained for the vertical dependence, especially in the base part of the branch, may be due to the higher content of inactive heartwood and extraneous material, which elevate the basic density, to that in branch top. This lowers the moisture content expressed as a percentage of the fresh mass (Hakkila, 1989).

Figure 21 illustrates the variations of moisture content of branch wood when the geographical location was added as a variable in the model. The moisture content of branch wood did vary insignificantly at level p>0.05 in relation to the geographical location.

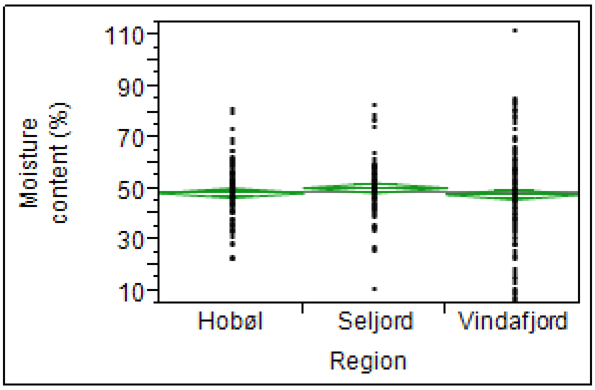

Figure 21. Differences in mean values of moisture content for branch wood collected during the summer period in relation to the geographical location.

Statistical analysis presented in Table 14 proofed that the site index variable did not influence the moisture content in branch wood. On the other hand we found that the vertical dependence of moisture content for branch was regular, increasing towards the branch top and did vary significantly at level p<0.0001*. Based on the obtained results it can be reported that the vertical dependence of moisture content of branch wood towards the crown top and the branch top originated from the Hobøl site (S3) did differ more than that from the Seljord (S2) and Vindafjord site (S1).

Table 14. p value of arithmetic means differences of moisture content for Norway spruce branch wood harvested during the summer period in relation to the site index, crown level and branch part.

Geographical location	**Site index**	**Crown level**	**Branch part**

S1 Vindafjord	p=0.0621	p=0.5656	p=0.0004*
S2 Seljord	p=0.0547	p=0.2140	p<0.0001*
S3 Hobøl	p=0.5174	p<0.0001*	p<0.0001*

It can be concluded that lower moisture content of raw material is considered to be the primary prerequisite for a combustion fuel. Thus, variation in the relative proportion of bark to wood can be expected to have a large impact on the value of energy conversion for a particular raw material feedstock.

3.5 Chemical composition

3.5.1 CHEMICAL COMPOSITION OF STEM WOOD AND STEM BARK

The vertical dependence of the chemical composition of stem wood and stem bark presents Table 15. Primary data were obtained from study Dibdiakova *et al*. (2014).

Table 15. Average values of chemical components (%) and standard deviation of Norway spruce stem wood and stem bark originated from different geographical locations.

Chemical component	**Geographical location**	**Stem wood**				**Stem bark**			
		Tree height (%)				**Tree height (%)**			
		Base	**DBH**	**40**	**80**	**Base**	**DBH**	**40**	**80**
Extractives	S1 Vindafjord	0.26 (0.04)	0.32 (0.04)	0.28 (0.04)	0.27 (0.04)	0.59 (0.07)	0.73 (0.07)	0.88 (0.07)	0.82 (0,.7)
	S2 Seljord	0.22 (0.03)	0.24 (0.03)	0.28 (0.03)	0.33 (0.03)	0.75 (0.10)	0.70 (0.10)	0.76 (0.10)	0.86 (0.10)
	S3 Hobøl	0.32 (0.10)	0.36 (0.10)	0.36 (0.10)	0.37 (0.10)	0.73 (0.06)	0.79 (0.06)	0.79 (0.06)	0.82 (0.06)
Holocellulose	S1 Vindafjord	77.8 (0.40)	77.9 (0.40)	77.8 (0.40)	77.6 (0.40)	51.0 (0.58)	51.5 (0.58)	53.4 (0.58)	54.5 (0.58)
	S2 Seljord	77.9 (0.35)	77.8 (0.35)	77.6 (0.35)	76.9 (0.35)	52.9 (0.93)	55.9 (0.93)	58.6 (0.93)	57.9 (0.93)
	S3 Hobøl	76.5 (0.49)	77.1 (0.49)	77.0 (0.49)	76.6 (0.49)	53.5 (2.70)	59.0 (2.70)	57.5 (2.70)	57.7 (2.70)
Lignin	S1 Vindafjord	21.2 (0.37)	21.0 (0.37)	21.1 (0.37)	2.,4 (0.37)	44.4 (0.52)	43.0 (0.52)	41.3 (0.52)	40.5 (0.52)
	S2 Seljord	21.1 (0.31)	21.0 (0.31)	21.3 (0.31)	21.8 (0.31)	42.1 (0.86)	38.6 (0.86)	36.3 (0.86)	37.1 (0.86)
	S3 Hobøl	22.0 (0.49)	21.5 (0.49)	21.6 (0.49)	21.9 (0.49)	41.5 (2.65)	35.5 (2.65)	37.1 (2.65)	37.0 (2.65)

Qualitative differences in chemical composition did vary based on the material origin. In average, stem bark was more abundant in extractives and lignin than stem wood, respectively. On the other hand, rich content of holocellulose (approximately 77 %) was detected for the stem wood. The chemical composition did vary vertically within different pattern for stem wood and for stem bark. Axially increasing trend in extractives and lignin content and decreasing trend in holocellulose towards the top was found for stem wood. While the stem bark on the top was rich in extractives and holocellulose and poorer in lignin content. Stem wood showed to have significantly higher amount of holocellulose (at level $p<0.05^*$) than that for stem bark, whereas significantly higher content of lignin contained bark in comparison to stem wood (at level $p<0.05^*$).

Table 16 shows the p value of arithmetic means differences of chemical composition of stem wood and stem bark depending on the geographical location, site index and tree height.

Table 16. p value of arithmetic means differences of chemical composition for stem wood and stem bark of Norway spruce in relation to the geographical location, site index and tree height.

Chemical component	**Stem wood**			**Stem bark**		
	Geographical location	**Site index**	**Tree height**	**Geographical location**	**Site index**	**Tree height**
Extractives	p=0.0122	p=0.9986	p=0.5184	p=0.0042*	p=0.8990	p=0.0066
Holocellulose	p=0.0024*	p=0.7584	p=0.1764	p=0.0009*	p=0.9766	p=0.0079*
Lignin	p=0.0474*	p=0.9800	p=0.2280	p=0.0005*	p=0.9998	p=0.0067*

Chemical composition of samples did differ when the geographical location was added as a variable in our model, with more pronounced dependence for stem bark at level $p<0.005$* than for stem wood at level $p<0.05$*, respectively. Statistically no significant relationship between the amount of chemical components and their position along the stem was found for stem wood at $p>0.05$, but significant one for stem bark at level $p<0.05$*, Table 16. Chemical composition of stem wood and stem bark did not vary significantly when the site index variable was added in the model. In average, for stem wood originated from the Hobøl site (S3) was observed the highest content of extractives and lignin, and the lowest content of holocellulose. Furthermore we found that the stem bark originated from Hobøl site (S3) showed to have the highest content of extractives and holocellulose, and the lowest content of lignin in comparison to the two other sites (S1, S2).

3.5.2 CHEMICAL COMPOSITION OF BRANCH WOOD

Axial dependence of chemical composition of branch wood along the branch and crown shows Table 17. Primary data were obtained from study Dibdiakova *et al*. (2014).

Table 17. Average values of chemical composition (%) and standard deviation of Norway spruce branch wood originated from different geographical locations.

Geographical location	**Chemical component**	**Branch part**	**Crown level**		
			Bottom	**Middle**	**Top**
S1 Vindafjord	Extractives	Base	0.73 (0.06)	0.59 (0.06)	0.65 (0.06)
		Twigs	0.66 (0.06)	0.76 (0.06)	0.79 (0.06)
S1 Vindafjord	Holocellulose	Base	52.67 (0.06)	53.40 (0.06)	53.16 (0.06)
		Twigs	56.04 (0.06)	56.66 (0.06)	59.00 (0.06)
S1 Vindafjord	Lignin	Base	34.13 (0.04)	34.20 (0.04)	33.20 (0.04)
		Twigs	32.09 (0.06)	31.42 (0.06)	30.15 (0.06)
S2 Seljord	Extractives	Base	0.72 (0.05)	0.62 (0.05)	0.68 (0.05)
		Twigs	0.68 (0.05)	0.77 (0.05)	0.80 (0.05)
S2 Seljord	Holocellulose	Base	53.17 (0.06)	52.79 (0.06)	53.53 (0.06)

		Twigs	52.14 (0.06)	58.10 (0.06)	57.51 (0.06)
S2 Seljord	Lignin	Base	36.23 (0.04)	35.10 (0.04)	35.00 (0.04)
		Twigs	32.09 (0.04)	30.32 (0.04)	30.00 (0.04)
S3 Hobøl	Extractives	Base	0.75 (0.05)	0.61 (0.05)	0.67 (0.05)
		Twigs	0.67 (0.05)	0.77 (0.05)	0.81 (0.05)
S3 Hobøl	Holocellulose	Base	55.37 (0.06)	54.79 (0.06)	54.74 (0.06)
		Twigs	59.14 (0.06)	60.10 (0.06)	59.31 (0.06)
S3 Hobøl	Lignin	Base	35.33 (0.05)	35.11 (0.05)	34.77 (0.05)
		Twigs	31.33 (0.05)	30.42 (0.05)	30.42 (0.05)

Chemical composition of Norway spruce samples did vary considerably based on raw material origin. The chemical composition for branch wood did vary significantly at level $p<0.05^*$ when the branch position was added as a variable in the model. Contrary, no significant vertical dependency in chemical composition was observed between the position in branch and the crown level. Branch wood was more abounded in lignin content (35.1 %) in their lower part. While the top branch parts had considerably higher content of extractives (0.75 %) and holocellulose (59.52 %) than the lower parts, respectively. In respect to raw material origin, the fact that branch top - twigs included the very mix of wood, bark and needles, whereas the branch base contained only wood and bark has to be taken into consideration in order to understand differences between these two branch segments. Although the chemical composition of branch wood did not vary significantly within the crown level (at level $p>0.05$), we observed specific patterns showing the differences. The branch base had vertically decreasing trend in holocellulose and lignin content, and increasing pattern in extractives towards the top crown. While the top branch showed to have slightly richer amount of holocellulose and lower content of extractives as well as of lignin, respectively.

In order to estimate more precise knowledge of Norway spruce branch wood chemical composition the geographical location, site index, crown level and branch part were added as a variables in our models. Table 18 shows the p value of the branch chemical composition differences for these dependences.

Table 18. p value of arithmetic means differences of chemical composition for Norway spruce branch wood in relation to the geographical location, site index, crown level and branch part.

Chemical component	**Geographical location**	**Site index**	**Crown level**	**Branch part**
Extractives	p=0.5882	p=0.9986	p=0.6535	p=0.0010*
Holocellulose	p=0.4566	p=0.584	p=0.5072	p<0.0001*
Lignin	p=0.4587	p=0.9800	p=0.3577	p<0.0001*

Branch part dependency for chemical composition was significant at level $p<0.0001^*$. The geographical location, site index and crown level variables did not have statistically significant influence on chemical composition of branch wood. We can report that the vertical position within branch had significantly high impact on the chemical composition in branch. A similar axial dependency has also been found (Hakkila, 1989).

3.6 Net calorific value

3.6.1 NET CALORIFIC VALUE OF STEM WOOD AND STEM BARK

Overview about the results obtained for axial dependence of the net calorific value dry of stem wood and stem bark are listed in Table 19.

Table 19. Average values of net calorific value (kWh/kg) at 0 % moisture content and standard deviations of Norway spruce stem wood and stem bark along the tree trunk.

Geographical location	Site index	Stem wood						Stem bark					
		Tree height (%)						Tree height (%)					
		Base	BH	20	40	60	80	Base	BH	20	40	60	80
S3 Hobøl	23	5.10 (0.08)	5.22 (0.11)	5.20 (0.25)	5.22 (0.06)	5.21 (0.11)	5.21 (0.17)	5.27 (0.11)	5.28 (0.06)	5.30 (0.03)	5.38 (0.11)	5.41 (0.03)	5.45 (0.18)
S3 Hobøl	20	5.18 (0.28)	5.20 (0.13)	5.14 (0.22)	5.13 (0.12)	5.22 (0.18)	5.23 (0.04)	5.25 (0.12)	5.24 (0.12)	5.32 (0.02)	5.36 (0.29)	5.39 (0.18)	5.44 (0.15)
S3 Hobøl	14	5.09 (0.19)	5.16 (0.12)	5.17 (0.06)	4.91 (0.08)	4.99 (0.08)	5.22 (0.04)	5.23 (0.22)	5.29 (0.05)	5.30 (0.03)	5.34 (0.11)	5.38 (0.06)	5.39 (0.17)
S2 Seljord	17	5.08 (0.10)	5.16 (0.25)	5.14 (0.11)	4.92 (0.22)	5.04 (0.09)	5.14 (0.07)	5.19 (0.08)	5.17 (0.25)	5.30 (0.03)	5.34 (0.22)	5.37 (0.01)	5.37 (0.03)
S2 Seljord	13	5.08 (0.15)	5.12 (0.10)	5.18 (0.03)	5.07 (0.09)	5.15 (0.04)	5.16 (0.02)	5.11 (0.22)	5.21 (0.16)	5.26 (0.12)	5.32 (0.22)	5.36 (0.09)	5.38 (0.04)
S2 Seljord	11	5.02 (0.16)	5.04 (0.21)	5.10 (0.08)	5.08 (0.05)	5.15 (0.03)	5.22 (0.26)	5.24 (0.23)	5.24 (0.06)	5.30 (0.04)	5.35 (0.11)	5.38 (0.09)	5.40 (0.21)
S1 Vindafjord	23	5.09 (0.07)	5.12 (0.11)	5.12 (0.26)	4.97 (0.08)	5.03 (0.30)	5.19 (0.25)	5.24 (0.06)	5.23 (0.11)	5.34 (0.32)	5.35 (0.18)	5.39 (0.09)	5.43 (0.08)
S1 Vindafjord	17	4.91 (0.04)	4.82 (0.10)	4.90 (0.29)	5.15 (0.16)	5.13 (0.08)	5.19 (0.21)	5.13 (0.10)	5.25 (0.22)	5.27 (0.05)	5.31 (0.05)	5.35 (0.25)	5.38 (0.20)
S1 Vindafjord	11	5.08 (0.02)	5.16 (0.07)	5.15 (0.02)	5.12 (0.10)	5.11 (0.05)	5.20 (0.01)	5.24 (0.02)	5.27 (0.20)	5.31 (0.21)	5.34 (0.17)	5.35 (0.10)	5.36 (0.02)

Net calorific values did differ in raw material origin. Net calorific value for stem wood was in range 4.82-5.23 kWh/kg and for stem bark 5.11-5.45 kWh/kg, respectively. The vertical dependence trend of net calorific value for Norway spruce stem wood was similar to that for stem bark. Regular increasing pattern towards the top was observed. We observed significantly higher calorific value at level $p<0.05$* in stem bark than in stem wood. This elevated energy content of stem bark may be due to its corresponding chemical composition, which consequently affects its calorific value. At the same time is important to know the quantity of these components in order to understand the variations in different tree components. Energy content of biomass feedstock is closely correlated with its content of energy rich components – lignin and extractives (resins, fats, oils, etc.) (Tillman, 1978; Krigstin, 1985). In our study we found that the chemical composition of stem bark had higher percentage of lignin and extractives (17 % and 40 %, respectively, the remaining 43 % is holocellulose), compared to stem wood (10 % and 6 %, respectively, the remaining 84 % is holocellulose), as presented in previous Table 15.

Net calorific value of investigated Norway spruce biomass did differ at significant level p<0.005* for stem wood and at significant level p<0.05* for stem bark, when the geographical location was added as a variable in the model. Figure 22 illustrates the variations of net calorific values for stem wood and stem bark samples collected in three geographical sites in South Norway.

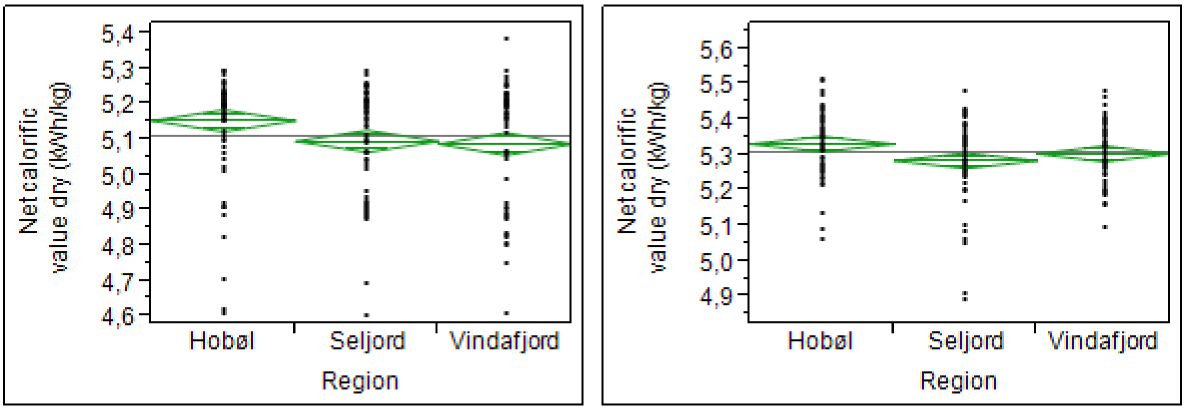

Figure 22. Differences in mean values of net calorific value at 0 % moisture content for stem wood (left) and stem bark (right) in relation to the geographical location.

Furthermore we did find significant dependence of the site index for net calorific values of stem wood and stem bark. Our model proved a significantly strong vertical dependence of the net calorific value for stem bark at level p<0.0001*. These statistical differences present Table 20.

Table 20. p value of arithmetic means differences of net calorific value of stem wood and stem bark in relation to the site index and tree height.

Geographical location	**Stem wood**		**Stem bark**	
	Site index	**Tree height**	**Site index**	**Tree height**
S1 Vindafjord	p=0.1932	p=0.0015*	p=0.4427	p<0.0001*
S2 Seljord	p=0.6354	p=0.0734	p=0.2381	p<0.0001*
S3 Hobøl	p=0.0830	p=0.2216	p=0.2124	p<0.0001*

3.6.2 NET CALORIFIC VALUE OF BRANCH WOOD

For better understanding of net calorific value behaviour in branch wood the variables of vertical position within the branch and crown were added in the models. Differences in these dependencies of net calorific value of branch wood present Table 21.

Table 21. Average values of net calorific value (kWh/kg) at 0 % moisture content and standard deviations of Norway spruce branch wood along the crown and along the branch.

Geographical location	**Site index**	**Bottom crown**				**Middle crown**				**Top crown**			
		Branch part				**Branch part**				**Branch part**			
		Base	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**
S3 Hobøl	23	5.34 (0.07)	5.37 (0.12)	5.41 (0.06)	5.44 (0.05)	5.34 (0.05)	5.38 (0.01)	5.40 (0.01)	5.44 (0.10)	5.37 (0.10)	5.40 (0.06)	5.44 (0.10)	5.49 (0.06)
S3 Hobøl	20	5.37 (0.11)	5.40 (0.02)	5.46 (0.10)	5.48 (0.24)	5.35 (0.13)	5.37 (0.01)	5.41 (0.08)	5.48 (0.12)	5.37 (0.01)	5.40 (0.10)	5.43 (0.01)	5.47 (0.07)
S3 Hobøl	14	5.34 (0.01)	5.36 (0.21)	5.39 (0.16)	5.45 (0.06)	5.35 (0.00)	5.38 (0.03)	5.43 (0.07)	5.52 (0.09)	5.38 (0.30)	5.38 (0.01)	5.41 (0.06)	5.46 (0.08)

S2 Seljord	17	5.33 (0.01)	5.36 (0.10)	5.41 (0.06)	5.44 (0.01)	5.33 (0.10)	5.36 (0.30)	5.40 (0.06)	5.45 (0.06)	5.34 (0.07)	5.38 (0.05)	5.42 (0.10)	5.50 (0.05)
S2 Seljord	13	5.33 (0.05)	5.35 (0.12)	5.39 (0.04)	5.45 (0.07)	5.34 (0.21)	5.36 (0.21)	5.38 (0.02)	5.42 (0.00)	5.33 (0.01)	5.36 (0.06)	5.40 (0.14)	5.44 (0.03)
S2 Seljord	11	5.35 (0.10)	5.38 (0.01)	5.44 (0.32)	5.50 (0.00)	5.35 (0.10)	5.39 (0.01)	5.41 (0.06)	5.47 (0.21)	5.36 (0.21)	5.38 (0.06)	5.41 (0.01)	5.46 (0.07)
S1 Vindafjord	23	5.35 (0.06)	5.37 (0.07)	5.41 (0.05)	5.46 (0.06)	5.38 (0.06)	5.40 (0.05)	5.44 (0.10)	5.48 (0.12)	5.41 (0.10)	5.44 (0.10)	5.47 (0.30)	5.51 (0.21)
S1 Vindafjord	17	5.34 (0.30)	5.35 (0.12)	5.39 (0.10)	5.42 (0.07)	5.37 (0.01)	5.39 (0.06)	5.42 (0.06)	5.44 (0.05)	5.39 (0.06)	5.41 (0.02)	5.42 (0.30)	5.44 (0.01)
S1 Vindafjord	11	5.33 (0.20)	5.35 (0.10)	5.40 (0.06)	5.47 (0.06)	5.34 (0.01)	5.36 (0.05)	5.41 (0.21)	5.47 (0.06)	5.34 (0.01)	5.36 (0.10)	5.41 (0.08)	5.45 (0.22)

Net calorific value of branch wood was in range 5.33-5.52 kWh/kg, respectively. The vertical variations of net calorific value for branch wood showed an increasing pattern towards the branch top and upwards the crown top. We found increasing pattern in net calorific value of branch wood from the branch base towards its top. It is important to note that the twigs part contained mix of wood, bark and needles which all together may elevate the calorific value (for deeper explanation see chapter 3.5.2). This trend can be partly explains by the chemical composition of needles. In our study we observed the elevated content of extractives in upper part of branch. In fact, needles contain considerably higher quantities of extractives which consequently contribute to higher calorific values (Nurmi, 1993, 1997). Our model proofed that the net calorific value of branch wood did vary significantly at level $p<0.05^*$ along the branch towards the twigs. Contrary, the vertical dependence of branch net calorific value in crown position did not differ significantly at level $p>0.05$. We can demonstrate that an axial position within crown did not affect the energy content of the branch wood. Indeed, this gives a good indication between chemical composition of woody-based biomass and its heating value.

Net calorific value of branch wood did differ significantly when the geographical location was added as a variable in our model at level $p<0.05^*$, but insignificantly when the site index variable was used. Figure 22 shows the variations of the net calorific value of branch samples collected from three locations in South Norway.

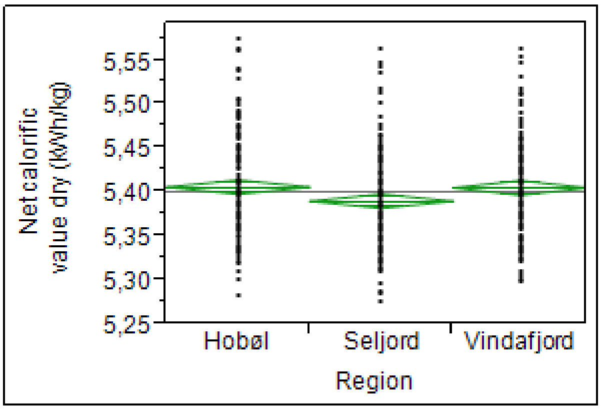

Figure 22. Differences in mean values of net calorific value at 0 % moisture content for branch wood in relation to the geographical location.

3.7 Ash content

3.7.1 ASH CONTENT OF STEMWOOD AND STEM BARK

Overview about the axial dependence of the ash content for stem wood and stem bark towards the top gives Table 22.

Table 22. Average values of ash content (%) and standard deviations of Norway spruce stem wood and stem bark originated from trees in three geographical locations in South Norway.

Geographical location	**Site index**	**Stemwood**						**Stem bark**					
		Tree height (%)						**Tree height (%)**					
		Base	**BH**	**20**	**40**	**60**	**80**	**Base**	**BH**	**20**	**40**	**60**	**80**
S3 Hobøl	23	0.18 (0.01)	0.19 (0.01)	0.20 (0.03)	0.19 (0.01)	0.19 (0.00)	0.20 (0.01)	1.49 (0.00)	1.65 (0.05)	1.96 (0.01)	2.11 (0.04)	2.02 (0.05)	1.96 (0.00)
S3 Hobøl	20	0.18 (0.00)	0.18 (0.04)	0.19 (0.03)	0.19 (0.01)	0.18 (0.03)	0.20 (0.04)	2.14 (0.01)	2.21 (0.04)	2.39 (0.05)	2.44 (0.05)	2.16 (0.05)	2.00 (0.00)
S3 Hobøl	14	0.18 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.20 (0.00)	1.86 (0.01)	1.90 (0.00)	2.47 (0.05)	2.56 (0.03)	2.11 (0.05)	1.97 (0.00)
S2 Seljord	17	0.18 (0.00)	0.18 (0.03)	0.19 (0.04)	0.20 (0.01)	0.19 (0.03)	0.18 (0.03)	1.54 (0.04)	1.79 (0.03)	2.54 (0.01)	2.45 (0.05)	1.88 (0.03)	1.68 (0.05)
S2 Seljord	13	0.18 (0.02)	0.18 (0.05)	0.19 (0.01)	0.20 (0.00)	0.19 (0.01)	0.18 (0.00)	1.52 (0.03)	1.65 (0.00)	2.19 (0.05)	2.37 (0.04)	2.07 (0.05)	1.84 (0.05)
S2 Seljord	11	0.18 (0.00)	0.19 (0.03)	0.19 (0.04)	0.18 (0.01)	0.19 (0.01)	0.20 (0.01)	1.52 (0.01)	1.69 (0.03)	1.96 (0.03)	2.17 (0.05)	2.09 (0.00)	1.86 (0.05)
S1 Vindafjord	23	0.17 (0.03)	0.17 (0.01)	0.19 (0.01)	0.18 (0.01)	0.22 (0.04)	0.20 (0.03)	1.94 (0.03)	2.02 (0.03)	2.56 (0.01)	2.56 (0.01)	2.18 (0.04)	2.16 (0.05)
S1 Vindafjord	17	0.18 (0.01)	0.18 (0.02)	0.20 (0.00)	0.20 (0.01)	0.20 (0.04)	0.20 (0.03)	1.81 (0.04)	1.85 (0.00)	2.49 (0.01)	2.63 (0.01)	2.11 (0.05)	2.02 (0.00)
S1 Vindafjord	11	0.17 (0.02)	0.18 (0.00)	0.18 (0.03)	0.19 (0.04)	0.20 (0.00)	0.18 (0.01)	1.85 (0.03)	1.93 (0.00)	2.47 (0.00)	2.48 (0.03)	1.82 (0.01)	1.77 (0.03)

Ash content expressed on a dry basis did differ considerably based on the raw material origin. The ash content for stem wood was in range 0.17-0.22 % and for stem bark was 1.49-2.63 %, respectively. Applied combustion process of stem bark samples performed under the oxidative atmosphere resulted in higher residue mass (ash content) produced at 550±10 °C compare to stem wood. This finding has been found (Dibdiakova *et al*., 2014). The vertical dependence of ash content for stem wood and stem bark showed the same pattern common for both materials, increasing trend towards the top was observed, respectively. Significantly higher ash content at level $p<0.05^*$ was found for stem bark than that for stem wood.

Figure 23 illustrates the statistical variations of ash content for both materials collected in three locations in South Norway. The ash content of stem wood did not differ significantly at level $p>0.05$ when the geographical location was added as a variable in the model, but it did differ at significant level $p<0.05^*$ for stem bark, respectively.

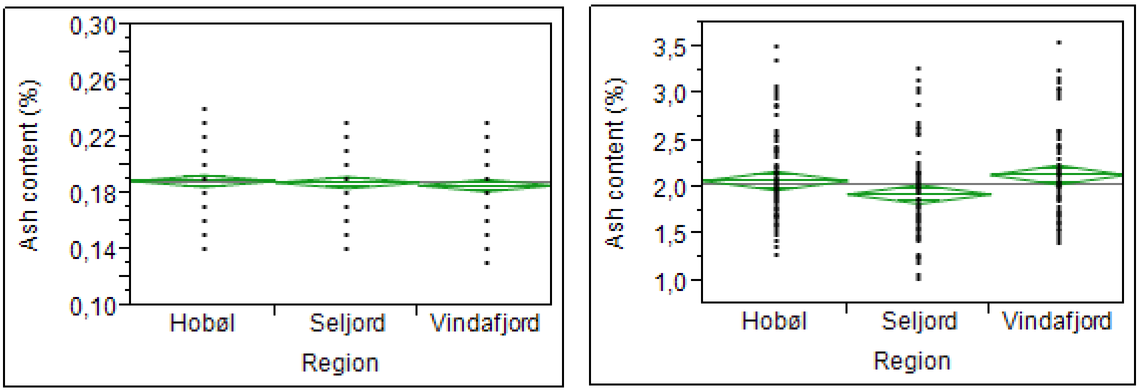

Figure 23. Differences in mean values of ash content for stem wood (left) and stem bark (right) in relation to the geographical location.

The p values originated from our statistical models presented in Table 23 proofed that the ash content in stem wood and stem bark did not vary significantly in relation to the site index. The vertical dependence of ash content in stem wood and stem bark did not vary significantly, except the variations for stem wood and stem bark in Hobøl site (S3) at significant level p<0.05*, respectively.

Table 23. p value of arithmetic means differences of ash content for stem wood and stem bark in relation to the site index and tree height.

Geographical location	**Stem wood**		**Stem bark**	
	Site index	**Tree height**	**Site index**	**Tree height**
S1 Vindafjord	p=0.9992	p=0.1006	p=0.1786	p=0.8352
S2 Seljord	p=0.8758	p=0.2205	p=0.1399	p=0.4979
S3 Hobøl	p=0.7834	p=0.0441*	p=0.3669	p=0.0502*

Relationship between the net calorific value and ash content of stem wood and stem bark shows Figure 24. An increasing pattern of ash content with higher net calorific value was observed. We can conclude that with the higher net calorific value of Norway spruce stem wood and stem bark the content of produced ash increased as well.

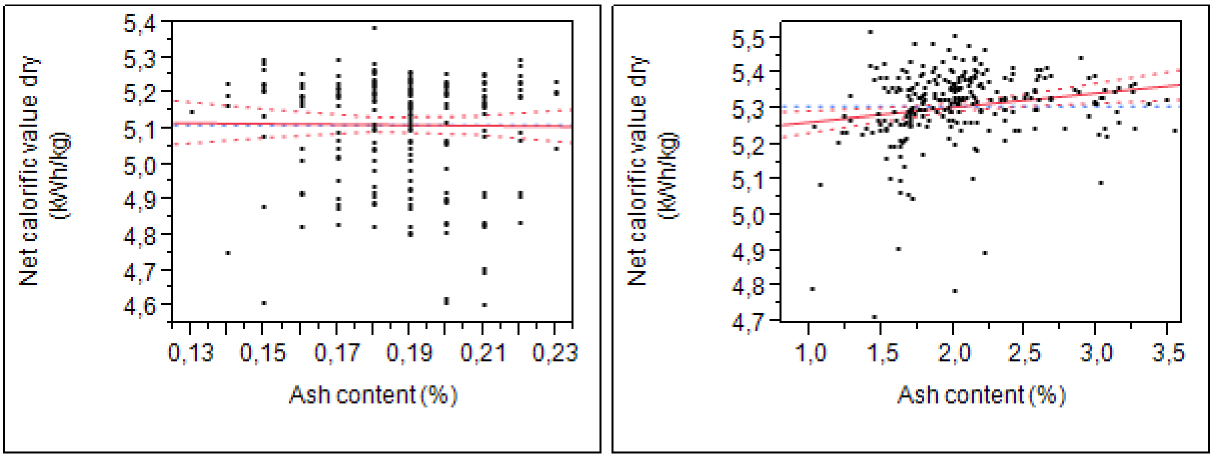

Figure 24. Plot showing the relationship between net calorific value at 0 % moisture content and ash content of Norway spruce stem wood (left) and stem bark (right).

3.7.2 ASH CONTENT OF BRANCH WOOD

Results overview about the vertical dependence of ash content for branch wood towards the top crown and branch top are presented in Table 24.

Table 24. Average values of ash content (%) and standard deviations of Norway spruce branch wood along the crown and along the branch harvested from three geographical locations in South Norway.

Geographical location	**Site index**	**Bottom crown**				**Middle crown**				**Top crown**			
		Branch top				**Branch top**				**Branch top**			
		Base	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**	**Base**	**Middle**	**Top**	**Twigs**
S3 Hobøl	23	1.17 (0.02)	1.28 (0.03)	1.41 (0.21)	1.69 (0.01)	1.22 (0.14)	1.34 (0.43)	1.56 (0.21)	1.79 (0.11)	1.32 (0.16)	1.50 (0.16)	1.69 (0.25)	1.89 (0.01)
S3 Hobøl	20	1.16 (0.43)	1.46 (0.11)	1.71 (0.17)	1.80 (0.54)	1.26 (0.20)	1.59 (0.03)	1.74 (0.14)	1.76 (0.21)	1.41 (0.54)	1.65 (0.43)	1.81 (0.12)	1.88 (0.41)
S3 Hobøl	14	1.21 (0.50)	1.29 (0.30)	1.67 (0.05)	1.95 (0.22)	1.30 (0.02)	1.34 (0.17)	1.72 (0.00)	2.03 (0.22)	1.40 (0.12)	1.47 (0.10)	1.86 (0.06)	2.17 (0.16)
S2 Seljord	17	1.54 (0.33)	1.60 (0.07)	1.96 (0.32)	2.15 (0.21)	1.94 (0.02)	1.66 (0.46)	2.01 (0.13)	2.22 (0.16)	2.01 (0.12)	1.78 (0.42)	2.07 (0.26)	2.35 (0.31)
S2 Seljord	13	1.28 (0.13)	1.42 (0.10)	1.48 (0.15)	1.69 (0.15)	1.34 (0.00)	1.44 (0.33)	1.41 (0.46)	1.75 (0.23)	1.37 (0.31)	1.45 (0.15)	1.61 (0.11)	1.88 (0.13)
S2 Seljord	11	1.32 (0.22)	1.43 (0.17)	1.81 (0.24)	2.17 (0.03)	1.37 (0.11)	1.50 (0.15)	1.88 (0.35)	2.27 (0.19)	1.48 (0.33)	1.52 (0.02)	1.98 (0.08)	2.49 (0.08)
S1 Vindafjord	23	1.14 (0.06)	1.26 (0.14)	1.41 (0.08)	1.58 (0.12)	1.29 (0.42)	1.45 (0.12)	1.52 (0.25)	1.73 (0.09)	1.44 (0.16)	1.40 (0.05)	1.58 (0.08)	1.88 (0.32)
S1 Vindafjord	17	1.11 (0.15)	1.20 (0.04)	1.42 (0.13)	1.66 (0.10)	1.16 (0.19)	1.24 (0.12)	1.38 (0.07)	1.68 (0.12)	1.25 (0.10)	1.36 (0.00)	1.42 (0.12)	1.74 (0.05)
S1 Vindafjord	11	1.20 (0.02)	1.24 (0.03)	1.55 (0.12)	1.83 (0.09)	1.31 (0.10)	1.42 (0.12)	1.50 (0.41)	1.84 (0.11)	1.35 (0.12)	1.43 (0.16)	1.68 (0.21)	1.97 (0.06)

Ash content in branch wood was in range 1.11-2.49 %, respectively. Applied combustion process of twigs performed under the oxidative atmosphere resulted in higher residue mass (ash content) produced at 550±10 °C compare to the branch base, which confirms earlier study (Dibdiakova *et al*., 2014). The vertical dependence of ash content was observed, increasing trend in ash content towards the needle top (twigs) as well upwards the top crown, respectively. The ash content of branch wood did not vary significantly at level $p>0.005$ within the crown position. On the other hand the ash content strongly varied along the branch towards the needle top (at level $p<0.05$*). We can demonstrate that the ash content of Norway spruce branch wood did vary axially along the branch whereas the very position of branch within the crown did not affect the ash content.

The ash content of branch wood did vary significantly at level $p<0.05$* when the geographical location was added as a variable in our model. Figure 25 illustrates the variations of ash content of branches collected from three locations in South Norway.

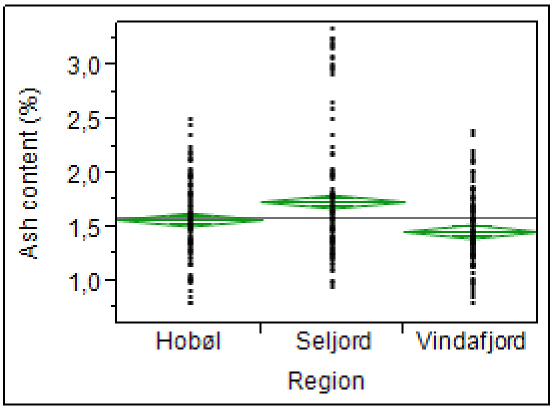

Figure 25. Differences in mean values of ash content for branch wood in relation to the geographical location.

The variations of ash content obtained from statistical models for the site index and crown level dependence, Table 25, showed insignificant effect at level $p>0.05$. On the other hand our model proofed that the ash content in branch wood did vary significantly axially at level $p<0.0005$* within the very branch position, respectively.

Table 25. p value of arithmetic means differences of ash content for Norway spruce branches in relation to the site index, crown level and branch part.

Geographical location	**Site index**	**Crown level**	**Branch part**
S1 Vindafjord	p=0.7656	p=0.6356	p<0.0005*
S2 Seljord	p=0.9599	p=0.6022	p<0.0005*
S3 Hobøl	p=0.9203	p=0.6855	p<0.0005*

Relationship between the net calorific value and ash content illustrates Figure 26. A clear trend was observed, the increasing pattern in ash content of Norway spruce branch wood with higher net calorific value, respectively. The same elevated pattern was observed for stem wood and stem bark (see chapter 3.6.1). We can conclude that the higher net calorific value of Norway spruce biomass consequently generated higher content of the residual mass.

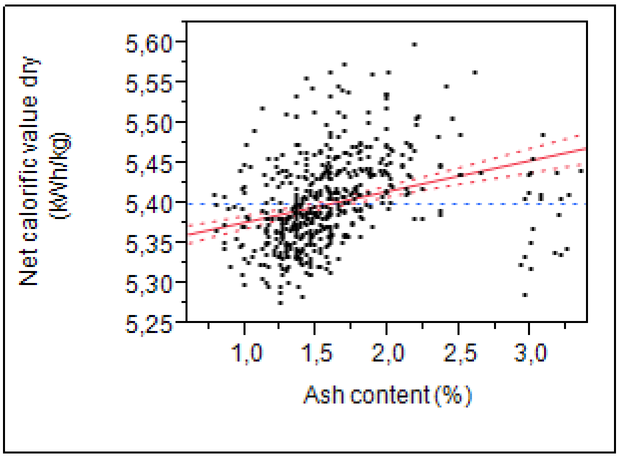

Figure 26. Plot showing the relationship between net calorific value at 0 % moisture content and ash content of Norway spruce branch wood.

4 CONCLUSIONS

There were considerable variations of qualitative properties between stem wood, stem bark and branch wood of Norway spruce tree species among geographical locations and vertically along the stem. In average, the highest basic density showed to have branch wood, lower stem wood and the lowest one stem bark. Basic density of stem wood decreased from the stem base till 20 % of the tree height and afterwards increased towards tree top. Branch wood density decreased moderately within the axial direction along the crown. Branch wood had a higher basic density than stem wood. The basic density of branch wood decreased in the direction from the branch basis to its top. Branch diameter strongly affected the basic density distribution along the branch. There was found relationship between basic density of stem wood, stem bark and branches and the geographical locations. The highest basic density of Norway spruce biomass was observed for the east part of South Norway, in Hobøl sites.

Bark proportion and bark thickens were highly linear to the tree height. Bark originated from trees collected from the middle part of South Norway in Seljord site had considerably higher proportion and thickness. Bark proportion and thickness may be relevant aspects for the utilization of biomass feedstock from Norway spruce raw material. Average moisture content of stem wood and stem bark harvested during the summer season increased vertically from the base toward tree top. Stem bark originated from Seljord site showed to have relatively higher moisture content compare to stem wood. The lower the moisture content in the biomass fuel the higher is its calorific value. Thus, variation in the relative proportion of bark to wood can be expected to have a large impact on the value of energy conversion for a particular feedstock.

We found indications that the net calorific value of Norway spruce biomass was highly affected by its corresponding chemical composition. Increased in net calorific value of Norway spruce stem wood, stem bark and branch wood consequently generated higher content of ash. More ever we found that the ash content of Norway spruce branch wood did vary along the branch whereas the position of branch in crown did not affect the ash content.

Elevated net calorific value of stem bark, and branch wood because of their higher amount of extractives and lignin content make these materials a valuable energy source for bioenergy use in Norway.

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