# Estimation of potential production of energy wood in the Leningrad region of Russia

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Academic dissertation
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## ABSTRACT

The forests of the Russian Federation are the world's largest reserve of wood for different purposes. In order to satisfy the growing demand for wood, forestry in Russia has to be intensified. This study analysed energy wood resources in the Leningrad region of Russia, in the context of intensification of forestry and technical, socio-economic and climatic issues. The assessment was done using the resource-focused approach and statistical, spatial and cost-comparative analyses. Three scenarios of energy wood availability, based on different intensities of forestry, were analysed at regional and district levels to compare the efficiency of wood supply chains, to estimate employment effects of forest chip production and to analyse cost competitiveness of forest chips. The impact of climate change on the technical accessibility of forests and harvestable volumes of industrial and energy wood was analysed.

In the scenario *Allowable*, the availability of energy wood increased from 4.1 to 6.3 Mm$^3$ (+54%) compared with the scenario *Recent*. In the scenario *Potential*, the total volume of available energy wood would be 9.2 Mm$^3$ (+124% compared with scenario *Recent*). Comparable results were obtained at the district level, +50% and +83%, respectively. The average productivity of logging operations in the Russian companies investigated was 20% to 30% lower than that in Finland. The employment effect from the utilisation of energy wood depended on the availability scenarios and the type of chipper used. The number of employment positions could be increased by 84% in the scenario *Potential* compared with the scenario *Recent*. Forest chips were 2–3 times more expensive than natural gas and coal but cheaper than heavy oil. Each decade, the duration of the winter felling season will become 3-4 days shorter. By 2015, the potential losses of a typical large logging company due to the technical inability of entering forests could be about 360 000 euro.

The study area has large available volumes of energy wood but their utilisation is limited by technical and economic factors. The methodology proposed in this study could help logging companies and local authorities predict economic and social effects from the utilisation of energy wood.

**Keywords**: forest chips, technical accessibility, supply system, climate change

**ACKNOWLEDGEMENTS**

**LIST OF ORIGINAL ARTICLES**

This thesis is a summary of the papers presented below. The papers are referred to in the text by the Roman numerals I-IV. The articles were reprinted with the kind permission of the publishers.

I       Gerasimov Y., Karjalainen T., Ilavský J., Tahvanainen T. & Goltsev V. (2007). Possibilities for energy wood procurement in north-west Russia: Assessment of energy wood resources in the Leningrad region. Scandinavian Journal of Forest Research 22(6): 559-567.
        doi: 10.1080/02827580701671958

II      Goltsev V., Ilavský J., Gerasimov Y. & Karjalainen T. (2010). Potential of Energy Wood Resources and Technologies for their Supply in Tikhvin and Boksitogorsk Districts of the Leningrad Region. Biomass and Bioenergy 34 (10): 1440-1448.
        doi:10.1016/j.biombioe.2010.04.007

III     Goltsev V., Ilavský J., Gerasimov Y. & Karjalainen T. (2010). Potential for biofuel development in Tikhvin and Boksitogorsk districts of the Leningrad region - the analysis of energy wood supply chains and costs. Forest Policy and Economics 12(4): 308-316.
        doi:10.1016/j.forpol.2009.10.007

IV      Goltsev V. & Lopatin E. (2013). The impact of climate change on the accessibility of industrial and energy wood in the Tikhvin district of the Leningrad region of Russia. International Journal of Forest Engineering 24 (2): 148-160.
        doi: 10.1080/19132220.2013.792150

Vadim Goltsev had the main responsibility for all the work done in Papers II-IV. Co-authors have participated in the work by commenting on the manuscripts. In Paper I, Vadim Goltsev contributed to the planning of the study, data collection and processing and the writing and commenting of the text.

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## ACRONYMS AND ABBREVIATIONS

CPY – central processing yard
CTL – cut-to-length (logging method)
EU – European Union
FT – full tree (logging method)
FMU – state forest management unit
GDP – gross domestic product
IMAGE – Integrated Model to Assess the Global Environment
LR – logging residues
Mha – million of hectares
$Mm^3$ – million solid cubic metres
NIW – non-industrial round wood
RB – residue bundles
TL – tree length (logging method)
TS – tree section (logging method)

# 1. INTRODUCTION

## 1.1. General

Nowadays, humanity faces many challenges; the most serious are poverty, the growing demand for resources and the deterioration of the environment. A green economy is a pathway to solve these challenges (UNEP, 2011). The targets of a green economy are improved quality of human life, accompanied by reduced pressure on the environment and increased efficiency in the use of resources. These targets cannot be achieved without the sustainable use of renewable resources. Wood is among the most needed natural resources, it is one of very few renewable resources that are relatively easy to obtain. Wood can serve as a raw material for numerous industries, which are crucial for the wellbeing of humanity – the construction, chemical and energy industries. Additionally, attention is being increasingly paid to the production of energy from wood (FAO, 2012). These features make forests and woody biomass especially valuable to the success of a green economy (UNECE/FAO, 2009).

As a source of energy, wood has several features that separate it from other energy sources. Firstly, the renewability of wood makes it a secure energy source. Secondly, the sustainable use of wood to produce energy is characterised by a closed carbon cycle in the atmosphere, because the volume of carbon emissions that results from the burning of wood is equal to the volume sequestrated by the trees during their lifetime. Production of fuels from wood, such as forest chips, is less carbon intensive compared with the extraction of fossil fuels, because it does not need complex infrastructure and at the same time, it facilitates the utilisation of logging residues and low-quality wood, which otherwise would have no purpose. Therefore, wood fuels appear to be interesting alternatives to fossil fuels. However, when substituting fossil fuels with wood fuels the carbon debt has to be considered, because the burning of wood releases carbon that otherwise would be stored in the growing trees. The efficiency of such substitution depends on those factors determining the efficiency of the wood to energy conversion, especially regarding the carbon emissions caused by wood harvesting (Mitchell et al., 2012).

Many countries in the world have set ambitious targets to increase the share of renewable energy in their total energy generation. The European Union, one of the world leaders in development of renewable energy, intends to increase the share of renewable sources in energy generation by up to 20% by 2020 (EP&C, 2009). Wood is considered as one of the main sources of renewable energy; therefore, fulfilment of these targets places additional pressure on wood resources.

In order to satisfy the growing demand for wood, forestry in many countries has to be intensified. The Russian Federation is one of the world's regions where the potential gains from intensification[1] of forestry are high. Russia has the largest forest area in the world (892 Mha (MCR and FSSS, 2012)) and also the largest annual allowed cut, which was according to the federal felling plan about 600 Mm$^3$ (here and after m$^3$ refers to solid cubic metre over bark) in 2009 (Karakchieva, 2010). However, Russia provided only 5% (Eskin

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[1] - Intensification of forestry means improvements of forest management in order to reach the maximal sustainable level of forest use. It includes development of forest infrastructure and application of efficient technologies and methods.

and Lipin, 2007) of global wood trade in 2005 (including domestic use/trade) and in 2010, the annual actual cut was only 29% of the annual allowed cut (MCR and FSSS, 2012). Therefore, forests of the Russian Federation are often considered to be the world's reserve of wood for different purposes. Intensification of forestry in Russia will result in increased availability of industrial and energy wood for the global wood market. This will allow reallocation of local wood resources in countries that have developed wood processing and bioenergy industries (e.g., Finland).

There are several promising regions within Russia for the intensification of forestry. One of these regions is north-western Russia, which comprises eight administrative units: the Republic of Karelia (*Respublika Kareliya*), the Republic of Komi (*Respublika Komi*), the Arkhangelsk region (*Arkhangelskaya oblast*), the Murmansk region (*Murmanskaya oblast*), the Vologda region (*Vologodskaya oblast*), the Leningrad region (*Leningradskaya oblast*), the Novgorod region (*Novgorodskaya oblast*) and the Pskov region (*Pskovskaya oblast*). North-western Russia has a long border with the European Union and a relatively well-developed logging and wood processing industry. Only 12% of the total wood stock of Russia is located in north-western Russia but in 2010 the region produced 27% of the total round wood removals in Russia (MCR and FSSS, 2012). The region is even more important in terms of wood processing. In 2008, the region's contribution to the total production of wood goods in Russia was: 53% for pulp, paper and cardboard, 36% for plywood and 28% for sawnwood (Gerasimov et al., 2009). In 2008, only 40% of the 94 $Mm^3$ allowable annual cut was utilised by final fellings in the region (Gerasimov et al., 2009), which highlights the gains possible from intensification of forestry.

However, intensification of forestry in the region faces technical (e.g., low productivity of felling operations, lack of forest roads), socio-economic (e.g., lack of skilled operators, weak demand for low-quality deciduous wood available in large volumes) and climatic challenges (e.g., short winters). Low productivity of felling operations increases wood supply costs, which limits the economic accessibility[2] of forests. For instance, large forest areas in Russia are only accessible for wood harvesting and transportation during the frosty season with a stable snow cover. Such areas include forests on wetlands and soils with weak bearing capacity or high risk of compaction and forests with dense undergrowth. In the Leningrad region, about 80% of the actual annual fellings are undertaken during the winter season (Bolmat, 2007).

The main reason for the limited technical accessibility[3] of forests in Russia is the lack of all-season forest roads (Karjalainen et al., 2009). Taking into account the current development of the forest road network in Russia and the growing mean annual air temperature, it is reasonable to presume that technical accessibility of the forest in Russia will deteriorate due to the decreasing duration of the frosty season. Furthermore, this could decrease the volume of winter felling if proper measures are not undertaken in advance. Consequently, this could influence the economic viability of the logging companies. The probability of this scenario is high and was proven by the anomalous warm winter of 2006–2007, during which logging companies in the north-western part of Russia faced significant financial losses due to their inability to access forests and fulfil their harvesting plans (Bolmat, 2007).

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[2] - Economic accessibility means the ability to implement economically feasible fellings in technically accessible forests.

[3] - Technical accessibility means the suitability of forest sites for logging operations from the technical point of view.

**Table 1.** Primary energy sources in north-western Russia (Kholodkov, 2010)

| Energy source | Share, % of the total consumption |
|---|---|
| Natural gas | 56.1 |
| Coal | 19.4 |
| Heavy oil | 13.1 |
| Light oil | 8.5 |
| Wood | 2.8 |
| Peat | 0.1 |

The availability of large volumes of low-quality deciduous wood could be seen as an opportunity when thinking about wood as an energy source. Development of wood-based energy in the region could facilitate intensification of forestry by creating demand for low-quality wood. Moreover, increasing use of wood for energy will open up new business opportunities for logging companies, create a growing market for producers of forestry machinery and stimulate energy technologies that will result in increased employment, not only in the region but also in neighbouring countries. Unfortunately in Russia there are several factors hindering the development of wood based energy. Recently, share of wood fuels in the total use of primary energy sources[4] in north-western Russia was small (Table 1).

Wood fuels in Russia have to compete with fossil fuels which are often cheaper and easily available. The same situation was earlier in the EU. In order to improve competitiveness of wood fuels many countries of the EU elaborated energy policy which included different measures to encourage the production and the use of wood fuels. Despite the fast resources, potential of wood fuels is neglected by Russian energy related policy at the national level. The energy strategy of the Russian Federation (MERF, 2010) is the main document which directs the development of the Russian energy sector specifying targets on energy generation, main energy sources and technologies. There are also numerous federal laws and acts (RAE, 2012) which are related to renewable energy in particular. Russia, as a country which has ratified the Kyoto protocol, has to pay attention to mitigation of climate change when elaborating energy policy. One of the main aims of Russian energy policy is to decrease greenhouse gas emission to the atmosphere. The European countries having similar targets are focused on increasing use of renewable energy sources. In contrast, Russian energy policy sets improving of overall energy efficiency of the Russian economy as a main tool to decrease greenhouse gas emissions at the national level. According to the strategy, renewable energy sources will have only a minor value. It is expected that in 2020 generation of renewable energy will reach 4.5% of the total primary energy generation compared to 1.5% in 2010. Russian national energy policy is being criticised (Muñoz and Goltsev, 2012; RAE, 2012) for its inconsistency and neglecting of wood based energy. For example, the energy strategy of the Russian Federation provides only a general target for generation of renewable energy in Russia in the future and it does not specify the use of different renewable energy sources. The terms related to wood based energy, e.g. "wood fuels", "fire wood" or "pellets" are not mentioned in the strategy. Wood based energy gets more attention in several regions of Russia which have available wood resources. Some of the regions, like the Arkhangelsk region, the Vologda region and the Republic of Karelia elaborated own strategies. These strategies have different targets depending on the priorities

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[4] - here and further a primary energy source means any energy source which is utilised to generate heat or electricity by end users.

of the regional governments, e.g. development of pellet production in the Arkhangelsk region or substitution of fossil fuels by wood fuels for municipal heating plants in the Republic of Karelia. These strategies take into account local conditions and propose practical measures on development of wood based energy in the regions. At the same time implementation of these strategies is hindered by lack of knowledge and finances (Munoz and Goltsev, 2012).

In regions like north-western Russia, where potential gains from the intensification of forestry are high, there are knowledge gaps regarding the availability of resources and efficiency of existing technologies for production of wood fuels. It is necessary to fill in these gaps in order to quantify the potential gains and to understand what the development of bioenergy can offer. This requires the estimation of resources, the transfer of best available technologies and their evaluation in terms of economic performance and the technical applicability for production of wood fuels in the conditions of north-western Russia. In order to obtain the required knowledge, several case studies and in-depth analyses (Gerasimov et al., 2007; Goltsev et al., 2010a; Goltsev et al., 2010b; Goltsev and Lopatin, 2013) have been implemented in the Leningrad region of Russia. The region was selected as a study area because of its relatively well-developed forestry sector, the availability of data and the proximity to the EU.

## 1.2. Theoretical background

### 1.2.1.  Biomass potentials

In the context of this study, resource potential is an estimation showing how much woody biomass is available/accessible/required under certain conditions or scenario assumptions. The selection of the type of biomass potential to be estimated is a crucial step, because to a large extent, this defines the approach, methods and input data of a biomass assessment (Smeets et al., 2010a). The definitions for types of resource potential are presented below (Smeets et al., 2010a):

- Theoretical potential: the overall amount of biomass produced by trees that can be considered theoretically available for bioenergy production within fundamental bio-physical limits, taking into account the amount of woody biomass needed for other purposes.
- Technical potential: the fraction of the theoretical potential that is available under certain infrastructural conditions (e.g., density of forest road network), technical conditions (e.g., steepness of slopes) and ecological limitations (e.g., fertility of forest soils). Conflicts of interests due to possible other land uses (food, feed and fibre production) could be also taken into account.
- Economic potential: the share of the technical potential the utilisation of which is economically profitable under the given conditions.
- Implementation potential: the fraction of the economic potential that could be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives.
- The ecologically sustainable potential: the fraction of the theoretical potential that is limited by certain ecological constraints.

*1.2.2.    Approaches of biomass assessments*

There are several approaches for estimating available biomass resources and numerous methods within them. The approaches are, namely: resource-focused approach, demand-driven approach, wood resource balance and integrated assessment approach. The two first approaches have longer history. According to Berndes et al. (2003), the resource-focused approach allows estimation of the total bioenergy resource base and one can take into account the competition between different uses of the resource (supply side). The demand-driven approach is suitable for estimation of the amount of biomass needed to reach targets on bioenergy generation (demand side) and can also help analyse the competitiveness of biofuels compared with other energy sources. The wood resource balance approach is relatively new and enables analysis of inter-sector trade flows and consequent uses, estimating the possible demand for wood and its supply by taking into account the multiple uses of wood (UNECE/FAO, 2009). The integrated assessment approach is the most complex of those mentioned. This approach is based on the application of integrated assessment models, such as IMAGE (IMAGE-team, 2001). These models are capable of considering numerous factors related to supply (forest areas, accessibility of forests, etc.), demand (targets on supply bioenergy, competitive uses of land, policy, etc.), economics (cost competitiveness of bioenergy, etc.) and ecological (emissions of greenhouse gases, soil erosion, etc.) concerns. Integrated assessment models are used to analyse interrelations of these factors and to create different scenarios of biomass availability and demand, in order to predict future development of bioenergy and develop associated policy measures.

*1.2.3.  Methods of biomass assessments*

All of the mentioned approaches have their strengths and weaknesses. The resource-focused approach provides an estimation of the availability of wood resources for energy generation. Different technical and environmental limitations could be taken into account when assessing resource potential. However, this approach does not provide the methods needed to see, for example, how such factors as the development of energy conversion technologies or the competitive use of wood will affect the available biomass potential. The factors mentioned above and those that originate directly from the demand for wood energy could be taken into account within the demand-driven approach. Using this approach, it is possible to quantify the effects of development of the energy and wood industries, land availability and political and social aspects on the available biomass potential. The weak point of this approach is that the reliability of the results obtained strongly depends on conversion factors used to translate demand into the quantity of woody biomass. Wood resource balance analyses interconnect wood supply and demand flows to estimate actual volumes of wood supply and demand taking into account competitive and multiple uses of wood. The approach is also suitable for identifying uncertainties and gaps in the available statistical data. However, the reliability of this approach depends strongly on the conversion factors used to convert the quantity of produced wood goods to round wood equivalents. These factors vary depending on the wood processing technologies, quality of wood and tree species, etc., (Thivolle-Cazat, 2008). The integrated assessment approach facilitates the creation of comprehensive models of biomass supply and demand; however, these models are very expensive to build and run.

Depending on the approach, different methods are used to assess biomass resources. Relatively simple computational methods could be used to analyse forest inventory data

within the resource-focused approach, in order to quantify the theoretical potential of woody biomass. The inventory analysis methods could be supplemented with methods of geospatial analysis to account for spatial factors that affect the availability of the biomass and with different growth models to predict the volumes of wood available in the future. Methods of economic statistics, demand analysis, cost comparative analysis and energy-economic models are used within the demand-driven approach. The analysis of wood flow statistics is the main method of the wood resource balance approach. All the methods mentioned above, as well as methods of policy analysis and different climate, physical and chemistry models are used within the integrated assessment approach. Irrespective of the approach, the reliability of all these methods depends strongly on the input data and our understanding of the different processes affecting availability and use of woody biomass.

## 1.3. Thesis framework and research environment

Biomass assessments are time-consuming and costly studies. When estimating available or needed biomass resources, one has to collect and analyse large amounts of data and consider numerous factors affecting biomass potentials. In the case of woody biomass derived from forests, reliable results can be obtained only if respective reliable forest inventory data are available and if forestry practices and technologies applied in the area of concern are well known to the evaluator.

It was mentioned previously that the selection of the type of resource potential defines the approach and the methods of the biomass assessment. At the same time, the availability of input data and their content have clear importance when designing research framework. Among the considered biomass potentials it is easiest to estimate the theoretical potential of woody biomass using the resource-focused approach. This requires only relatively simple conversion of the standing volumes received from forest inventory data into the overall volumes of woody biomass. However, the theoretical potential has little practical value. This type of biomass potential does not take into account factors, such as technical accessibility of forests and felling methods used, which affect the actual volumes of wood that could be used to produce a fuel. Therefore, the theoretical potential cannot be considered, for example, for the planning of forest chip supply to municipal heat plants.

The results of assessments done using the demand-driven or integrated assessment approaches (estimations of economic or implementation potentials) reflect reality sufficiently well to be used as a base for developing bioenergy strategies or even business plans. However, these assessments require the application of comprehensive models, such as energy-econometric models or integrated assessment models.

Despite some disadvantages of the resource-focused approach related to the economic side of bioenergy, this approach can also provide useful results. It is possible to obtain good estimations of how much wood could actually be used for fuel production, by applying methods of spatial analysis to limit the theoretical potential and by taking into account spatially-related factors and cost-comparative analyses to consider the impact of economic factors, such as the costs of wood fuel supply. However, spatial analysis requires the availability of digital maps of forests with all the necessary attributive data. When these digital maps are not available, even digitising forests areas on a district level is very costly. A cost-comparative analysis provides reliable results only if detailed data on productivity and costs of wood fuel supply are available.

The PhD study was done at two spatial levels. The more general study, described in paper I, estimated the availability of energy wood derived from two sources: wood harvesting and wood processing, in the Leningrad region located in north-western Russia. This region was selected as the study area for several reasons. The first reason was the relatively good theoretical potential for the development of bioenergy because of the availability of wood resources for production of forest chips and the efforts of the region's government to increase the use of local fuels for energy generation (Gerasimov et al., 2007). The second reason was proximity to the European Union (EU); the region has a common border with two EU countries: Finland and Estonia. Also, the good transport connections between the Leningrad region and the EU, including railways and waterways, are useful when considering the possible export of wood fuels to the EU. The availability of raw material for the production of forest chips is the result of high (compared with other regions of Russia) utilisation of the annual allowable cut and a significant share of deciduous wood (37% of the total volume), which often has no use other than for energy (Figure 1). In 2007, the utilisation ratio of the annual allowable cut reached 65%, or 4.4 $Mm^3$ of 6.8 $Mm^3$ (Gerasimov et al., 2009).

More specific case studies, described in papers II-IV, were done in the Tikhvin and Boksitogorsk districts of the Leningrad region. These districts are among the richest in the Leningrad region in terms of forests. In both districts, the share of the forested area is more than 80% of the total land area (84% in the Tikhvin district and 88% in the Boksitogorsk district). Forests of these districts are almost equally presented by coniferous and deciduous tree species. Pine and spruce cover over 50% of the forest area, about 30% is covered by birch and aspen and the rest is different species of alder and willow. The districts' annual allowable cut, calculated only for final fellings, is not fully utilised. In 2004, the annual



**Figure 1.** Logging residues and aspen round wood left decaying at the roadside (Ilavský et al., 2007)

allowable cut in the Boksitogorsk district was 366 000 m$^3$ and 53% (197 000 m$^3$) of this volume was actually harvested. The utilisation ratio on the annual allowable cut in the Tikhvin district was much higher; about 87% (244 000 m$^3$) of 280 000 m$^3$ was harvested. For comparison, the annual allowable cut in the neighbouring Shugozersky district was 580 000 m$^3$ but its utilisation ratio was less than 47% (269 000 m$^3$).

At the time of the implementation of the studies in the districts there were several big logging companies each with an annual actual cut of over 200 000 m$^3$, as well as several smaller companies. The biggest companies belonged to different international wood processing corporations. Forests in Russia are a state property and logging companies have to obtain leasing rights for forest areas via auctions in order to be allowed to harvest wood. There were 14 companies leasing forests for harvesting in the territory covered by the study.

Wood in the region is mainly harvested by two methods: the cut-to-length method (CTL) and the tree-length method (TL). Regarding wood fuel production, there is a significant difference between these methods. The difference is the place where the raw materials for forest chip production are generated. When the CTL method is used, felled trees are cross-cut and delimbed at the felling sites. Thus, all raw materials for chipping, non-industrial wood, branches and tops, lump wood and cut ends are left in the forests. Only branches and tree-tops are left at the felling sites when the TL method is used. Non-industrial wood, most of the lump wood and cut ends are amassed at central processing yards where tree-lengths are cross-cut. Big logging companies usually used both methods but the TL method is more commonly used by small logging companies due to the lower machinery costs for this method. However, the share of the CTL method is continuously growing at the expense of the TL method. When renewing their logging machinery, companies increasingly shift to the CTL method.

In papers II and III, two additional methods: the full-tree method (FT) and the tree-section method (TS) were considered to benchmark most common CTL and TL logging methods used in the study area. FT and TS are logging methods not widely used in the districts. However, from the viewpoint of forest chip production, these methods have advantages over CTL and TL. Logging residues are distributed over the whole logging site when felling by the CTL and TL methods; thus, the collection of logging residues for chipping causes additional costs. In contrast, trees or tree sections can be delimbed and bucked at the roadside if the FT or TS methods are used. In this case, all energy wood is amassed at the roadside, which facilitates chipping. However, the FT and TS logging methods should be used carefully because of their environmental impact on forest soils and the remaining trees (Grigorev et al., 2008).

Traditional chopped firewood was the most common type of wood fuel in the study area. Firewood is one of the cheapest fuels available in the areas and it was used mainly for the heating of family houses. The logging companies operating in these districts had social obligations to supply firewood to certain social groups at a price lower than market price. Firewood is especially important in rural areas, where remote villages are too small to be connected to natural gas pipelines, or where their population is too poor to pay to be connected and where traditional fire wood is the most common fuel. There are a few municipal boiler-houses using wood as fuel and some larger logging and wood processing companies have their own boilers, which utilise their own wood residues as fuel to produce heat energy for their own consumption.

Logging companies in the region face several problems despite the relatively high utilisation ratio of the annual allowable cut. First, is the low accessibility of forests due to

the lack of roads and because a significant proportion of the forests are located on wet soils, which can only be harvested during stable frosts in winter. In the study area there is less than 1 m ha$^{-1}$ (Mönkkönen and Dahlin, 2008) of forest roads capable of bearing conventional logging trucks all year round. The optimal length of good quality forest roads is 10.5 m ha$^{-1}$, which is ten times greater (Mönkkönen and Dahlin, 2008). Construction of forest roads within leased forest is a duty of logging companies. The companies do not actively develop their networks of all-season roads for one main reason. In the conditions of north-western Russia construction of winter forest road is 4-10 times cheaper than construction of all-season road (Ermilova, 2008). Therefore, logging companies tend to build winter forest roads and to use during summer off-road trucks for intermediate transportation of wood between forwarder unloading sites and good quality forest roads. The small load capacity of the off-road trucks, their low speed and additional loading-unloading operations increases transportation costs; however, they do have lower capital costs compared with imported logging trucks (Goltsev et al., 2011). Other problems are forest fires and the large volumes of deciduous wood for which, often there is no demand.

Recently, increasing unemployment in forest villages has become an important issue that has placed pressure both on the logging companies and the local authorities. These problems, at least partly, could be solved by the development of local wood fuel supply chains. Therefore, the development of the supply of forest chips has attracted attention from some of the logging companies and the local authorities. In their opinions, the production and use of forest chips has positive economic and social benefits. The logging companies presume that production of forest chips will allow them to increase income from leased forest areas and solve the problems related to the utilisation of low-quality deciduous wood, the cleaning of felling sites and the prevention of forest fires. Increased income from forest areas will allow the forest leasers to build more forest roads and access remote harvesting sites. From the mid of the 2000s, the local authorities suppose that forest chips could be used as a fuel for municipal boiler houses (Benin, 2006). This would create employment, decrease the cost of heat for the local population and reduce the dependency of the region on increasingly costly fossil fuels. This positive attitude of the logging companies and the local authorities to wood-based energy has supported the implementation of these studies. All the data used in the studies were obtained thanks to the close cooperation of the logging companies operating in the study area and the administration of the districts.

## 1.4.    Aims of the study

The overall aim of the studies was to propose a methodology for the evaluation of the resource potential of north-western Russia from the viewpoint of bioenergy development, taking into account the potential of intensification of forestry and the technical, socio-economic and climatic challenges. Using the proposed methods, it was also possible to estimate: the technical accessibility of forests, the techno-economic efficiency of available forest chip production technologies and the employment effects of forest chip supply. The proposed methodology was tested in the Leningrad region of Russia to solve the following specific research tasks:

      1.    To estimate the availability of energy wood in north-western Russia at the regional level (paper I)

      2.    To quantify employment effects from the supply of forest chips at local level (paper II)

3. To compare the efficiency of different technologies for the production of forest chips and to estimate the cost competitiveness of forest chips within a case study in the Tikhvin district of the Leningrad region of Russia (paper III)

4. To evaluate the technical accessibility of wood resources in the study area, taking into account the impact of climate change (paper IV)

In order to achieve the targets of this PhD thesis and to keep costs of the research within acceptable limits, the resource-focused approach was selected. Analytical methods, such as: the analysis of forest inventory data, spatial analysis, cost-comparative analysis and statistical methods were used to provide an estimation of the biomass potential in the area of concern, as close to reality as was allowed by the available input data.

## 2. MATERIAL AND METHODS

### 2.2. Estimation of energy wood potential at the regional level

In the context of the thesis, the aim of the methodology development study (paper I) was to establish a basis for the consequent case studies, by estimation of the annual availability (theoretical potential) of energy wood resources (non-industrial round wood and by-products of wood processing) at a regional level. The Leningrad region of Russia was selected as the study area. The estimation was done for two sources of energy wood:

- Wood harvesting, including non-industrial wood and wood residues from final fellings, thinnings and other fellings and central processing yards of logging companies
- Wood processing – production of sawn wood.

Depending on its source, the forms and volumes of energy wood are affected by many factors, such as: type of felling, forest characteristics (species, age, quality) logging methods used, bucking patterns, harvesting and sawmilling machinery. In this study, the term "energy wood" includes the following types of woody biomass:

- Logging residues (branches, tree-tops and lump wood) generated during production of tree-lengths or assortments
- Non-industrial wood (round wood that has no demand from conventional wood processing industry)
- Sawmill by-products (sawdust, bark, slabs and cut-ends)

Three scenarios of energy wood availability were considered to analyse the effect of intensification of forest use on the resource potential. The *"Recent"* scenario reflects the potential of energy wood, taking into account the intensity of fellings and sawmilling as it was in 2004. In the original article (Gerasimov et al., 2007), the first scenario was named *"Actual"*; however, in the thesis, this scenario was renamed to *"Recent"* due to the time that had passed since the original publication. This scenario is based on the recent utilisation ratio of the annual allowable cut and the implementation of the cut-to-length method and respective sawn wood production, i.e., 7.9 $Mm^3$ fellings (5.1 $Mm^3$ final felling, 1.5 $Mm^3$ thinning, 1.3 $Mm^3$ other felling) and 0.6 $Mm^3$ sawn wood production. The *"Allowable"* scenario shows the potential of energy wood assuming full utilisation of the annual allowable cut, based on current logging technology and increasing sawn timber production, taking into account on-going greenfield projects, such as the Svir-Timber sawmill and the Mayr-Melnhof-Holz Efimovsky sawmill. This means an increase of the annual cut of up to 12.3 $Mm^3$ of felled wood, including full utilisation of the allowable cut of: 9.5 $Mm^3$ for final felling, 1.5 $Mm^3$ thinning, 1.3 $Mm^3$ other felling and the growth of

sawn wood production of up to 1 Mm$^3$. The *''Potential''* scenario shows energy wood resources in the case of the implementation of intensive forest management, which means a significant increase in thinnings, full utilization of annual allowable cut based on cut-to-length technology and the increase of sawn timber production according to available sawlog output in the region (no export). This means the full utilisation of fellings, i.e., 15.4 Mm$^3$ (9.5 Mm$^3$ final felling, 4.6 Mm$^3$ thinning and 1.3 Mm$^3$ other felling) and 2 Mm$^3$ sawn wood production per year.

### 2.2.1. *Input data*

The potential of energy wood from wood harvesting within the Leningrad region of Russia was estimated at the level of state forest management units (FMU, *lesnichestvo*), former *leskhozes*. The total number of FMUs in the Leningrad region is 28. The FMUs and their wood resources in terms of forest areas are shown in Figure 2.

Forests cover about 56% of the Leningrad region. The total forested area of the Leningrad region is 5.9 Mha, including 4.6 Mha under the administration of the Federal Forestry Agency, 0.9 Mha are former agricultural forests (forests belonged to former agricultural management units (*sovkhozez and kolkhozes*)) and 0.3 Mha are forests of the Ministry of Defence and other forests (forests of the Ministry of Defence and town forests). The stocked forests represent 75% of the total forested area or 4.4 Mha. In terms of cover



**Figure 2.** State FMUs of the Leningrad region and their stocked forest area (1000 ha).

and volume, pine and spruce each represent about 30%, birch 25% and aspen less than 10%. The quality of wood in forests is a very important characteristic when estimating biomass potential for fuel production. In most cases, non-industrial wood that has no other application is used for biofuel production. For the forests of the Leningrad region, an average output of non-industrial wood measured as a percentage of the total standing volume is 15% to 25% for spruce, 14% to 24% for pine, 46% to 74% for birch and 56% to 78% for aspen (Gerasimov et al., 2007). However, these species are not evenly mixed across the region. Coniferous forests dominate in the northern and eastern parts of the Leningrad region and the bigger proportion of deciduous forests can be seen in the western and southern parts.

The potential of sawmill by-products was estimated for each of the 16 administrative districts of the Leningrad region. A more detailed estimation was not possible because an administrative district is the smallest spatial unit available for Russian statistical data. For the study, state statistical data (PetroStat, 2006), literature (Anuchin, 1981; Kuropteev and Vaskova, 1986; Korobov and Rushnov, 1991; Usoltsev, 2001; Chemodanov and Tsarev, 2002) and data from logging companies were used as input data.

### 2.2.2. *Estimation of energy wood potential*

The potential of available energy wood at felling sites was calculated using equations (1–5) given below. Annul volume of non-industrial wood and logging residues not used for strip road improvement were calculated in cubic metres over bark ($m^3$ o.b.):

$$EW = EW_{fTL} + EW_{fCTL} + EW_{th} \qquad\qquad (1)$$

Where:
$EW$ – the annual energy wood volume from logging ($m^3$ $yr^{-1}$),
$EW_{fTL}$ – the annual energy wood volume from final fellings by the TL method ($m^3$ $yr^{-1}$),
$EW_{fCTL}$ – the annual energy wood volume from final fellings by the CTL method ($m^3$ $yr^{-1}$),
$EW_{th}$ – the annual energy wood volume from thinnings ($m^3$ $yr^{-1}$).

The type of logging method used influences the volumes of energy wood generated at the felling sites. Therefore, the annual potential of energy wood from final fellings had to be calculated separately for felling areas cut using CTL and TL. The annual volume of energy wood from CTL final fellings ($EW_{fCTL}$) was:

$$EW_{fCTL} = TH_f \times (1 + BT) - IRW_f \qquad\qquad (2)$$

Where:
$TH_f$ – the annual timber harvesting volume by final felling ($m^3$ $yr^{-1}$),
$IRW_f$ – the industrial round wood volume by final felling ($m^3$ $yr^{-1}$),
$BT$ – an expansion factor to account for branches and tops from final felling (value 0–1).

The factor $BT$ is used to take into account the volume of branches and tops of trees that is not used for strip road improvement. The value of $BT$ in this study was 0.052, meaning that 5.2% of the harvested woody biomass is used for energy wood supply in the form of branches and tree-tops (Gerasimov et al., 2007).

The annual volume of energy wood from TL final fellings ($EW_{fTL}$) was:

$$EW_{fTL}=TH_f\times(LS+BT) \tag{3}$$

Where:
LS – an expansion factor to account for lump stems and tops from final felling (value 0–1).

The factor LS reflects the average share of lump stems and tops of tree-lengths caused by improper cutting, skidding and loading operations before transporting the wood to the central processing yard in the total harvested volume and which is not used for strip road improvement. The value of LS in this study was 0.05, meaning that 5% of the harvested woody biomass is used for energy wood supply in the form of lump stems and tops of tree-lengths (Gerasimov et al., 2007).

The annual volume of energy wood from thinnings ($EW_{th}$) was calculated based on CTL fellings, because CTL is the most common method for thinnings in the study area:

$$EW_{th}=TH_{th}\times(1+BT)-IRW_{th} \tag{4}$$

Where:
$TH_{th}$ – the annual volume of thinnings (m$^3$ yr$^{-1}$),
$IRW_{th}$ – the volume of industrial round wood from thinnings (m$^3$ yr$^{-1}$),
BT – an expansion factor to account for branches and tops from thinnings (value 0–1).

The volume of wood residues accumulated at the central processing yards during cross-cutting was estimated as:

$$EW_y=(TH_f\times(1-LS)-IRW_f)\times(1+LS_Y) \tag{5}$$

Where:
$EW_y$ – the annual volume of energy wood from cross-cutting at the central processing yards (m$^3$ yr$^{-1}$),
$LS_Y$ – an expansion factor for including lump stems and tops from cross-cutting at central processing yards (value 0–1).

The value of $LS_Y$ in this study for the Leningrad region was 0.03, meaning that 3% of round wood delivered to the central processing yards is used for energy wood supply in the form of lump stems and tops of logs.

The production of sawn wood generates different types of by-product, such as: sawdust, shavings, bark, slabs and lump wood. The volumes of these by-products accumulated during wood processing depend to a large extent on the type of final product, sawing equipment, quality of wood and tree species. These factors can be taken into account only at the local level when a limited number of sawmills is covered by detailed surveys. In this study, it was not possible to conduct such surveys due to the wide spatial scope. Therefore, the annual volume of energy wood at sawmills was estimated based on the share of by-products in production of sawmills reported in the literature (Gerasimov et al., 2007). In this study, a share of 60% was used, meaning that 60% of the annual round wood volume consumed by sawmills is converted during wood processing into by-products.

### 2.3. Estimation of forest energy wood potential at a local level

The advantage of biomass assessments performed at a local level is the possibility to collect and analyse detailed data. The following data were used to estimate energy wood potential in the districts:

- tree species composition
- age structure
- growing stock
- actual volume of fellings
- allowable volume of fellings

In paper II these data were used to calculate three scenarios designed in the same way as was done in paper I. The first scenario *"Recent"* is based on the volume of fellings in 2004. The second scenario *"Available"* reflects the potential of energy wood when the annual allowable cut is fully utilised. The third scenario *"Potential"*, in addition to full utilisation of the annual allowable cut, assumes intensification of thinnings up to the level of 30% of the annual allowable cut; such intensity of thinnings can be seen, e.g., in Finland (Kariniemi, 2006). The volume of other fellings is the same in all scenarios. When estimating the potential of energy wood, the crown biomass harvested during thinnings was neglected due to its small amount. The volume of energy wood was estimated in solid $m^3$ over bark and the estimation procedure is described below in equations 6–11.

Available volume of energy wood was estimated by the equation:

$$EW_i = EWT_i + EWC_i + VWO_i \times (1 - IWO) \tag{6}$$

Where:
$i$ – Scenario
$EW_i$ – available volume of energy wood, $m^3 \ yr^{-1}$
$EWT_i$ – volume of energy wood from thinnings, $m^3 \ yr^{-1}$
$EWC_i$ – volume of energy wood from final fellings, $m^3 \ yr^{-1}$
$VWO_i$ – volume of other fellings, $m^3 \ yr^{-1}$
$IWO$ – ratio of industrial wood for other fellings, value 0.5

When first commercial thinnings are done, using the FT or TS methods, energy wood can include the entire above-ground biomass of low quality deciduous trees, non-industrial wood and crown wood. The CTL method provides only stem energy wood, because the collection of logging residues from thinnings is not economically viable (Ilavský et al., 2007). From the second commercial thinnings, only stem energy wood is available, because the FT and TS methods are not used due to high risk of damage to the remaining trees. The total volume of energy ($EWT_i$) wood available from thinnings was:

$$EWT_i = \sum_{n=1,2} \left( TV_{ni} * (1 - IW_n) \right) + TVF_i * CRF \tag{7}$$

Where:
$i$ – Scenario
$n$ – the 1st or the 2nd commercial thinnings
$TV_{ni}$ – total volume of stem wood from commercial thinning $n$, $m^3 \ yr^{-1}$
$IW_n$ – ratio of industrial wood for commercial thinning $n$; value 0.5
$TVF_i$ – total volume of stem wood from first commercial thinning, $m^3 \ yr^{-1}$

CRF – mean crown-to-stem wood ratio for the first commercial thinning; value 0.24

The soil conditions of the districts often require use of logging residues (LR) for improvement of the strip road bearing capacity. In many cases, it is possible to use only part of the total amount of LR for the improvement of strip roads and the rest could be used to produce forest chips. In the study area, most fellings are done during winter when there is no need to use LR for strip road improvement. Therefore, it was assumed that about 60% of the annually available LR from final fellings could be utilised for forest chip production. According to the companies' reports about 30% to 40% of felled aspen stem wood was used for forest road construction. Almost all aspen is low-quality wood that only has energy value. The use of aspen for road construction decreases the total volume of energy wood available from final felling. Energy wood from the final fellings includes stem wood, collectable LR and also, if the FT method is used, crown biomass:

$$EWC_i = TVC_i \times (1-IWC) - TVC_i \times SA \times WRC/100 + EWFT_i + CLR_i \qquad (8)$$

Where:
$i$ – Scenario
$TVC_i$ – volume of the final felling done by the CTL or TL methods, $m^3\ yr^{-1}$
$IWC$ – ratio of industrial wood for the final fellings; value 0.67
$SA$ – share of aspen in felled volume; value 0.25
$WRC$ – share of aspen stem wood used for road construction; value 35%
$EWFT_i$ – volume of energy wood from the final fellings done by the FT method, $m^3\ yr^{-1}$
$CLR_i$ – collectable volume of LR, $m^3\ yr^{-1}$

The volume of energy wood ($EWFT_i$) from final fellings done by the FT logging method was estimated as:

$$EWFT_i = VFT_i \times (1-IWC) + VFT_i \times ACR_{100} \qquad (9)$$

Where:
$VFT_i$ – volume of the final felling done by the FT method, $m^3\ yr^{-1}$
$ACR_{100}$ – average crown-to-stem wood ratio for final felling; value 0.14
The volume of collectable LR was:

$$CLR_i = SCLR_i/100 \times TVC_i \times ACR_{100} \qquad (10)$$

Where:
$SCLR_i$ – share of collectable LR in the total volume of LR, value 60%

Average tree species composition of felled wood volume, age of stand and crown-to-stem wood ratios reported by Usoltsev (2001) for tree species, were taken into account to estimate the mean crown-to-stem wood ratio for thinnings and final fellings:

$$ACR_a = \sum_{s=1}^{n} (CR_{sa} \times S_s) \qquad (11)$$

where:

$a$ – age of felling
$s$ – tree species
$ACR_a$ – average crown-to-stem wood ratio
$CR_{sa}$ – crown-to-stem wood ratio for tree species $s$ at age $a$, %
$S_s$ – share of tree species $s$ in species composition of felled wood volume; value 0–1

The values of industrial-to-stem wood ratio and crown-to-stem wood ratio used in equations 6–11 are given in Goltsev et al. (2010). The values of industrial-to-stem wood ratio were taken from Anan'ev and Grabovik (2009).

### 2.3.1.  *Productivity of forest chip supply chains*

The logging companies in the study area did not supply forest chips and did not utilise the respective machinery when this case study was undertaken. Theoretical forest chip supply chains were created, based on the industrial wood supply chains used by the logging companies, to find the most productive supply chain and to estimate the total number of machines and their operators necessary to process the available volume of energy wood. A bundler, mobile and stationary chippers and chip trucks were added to the industrial wood supply chains. The created forest chip supply chains differed by the logging method used and the type of wood comminution – mobile or stationary chipping. A Kesla C4560 drum chipper with its own engine and a Kesla F700 hydraulic crane were considered as a stationary chipper (end facility chipping). The same chipper installed on a KAMAZ truck was considered as a mobile chipper. The productivity was 23 and 17 solid $m^3$ of forest chips per hour of total working time, respectively (Goltsev et al. 2010). The same SCANIA R580 chip truck was included in all forest chip supply chains based on mobile chipping. The logging methods and the forest chip supply chains considered in the study are presented in Table 2.

The number of machines needed to harvest and process the available energy wood resources depends on the actual productivity of the machines forming a forest chip supply chain. Many factors, such as: the logging method, operators' experience, machines' technical parameters, cutting site characteristics, average distance of transportation and even size of the chip particles, affect the productivity of the machines. Characteristics of the cutting sites are one of the main factors affecting the availability of energy wood and productivity of wood harvesting. The forest inventory data received from the companies were summarised and averaged to obtain the characteristics of an average felling site in the study area. The average characteristics of the cutting areas, the recommended felling intensity (Anan'ev et al., 2005), the volume of felled wood and the volume of energy wood available are presented in Table 3. The volume characteristics were calculated according to the average tree species composition of the forests in the study area: spruce 28%, pine 19%, birch 28% and aspen 25% of the growing stock.

**Table 2**. Logging methods and supply chains considered in the study.

| Type of fellings | Logging method | Energy wood supply chains |
|---|---|---|
| 1st commercial thinnings | TS | Chainsaw, forwarder, chipper, chip truck |
| | TS | Chainsaw, skidder, chipper, chip truck |
| | TS | Harvester, forwarder, chipper, chip truck |
| | CTL | Chainsaw, forwarder, log truck, end facility chipping |
| | CTL | Harvester, forwarder, log truck, end facility chipping |
| | TL | Chainsaw, skidder, tree-length truck, end facility chipping |
| 2nd commercial thinnings | CTL | Chainsaw, forwarder, chipper, chip truck |
| | CTL | Harvester, forwarder, chipper, chip truck |
| | CTL | Chainsaw, forwarder, log truck, end facility chipping |
| | CTL | Harvester, forwarder, log truck, end facility chipping |
| | TL | Chainsaw, skidder, chipper, chip truck |
| | TL | Chainsaw, skidder, tree-length truck, end facility chipping |
| Final fellings | CTL | Harvester, forwarder, chipper, chip truck |
| | CTL | Harvester, forwarder, log truck, end facility chipping |
| | FT | Chainsaw, skidder, chipper, chip truck |
| | TL | Chainsaw, skidder, tree-length truck, end facility chipping |
| | CTL+RB[5] | Harvester, bundler, forwarder, chipper, chip truck |
| | CTL+RB | Harvester, bundler, forwarder, log truck, end facility chipping |

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[5] RB – residue bundles made by a bundler; a machine that collects, compacts and bundles logging residues at the felling site after wood harvesting.

**Table 3.** Average characteristics of cutting areas, felling intensity, volume of felled wood o.b. and volume of energy wood available for supply.

| Felling | Age of stand | Average growing stock*, $m^3\ ha^{-1}$ | Cutting intensity | | Industrial wood | Volume of aspen wood for road construction, $m^3\ ha^{-1}$ | Energy wood, $m^3\ ha^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | % | $m^3\ ha^{-1}$ | $m^3\ ha^{-1}$ | | Stem wood | Crown biomass | Collectable LR | Total |
| 1st commercial | 50 | 138 | 35 | 48 | 24 | - | 24 | 6 | - | 30 |
| 2nd commercial | 70 | 198 | 35 | 69 | 35 | - | 34 | - | - | 34 |
| Final felling | 100 | 272 | 100 | 272 | 182 | 24 | 66 | 38 | 23 | 104[**]/89[***] |

* reported by the companies, including over maturing stands
** FT method
*** CTL or TL method

Due to the limited geographical scale of this study it was possible to collect productivity data from the logging companies. The data included productivity values for manual felling, cutting by harvesters, forwarding and skidding for final felling. The collected data allowed the estimation of productivity as the volume of wood processed per hour of total working time. More detailed productivity estimations were not possible because the companies provided the productivity values as the volume of wood processed during eight hours of one machine shift. During the study it was also found out that the productivity of harvesters was different among the companies; some of the companies employed Russian operators, others had contractors from Finland. In most cases, the Russian operators had lower productivity due to insufficient experience.

The logging companies did not perform thinnings. Therefore, the productivity for harvesting and forwarding commercial thinnings was estimated using cost calculation software (Laitila et al., 2006) and taking into account the average characteristics of the cutting sites and the productivity difference between the forwarding after the felling of trees done by a harvester and by a lumberjack (Laitila et al., 2007). This calculation approach is based on productivity data and functions for Finland. The results obtained using this approach could not be used directly, because in reality, the productivity of the same supply chain under the conditions of the study could be lower than that calculated due to less-skilled operators and poorer forest infrastructure. A productivity reduction coefficient was applied to estimate the potential productivity of thinning operations, which could be reached by the logging companies in the region. The productivity reduction coefficient reflects the difference between the average productivity of harvesting and forwarding during final fellings in Finland and that reported by the companies. The coefficient was calculated as:

$$K=PC/PF \qquad (12)$$

where:
K – reduction coefficient of productivity, value 0–1
PC – productivity reported by the companies for final fellings, $m^3 h^{-1}$
PF – average productivity in Finland for final fellings, $m^3 h^{-1}$

The reduction coefficient allows the estimation of the presumptive productivity in thinnings for the companies using the calculated productivity for thinnings in Finnish conditions:

$$TP=CP \times K \qquad (13)$$

where:
TP – productivity of thinnings for the companies, $m^3 h^{-1}$
CP – calculated productivity for thinnings in Finnish conditions, $m^3 h^{-1}$

Table 4 shows the average productivity of wood harvesting and forwarding at the study area and in comparable conditions in Finland and the calculated reduction coefficient.

During final fellings, significant volumes of LR are accumulated at the cutting sites. Their collection and forwarding is a costly operation due to the low bulk density of LR. One of the methods for decreasing the costs of LR collection and forwarding is the bundling of LR using a bundler, which is a purpose-built machine. These machines were

**Table 4.** The average productivity of wood harvesting and forwarding reported by the companies for the study area and for comparable conditions in Finland (Nurminen et al., 2006) and the calculated reduction coefficient.

| Felling | Average stem volume, m$^3$ | Volume, m$^3$ ha$^{-1}$ | Productivity | | | | Reduction coefficient | |
|---|---|---|---|---|---|---|---|---|
| | | | Harvesting | | Forwarding | | Harvesting | Forwarding |
| | | | Study area | Finland | Study area | Finland | | |
| Final felling | 0.45 | 272 | 13 | 20 | 10 | 13.3 | 0.7 | 0.8 |

used, e.g., in Finland (Hakkila, 2004). The method was included in the study to evaluate its feasibility in Russian conditions.

### 2.3.2. *Quantification of the employment effect*

Production of forest chips could have a positive effect on employment in the area of concern (Hakkila, 2004). Knowing the available volumes of energy wood, it was possible to estimate the required number of machines and operators. When calculating the required number of machines, the following condition has to be taken into account:

$$QM_t \times AP_t \geq EW_{ti} \tag{14}$$

where:
$t$ – type of machine
$i$ – scenario
$QM_t$ – quantity of forest chip supply machines $t$, items
$AP_t$ – annual productivity of forest chip supply machine $t$, m$^3$ yr$^{-1}$
$EW_{ti}$ – available volume of forest chip for supply by machine $t$ in scenario $i$, m$^3$ yr$^{-1}$

The quantity of machines required to process the available volume of energy wood is:

$$QM_t = EW_{ti}/AP_t \tag{15}$$

The annual productivity of forest chip supply machines was estimated taking into account the average working schedule used by the companies:

$$AP_t = NWD_t \times DS_t \times NS_t \times HP_t \tag{16}$$

where:
$NWD_t$ – number of working days of machine $t$, value 221 days yr$^{-1}$
$DS_t$ – duration of a working shift, value 8 hours
$NS_t$ – number of shifts
$HP_t$ – hourly productivity of machine $t$, m$^3$ h$^{-1}$

The direct effect from the production of forest chips on the labour market can be estimated as the total number of operators of the supply machines:

$$TNO = \sum_{t=1}^{n}(NO_t \times NS_t \times QM_t) \qquad (17)$$

where:

TNO – the total number of operators

$NO_t$ – number of operators of machine $t$ per one work shift, value 1

$NS_t$ – number of work shifts

$QM_t$ – quantity of the supply machines $t$, items

## 2.4.     Efficiency of forest chip supply chains

### 2.4.1.     *Productivity of forest chip supply chains*

One of the main aims of paper III was to estimate forest chip supply costs. The main input for these calculations was the productivity of the forest chip supply chain, as estimated in paper II. However, in paper II, the productivity of long-distance transportation of energy wood was not estimated. Depending on the place where the chipping is done, energy wood is transported from forests to the end users in the form of forest chips or uncomminuted biomass (non-industrial round wood, residue bundles, or LR). The considered forest chip supply chains included roadside chipping and end facility chipping. Therefore, it was necessary to calculate the productivity of different types of trucks: tree-length trucks, log trucks and chip trucks, in order to estimate the forest chip supply costs. For this purpose, a truck productivity model based on the method of Salo and Uusitalo (2001) was modified (Gerasimov et al. 2006) to fit the techno-economic conditions of the study area. The model was used to calculate productivity and costs of energy wood transportation for 20, 60 and 100 km distances (Table 5). Recent local prices for trucks, fuel and lubricants, as well as the average salaries and working regimes, reported by the companies, were used as input data for the model.

**Table 5.** The estimated productivity of energy wood transportation.

| Type of trucks | Payload, solid $m^3$ | Transported energy wood | Transportation distance, km | | |
|---|---|---|---|---|---|
| | | | 20 | 60 | 100 |
| | | | Productivity, $m^3 \ h^{-1}$ | | |
| URAL tree-length truck | 15 | NIW | 8 | 5 | 4 |
| KAMAZ log truck | 25 | NIW, RB | 12 | 7 | 6 |
| SCANIA chip truck | 40 | Forest chips | 15 | 10 | 8 |

## 2.4.2. *Cost calculations*

The starting point for the calculation of forest chip supply costs was the collection of detailed data on the costs associated with the wood supply in the region. These data were collected from several logging companies and then averaged for the CTL and TL methods. The data included costs related to wood felling, forwarding (skidding), long-distance transportation, as well as additional expenses, such as costs of road construction, silvicultural works, marketing and administration. The total cost of forest chip supply was calculated by taking into account the cost of the wood resource (stumpage for thinning and forest rent for final fellings), costs of production of 1 m$^3$ of energy wood at each production stage and additional expense:

$$TC_y = CWR_y + \sum_{y,p=1}^{n} C_{yp} + \sum_{y,k=1}^{n} AE_{yk} \qquad (18)$$

Where:
$y$ – type of felling
$p$ – production stage
$k$ – kind of additional expense
TC – the total cost of forest chips, € m$^{-3}$
CWR – cost of wood resource, € m$^{-3}$
C – cost of energy wood, € m$^{-3}$
AE –additional expenses, € m$^{-3}$

There is a difference between the costs paid by a logging company to the state for wood harvested during final fellings and thinnings. A logging company is obliged to pay forest rent for mature forests designated for final fellings. If a logging company uses its own machinery and workers to thin leased middle-aged or maturing forests, the company pays stumpage for the removed wood instead of rent (FFAR, 2006). Stumpage, which should be paid by logging companies, is set by the local authorities depending on the tree species, quality of the wood and transportation distance. Usually, stumpage is much smaller than a rent payment per 1 m$^3$. Therefore, when calculating supply costs of forest chips made from raw material received from different fellings, it is important to know the average values of stumpage and rent per 1 m$^3$. Table 6 shows the values of stumpage and the average forest rent paid by the companies in 2005.

The operations of the logging companies in the study area were not limited just to wood harvesting. For example, the logging companies had to carry out forest regeneration, road construction and maintenance. All these operations placed additional costs on the wood

**Table 6.** Values of stumpage for commercial thinnings and forest rent for final felling in 2005.

| Payment | Value, € m$^{-3}$ | | | |
| --- | --- | --- | --- | --- |
| | Transportation distance, km | | | |
| | 0 | 20 | 60 | 100 |
| Stumpage (FFAR, 2005) | 0.31 | 0.27 | 0.23 | 0.18 |
| Average forest rent | | 1.84 | | |

**Table 7.** Values of additional expenses ($k$).

| Additional expenses | Value, € m$^{-3}$ |
|---|---|
| Repairing of machines | 0.86 |
| Reforestation | 0.06 |
| Road construction and maintenance | 0.89 |
| Loading-unloading works | 0.45 |
| Service of mechanisms | 0.02 |
| Overhead costs | 2.08 |
| General costs | 0.11 |
| Marketing costs[6] | 3.46 |
| Total | 7.93 |

harvested by the companies. These additional expenses also have to be taken into account when calculating forest chip supply costs. Table 7 shows the average values of the additional expenses which were included in the total cost of forest chips (equation 18) for final fellings. The values were provided by the companies.

Using the data provided by the companies, it was possible to calculate hourly productivity at each supply stage (paper II) and then to estimate the costs of forest chip supply:

$$HC_p = HPF_p \times CF_p \qquad (19)$$

where:
$HC_p$ – hourly cost of machinery utilisation, € h$^{-1}$
$HPF_p$ – hourly productivity for final felling at production stage $p$, m$^3$ h$^{-1}$
$CF_p$ – cost of wood of final felling at production stage $p$, € m$^{-3}$

In the case of final fellings, the cost of uncomminuted energy wood at each production stage was assumed to be equal with respect to the cost of industrial wood felling, forwarding (skidding) and transportation. These costs were obtained from the companies. The study considers several machines (chippers, bundlers and chip truck) and production stages (bundling, forwarding of bundles, chipping of wood and transportation of chips), which were not used by the companies. In order to estimate the hourly costs of these machines, the cost calculation methodology of Mäkelä (1986) was modified according to Gerasimov et al. (2006) with respect to the requirements of the Labour Code of the Russian Federation on calculation of workers' wages and compensations. The average salary paid by the companies and the working regimes of the companies were applied when calculating the cost of forest chip supply.

Costs of energy wood at each production stage for thinnings were calculated as:

$$CT_p = HC_p / HPT_p \qquad (20)$$

where:
$CT_p$ – cost of wood from thinnings at production stage $p$, € m$^{-3}$

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[6] - include salaries and incentives of sale managers, costs of advertisement, discounts, honoraria of middlemen etc.

HPT$_p$ – hourly productivity from thinnings at production stage $p$, m$^3$ h$^{-1}$

## 2.5.    Technical accessibility of forests and the impact of climate change

### 2.5.1.    *Estimation of duration of winter felling season*

Due to the lack of all-season forest roads, most fellings in the study area are done during the winter felling season, when continuing frost makes it possible to build and use cheap temporary winter roads for wood transportation. Thereby, accessibility of forests and as a result, the availability of woody biomass for wood processing and energy use, depends on the duration of the winter felling season, which continues while the air temperature remains below 0 °C. The duration of the winter felling season is expected to change due to global warming. There are numerous modelling studies that predict rising of annual mean air temperature in the future (Donner and Large, 2008). However, most of them are too complex and have too large geographical scope to be used by logging companies. In order to plan harvesting operations and road construction, logging companies need a simple method to predict the duration of the winter felling season. In this study, it is assumed that prediction of the duration of the winter felling season can be relatively easily done by extrapolating historical local meteorological data. The results of the extrapolation should be compared with the temperature trends built by one of the recognised climate models, in order to check the reliability of the predictions. The proposed method uses long-term data of local observations of air temperature.

There are several meteorological stations in the Tikhvin district but long-term data on temperature observations from these stations were not available. Therefore, long-term air temperature data (1949–2008) from those meteorological stations nearest to the study area (Verebje, St. Petersburg, Vytegra and Petrozavodsk) were used (Razuvaev et al., 1995; SRI, 2009). The data consist of values of air temperature measured four times a day. The data were averaged on a daily basis and then smoothed using the method of a simple moving average to build a temperature trend for 1978–2008. The simple moving average method is a filter used to reduce the influence of noise (the extreme high or low values in the given case). At any point of a data trend, a moving window of $n$ previous values is used to calculate the average of the data segment (Tham, 2009). This means that for the calculation, it is necessary to select a set of values that will be the first moving window. The values of the daily mean air temperature for 1949–1978 was included in the first moving window and therefore, these years were excluded from the smoothed trend. The trend was extrapolated from 2006 to 2099. The years 2007 and 2008 were excluded to avoid edge effects of smoothing (Velle et al., 2011). For the extrapolation, the MS Excel built-in linear extrapolation function was used. The results of the extrapolation were in accordance with predictions of air temperature received by the Intergovernmental Panel on Climate Change within a sophisticated modelling of climate change in Europe (IPCC, 2007).

The obtained trend showed the average daily air temperature for the past and the future, which allowed an estimation of the duration of the winter felling season by simple calculation of the days with air temperature below a certain value. After the air temperature drops below 0 °C, the forest soils still need some time to freeze to a sufficient depth to bear the weight of heavy forest machines. In the nature, freezing of the forest soils depends on several factors, such as snow depth, soil moisture and soil texture.  These factors were not considered in the study due to the lack of data describing snow depth variation within the

study area. Therefore, it was simply assumed that the winter felling season starts within the winter months when the air temperate was -5 °C or below for longer than five days. It was also assumed that the winter felling season does not end immediately when the air temperature rises above 0 °C, because the forest soils remain frozen under snow cover for some time after the air temperature has risen above freezing. The winter felling season ends during the spring months when the air temperate is 0 °C or above for longer than five days. The duration of the winter felling season was calculated as the total number of days between these two temperature limits, minus thaws of longer than 5 days. The simple average duration of the winter felling season on the 30-year basis (1949–1978) was calculated for 1978–2008, using MS Excel, to exclude the influence of extreme long and short winters on the future average duration of winter.

### 2.5.2. *Estimation of available volumes of industrial and energy wood in the winter felling forests*

The first step was to find forests where fellings can be done only during winter (hereafter – winter felling forests). Identification of such forests has a practical value only if it is done at the spatial level, which is detailed enough to look at single felling sites. This means that the data required for the identification should describe forests of the study area at the level of forest compartments. Unfortunately, such detailed data covering the whole study area was not available from public sources, because often it was considered as a commercial secret. One of the logging companies kindly presented, for the purpose of the study, detailed forest inventory data describing its leased forests in the form of a geo-information database. The data covered only 61% of forests of the Tikhvin district. However, the data included all the information necessary for the identification (see paper IV for the detailed description of the data set). Using the ESRI geographic information system ArcGIS Desktop 9.3.1 (ESRI, 2009) for the data analysis, it was possible to identify in the database forest sites that meet the criteria of winter felling sites (Figure 3):

    1.moisture of forest soil has to correspond to 3rd–5th moisture index of the Pogrebnyak's forest site classification (Martinov et al., 2008)[7]

    2.compartments for which forest management plans prescribe preservation of undergrowth during final fellings

    These criteria enabled the selection of forest sites where summer fellings would cause unacceptable damage to soil and undergrowth. Sites which met the criteria and were located by all-season forest roads were allocated as winter felling sites. Harvesting of wood on these sites during the spring and autumn will have a negative impact on the forest environment (Figure 4), which is not acceptable from the viewpoint of sustainable forest management. It was assumed that stable snow cover exists from the beginning to the end of the defined winter felling season. Such an assumption is acceptable, because several studies reported a relatively strong correlation (>0.6) between air temperature and depth of snow cover (Kitaev et al., 2011; Khan, 2012); however, some authors have proposed the opposite point of view (Bulygina et al., 2007).

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[7] - Pogrebnyak's site index is a combination of the soil fertility index, which covers various soils from poor soils of pine forests (A index) to the soils of oak forests (D index) and the soil moisture index – from very dry soils (0 index) to bog soils (5th index)
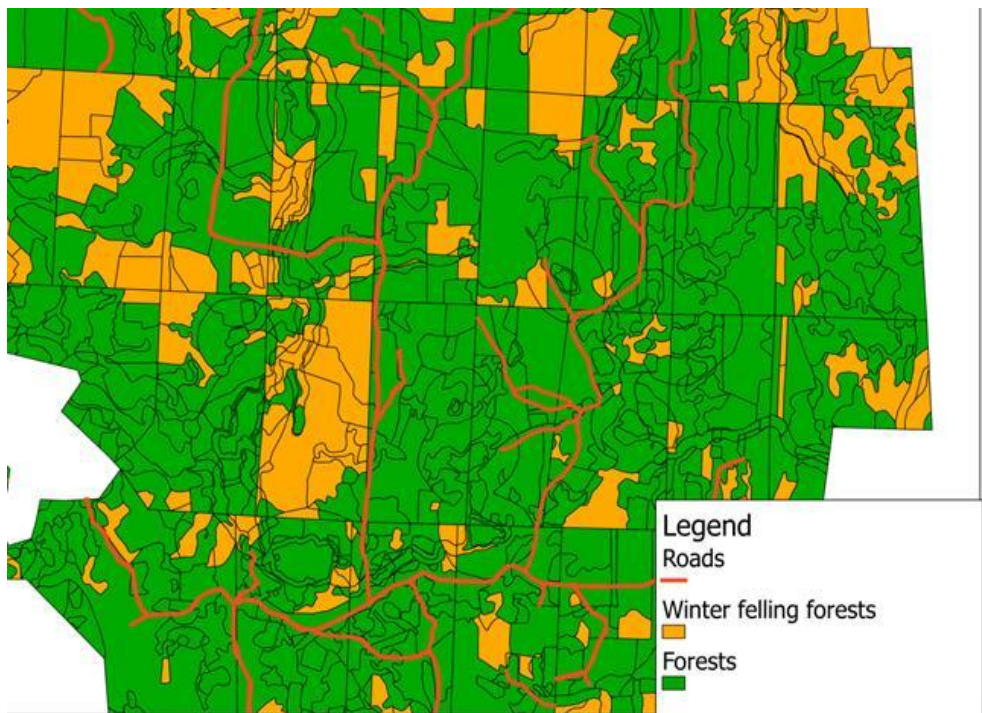
34



**Figure 3.** Fragment of the map created in this study to visualise the locations of the winter felling forests.



**Figure 4.** Forwarding on wet soils in summer (left photo by V. Katarov, June 2011, the Leningrad region) and in the beginning of winter (right photo by V. Sukhanov, December 2010, the Republic of Komi).

For example, the depth of ruts after forwarding at these sites can reach 70 cm (Goltsev et al., 2011), which means serious damage to roots of the remaining trees and a high risk of soil erosion. Performing fellings on such sites in winter prevents soil erosion and minimises the threat to the undergrowth. This should save money that could otherwise be spent on artificial reforestation.

The area, growing stock and age distribution of the identified winter felling sites were estimated using ArcGIS and the database. The winter felling sites were separated into two groups: deciduous and coniferous forests. This was done because Russian legislation allows final fellings in birch dominated forests from the age of 51 years, in aspen dominated forests from 41 years and in spruce and pine dominated forests from 81 years. Birch and aspen dominated forests were united in the deciduous group to simplify the calculations.

In Russia, there is no competition between material and energy uses of woody biomass. This simplifies the calculations of the resources available for the processing industry and energy generation, because all woody biomass can be divided into industrial wood and energy wood, the uses of which do not overlap.

After identification of the winter felling forests, the standing volumes of these sites were extracted from the database and summarised by age and tree species groups using the ArcGIS tools. Furthermore, the total standing volume of wood was converted into volumes of industrial and energy wood, as described in paper II. At this stage, it was assumed that final fellings are done by the fully mechanised CTL method.

## 3.    RESULTS

The results of the studies described in this thesis are summarised below in a top-down approach, starting from the large geographical scale of paper I, to the regional level in papers II-III and finishing at the level of forest compartments (paper IV).

### 3.2.    Potential of energy wood in the Leningrad region

The potential of energy wood in the Leningrad region was calculated for two major sources of energy wood: logging operations and sawmilling. The energy wood potential of the region was calculated according to the three scenarios: *Recent, Allowable and Potential*. In 2004, the volume of actual cut was 7.9 $Mm^3$ (including final fellings, thinnings and other fellings), which generated 3.5 $Mm^3$ of energy wood, including 2.3 $Mm^3$ of non-industrial round wood and 1.2 $Mm^3$ of residues from the central processing yards. About 65% of this volume was deciduous energy wood and 35% was coniferous. The potential of energy wood from sawmilling was 0.6 $Mm^3$, which is only 17% of that obtained from logging operations. Therefore, the total potential of energy wood in 2004, according to scenario *Recent*, was 4.1 $Mm^3$. The volumes of energy wood, estimated based on the assumptions of scenarios *Allowable* and *Potential*, are presented in table 8.

**Table 8.** Annual energy wood potential of the Leningrad region according to the different scenarios.

| Source | Scenarios | | | | | |
|--------|-----------|--|--|--|--|--|
| | Recent | | Allowable | | Potential | |
| | $Mm^3$ | TWh* | $Mm^3$ | TWh | $Mm^3$ | TWh |
| Cutting sites | 2.3 | 4.6 | 3.3 | 6.6 | 7.2 | 14.4 |
| CPY | 1.2 | 2.4 | 2.0 | 4.0 | - | - |
| **Logging operations total** | **3.5** | **7.0** | **5.3** | **10.6** | **7.2** | **14.4** |
| Sawmilling | 0.6 | 1.2 | 1.0 | 2.0 | 2.0 | 4.0 |
| **Total** | **4.1** | **8.2** | **6.3** | **12.6** | **9.2** | **18.4** |

\* - calculated assuming 50% moisture and 2 MWh of energy per $m^3$ of wood (Hakkila, 2004)

The *Allowable* scenario showed that in the Leningrad region, full utilisation of the annual allowable cut, would increase availability of energy wood by 54% from 4.1 up to 6.3 $Mm^3$. In practise, this means that the volume of the final fellings would increase from the 2004 level of 5.1 M $m^3$ to 9.5 $Mm^3$, i.e., by 86% under the *Allowable* scenario.

Intensification of thinnings from the 2004 level of 1.5 M $m^3$ to 4.6 $Mm^3$ and full utilisation of the annual allowable cut in the *Potential* scenario would result in significant growth of energy wood availability. In this scenario, the total volume of available energy wood would grow, compared with that of the *Recent* scenario, from 4.1 to 9.2 $Mm^3$ or by 124%.

Utilisation of the annual allowable cut is not the same in different FMUs (Figure 2) of the Leningrad region. Therefore, the effect of the intensification of forestry on the availability of energy wood differs among the FMUs (Table 9).

The lowest relative increase of availability of energy wood can be seen in the western part of the region (Figure 2), where the utilisation ratio of the annual allowable cut was the highest. In some FMUs (Rozhinsky and Severo-Zapadny), the availability of energy wood under the *Available* scenario was even higher than that under the *Potential* scenario. This can be explained by an overcut in 2004. In contrast, the availability of energy wood can be increased by more than 4 times in some FMUs (e.g., Kirishsky) located in the southern and eastern parts of the region. Such differences should be taken into account when planning production and use of wood fuels at the regional level.

**Table 9.** Annual available volumes of energy wood calculated according to the scenarios (volumes at cutting areas and at central processing yards are shown in parentheses) in the FMUs of the Leningrad region.

| Name | Volume of energy wood, 1000 m$^3$ by the scenarios | | |
| --- | --- | --- | --- |
| | Recent | Allowable | Potential |
| Boksitogorsk | 166 (93 / 73) | 251 (139 / 112) | 333 (333 / 0) |
| Efimovsky | 98 (62 / 36) | 141 (88 / 53) | 230 (230 / 0) |
| Gatchinsky | 62 (32 / 30) | 78 (40 / 38) | 109 (109 / 0) |
| Kingiseppesky | 92 (60 / 32) | 114 (73 / 41) | 123 (123 / 0) |
| Kirishsky | 97 (57 / 40) | 255 (145 / 110) | 403 (403 / 0) |
| Kirovsky | 94 (60 / 34) | 126 (78 / 48) | 180 (180 / 0) |
| Lisinsky | 44 (32 / 12) | 89 (57 / 32) | 105 (105 / 0) |
| Lodejnopolsky | 126 (78 / 48) | 174 (105 / 69) | 239 (239 / 0) |
| Lomonosovsky | 74 (69 / 5) | 77 (71 / 6) | 77 (77 / 0) |
| Lubansky | 132 (78 / 54) | 222 (127 / 96) | 325 (325 / 0) |
| Luzhsky | 103 (58 / 45) | 220 (124 / 96) | 341 (341 / 0) |
| Ojatsky | 53 (36 / 17) | 83 (55 / 28) | 128 (128 / 0) |
| Pashsky | 29 (19 / 10) | 65 (41 / 24) | 100 (100 / 0) |
| Podborovsky | 84 (57 / 27) | 147 (95 / 52) | 208 (208 / 0) |
| Podporozhsky | 128 (94 / 34) | 211 (149 / 62) | 359 (359 / 0) |
| Priozersky | 63 (53 / 10) | 70 (57 / 13) | 70 (70 / 0) |
| Rozhinsky | 157 (129 / 27) | 154 (128 / 27) | 154 (154 / 0) |
| Severo-Zapadny | 226 (180 / 46) | 219 (175 / 44) | 219 (219 / 0) |
| Shugozersky | 126 (73 / 53) | 259 (149 / 110) | 443 (443 / 0) |
| SiverskyLes | 39 (24 / 16) | 50 (29 / 21) | 52 (52 / 0) |
| Slantsevsky | 61 (42 / 19) | 85 (56 / 29) | 109 (109 / 0) |
| Sosnovsky | 52 (32 / 20) | 48 (30 / 18) | 48 (48 / 0) |
| Tikhvinsky | 148 (95 / 53) | 203 (127 / 76) | 271 (271 / 0) |
| Vinnitsky | 62 (41 / 21) | 145 (90 / 55) | 232 (232 / 0) |
| Volkhovsky | 110 (69 / 41) | 190 (115 / 75) | 300 (300 / 0) |
| Volovsky | 175 (95 / 80) | 228 (124 / 105) | 295 (295 / 0) |
| Voznesensky | 54 (35 / 19) | 104 (64 / 40) | 166 (166 / 0) |
| Vyritsky | 71 (41 / 30) | 132 (73 / 59) | 171 (171 / 0) |
| Agricultural FMUs | 613 (432 / 181) | 1031 (668 / 363) | 1197 (1197 / 0) |
| Other FMUs | 134 (89 / 45) | 169 (108 / 61) | 185 (185 / 0) |
| **Total** | **3472 (2314, 1158)** | **5344 (3379, 1966)** | **7174 (7174, 0)** |

### 3.3. Potential of energy wood in Boksitogorsk, Tikhvinsky and Shugozersky FMUs

A more detailed assessment of energy wood potential was performed in three FMUs: Boksitogorsk, Tikhvinsky and Shugozersky. These FMUs were selected for more detailed assessment because several of the logging companies that operated there showed interest in the production of forest chips and provided the necessary input data. Table 10 shows the volumes of energy wood available in the FMUs according to scenario.

**Table 10.** Volumes of energy wood calculated according to the scenarios in the three selected FMUs and increase to scenario *Recent* (%), thousand $m^3$ $yr^{-1}$ (under bark).

| FMUs | Scenario | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Recent | | | | Allowable | | | | Potential | | | |
| | Total cut | Energy wood | | | Total cut | Energy wood | | | Total cut | Energy wood | | |
| | | Stem wood | LR* | Total | | Stem wood | LR* | Total | | Stem wood | LR* | Total |
| Boksitogorsk | 328 | 131 | 17 | 148 | 497 | 186 | 31 | 217 (47%) | 572 | 224 | 31 | 255 (72%) |
| Shugozersky | 296 | 102 | 23 | 125 | 607 | 205 | 49 | 254 (103%) | 771 | 287 | 49 | 336 (169%) |
| Tikhvinsky | 344 | 131 | 20 | 151 | 380 | 142 | 24 | 166 (10%) | 413 | 159 | 24 | 183 (21%) |
| Total | 968 | 364 | 60 | 424 | 1484 | 533 | 104 | 637 (50%) | 1756 | 670 | 104 | 774 (83%) |

* volume of logging residues that can be sustainably collected

In 2004, the volume of fellings in the study area was about 968 000 m$^3$, which provided 424 000 m$^3$ of energy wood, including stem wood and LR. Full utilisation of the annual allowable cut would increase the energy wood potential by 50% compared with the *Recent* scenario or by up to 637 000 m$^3$ yr$^{-1}$. The study showed that in the study area thinnings can provide significant additional volume of energy wood. Intensification of thinnings in the *Potential* scenario and full use of the annual allowable cut would increase the volume of available energy wood by 83% compared with the *Recent* scenario or by up to 774 000 m$^3$ yr$^{-1}$. As in the regional study, the potential increase of biomass availability is not the same for the FMUs. The utilisation ratio of the annual allowable cut was highest in the Tikhvinsky FMU and the full utilisation of the annual allowable cut and intensification of thinnings would increase the available volume of energy wood only by 21%. However, in the Boksitogorsk FMU, the potential increase was 72% and in the Shugozersky FMU, the potential increase was 169% due to the low utilisation of the annual allowable cut (Table 10).

### 3.4.     Productivity of energy wood supply

The data provided by the logging companies allowed an estimation of the theoretical productivity of energy wood supply chains. The results of these calculations are given below in three tables. Table 11 provides data on productivity reported by the companies for final fellings, mean productivity of harvesting and forwarding in Finland and the calculated reduction coefficient. The calculated values of felling operations, forwarding and skidding for the 1$^{st}$ and 2$^{nd}$ commercial thinnings are presented in Table 12. Table 13 provides the calculated productivity of felling operations, forwarding and skidding for the final felling, taking into account the average stem volume and the reduction coefficient.

**Table 11.** Reported productivity of harvesting and forwarding in final felling, solid cubic metres over bark per 1 hour of work time ($m^3 h^{-1}$) and the calculated reduction coefficient.

| Felling | Average stem volume | Volume, $m^3 ha^{-1}$ | Productivity, $m^3 h^{-1}$ | | | | Reduction coefficient | |
|---|---|---|---|---|---|---|---|---|
| | | | Harvester* | Forwarder* | Harvester** | Forwarder** | Harvesting | Forwarding |
| Final felling | 0.45 | 272 | 13 | 10 | 20 | 13.3 | 0.7 | 0.8 |

\* reported by the companies operated in the study area

\** the values reported by Nurminen et al. (2006) for comparable forest sites in Finland

**Table 12.** Productivity of thinning operations in the three selected FMUs (here and below the data origins from the same area if not otherwise stated), solid cubic metres over bark per 1 hour of work time ($m^3 h^{-1}$).

| Thinning | Average for trees felled[*] | | | Productivity, $m^3 h^{-1}$ | | | | Skidding** |
|---|---|---|---|---|---|---|---|---|
| | Height, m | Diameter, cm | Stem volume, $m^3$ o. b. | Harvester[***] | Chain-saw[**] | Forwarding after[***] | | |
| | | | | | | Harvester | Lumberjack | |
| 1st commercial | 14 | 12 | 0.08 | 5.0 | 0.8 | 9.0 | 7.8 | 1.6 |
| 2nd commercial | 17 | 16 | 0.16 | 9.0 | 1.4 | 9.0 | 7.8 | 2.0 |

\* Groshev et al. (1980)

\** MTRF (1995)

\*** calculated, using the reduction coefficient and data of Laitila et al. (2006)

**Table 13.** Productivity of operations in final felling, solid cubic metres over bark per 1 hour of work time ($m^3 h^{-1}$).

| Felling | Average stem characteristics[*] | | | Productivity, $m^3 h^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Height, m | Diameter, cm | Stem volume, $m^3$ o. b. | Harvester[**] | Felling, delimbing, skidding[*] | Bundler[***] | Forwarder | | |
| | | | | | | | Stem wood[*] | LR[***] | RB[***] |
| Final felling | 21 | 23 | 0.45 | 13 | 4 | 9 | 10 | 5 | 14 |

[*] Groshev et al. (1980)

[**] average data from the companies

[***] calculated using data of Laitila et al. (2006), Kärhä et al. (2004), John Deer Company (JD, 2007) and the reduction coefficient

Table 11 shows that the difference between the average productivity of wood harvesting in Finland and in the investigated Russian logging companies was 20% to 30%. The lower productivity of wood harvesting (13 $m^3 h^{-1}$) and forwarding (10 $m^3 h^{-1}$) in the logging companies can be explained by the lack of experience in the use of the fully-mechanised CTL method. Smaller average stem volumes decreased the calculated productivity of felling operations during thinnings (Table 12). However, the impact was stronger on the harvesting productivity; it decreased from 13 $m^3 h^{-1}$ to 5 $m^3 h^{-1}$ and 9 $m^3 h^{-1}$ for the 1st and 2nd commercial thinnings, respectively. The change of the forwarding productivity was smaller; from 10 $m^3 h^{-1}$ to 9 $m^3 h^{-1}$. In the final fellings, the fully-mechanised CTL method was more productive than the TL method based on manual felling and skidding done by a Russian caterpillar skidder (Table 13). The calculated productivity of bundling was 9 $m^3 h^{-1}$ and the estimated productivity of the forwarding of bundles was even higher than the productivity of the forwarding of industrial wood. This can be explained by the bigger diameter of the bundles and their relatively even size. Forwarding of LR was the least efficient forwarding operation. Due to the low bulk density of LR, the calculated productivity of their forwarding was only 5 $m^3 h^{-1}$.

After hauling to the roadside, energy wood should be chipped and transported further by chip trucks, or transported to the end facility chipping in the form of round wood and residue bundles. Table 14 shows the productivity of tree-length, log and chip trucks calculated for 20, 60 and 100 km distances. The SCANIA log truck had the highest transportation productivity due to its large load capacity and ability to move faster with a load compared with the KAMAZ log truck. The URAL tree-length truck had the lowest productivity due to its lower load capacity and lower speed related to technical features. At the same time, this truck has the best off-road ability among the considered trucks.

## 3.5. Employment effect from utilisation of the available energy wood

The estimation of the energy wood potential and the calculation of productivity of energy wood supply were necessary input data to quantify the direct employment effect of the supply chains utilising available energy wood in three FMUs of the Leningrad region. Table 15 shows the calculated operational characteristics of the considered machines for energy wood supply.

**Table 14.** Productivity of energy wood transportation in the study area.

| Type of trucks | Payload, solid $m^3$ | Transported energy wood | Transportation distance, km | | |
|---|---|---|---|---|---|
| | | | 20 | 60 | 100 |
| | | | Productivity, $m^3 h^{-1}$ | | |
| URAL tree-length truck | 15 | NIW | 8 | 5 | 4 |
| KAMAZ log truck | 25 | NIW, RL | 12 | 7 | 6 |
| SCANIA log truck | 45 | NIW, RL | 20 | 13 | 10 |
| SCANIA chip truck | 40 | Forest chips | 15 | 10 | 8 |

**Table 15.** The calculated annual working time, number of operators and annual productivity of the energy wood supply machines.

| Machines | Working time, h yr$^{-1}$ | Shifts per day | Operators per machine | Productivity, m$^3$ yr$^{-1}$ |
|---|---|---|---|---|
| **Energy wood supply chains based on a mobile chipper** | | | | |
| Mobile chipper | 3536 | 2 | 2 | 60000 |
| SCANIA chip truck | 3536 | 2 | 2 | 35000 |
| **Energy wood supply chains based on a stationary chipper*** | | | | |
| Bundler | 5304 | 3 | 3 | 48000 |
| Forwarder RL | 5304 | 3 | 3 | 74000 |
| KAMAZ log truck* | 3536 | 2 | 2 | 25000 |
| SCANIA log truck* | 3536 | 2 | 2 | 46000 |
| Stationary chipper | 5304 | 3 | 3 | 122000 |

* - one of two truck options

Table 16 shows the number of machines required to supply the estimated volumes of energy wood (Table 10) according to the scenario.

When estimating the employment effect from the utilisation of energy wood, the study also showed how many machines are needed to supply the available volumes of energy wood. In other words, potential capacity of the local market of energy wood supply machines was quantitatively estimated. The employment effect from the utilisation of energy wood and the number of machines needed to supply the available volumes of energy wood depends on the availability scenario and the type of chipper used (Table 16). In scenario *Recent* 6 mobile chippers and 11 SCANIA chip trucks would be sufficient to supply the available energy wood to the end users. If the same volume of wood was chipped at the end user facilities, it would require 15 KAMAZ or 8 SCANIA log trucks and only 3 stationary chippers. The assumed transportation distance was 60 km. Utilisation of LR, together with stem energy wood, requires 4 additional machines: 2 bundlers and 2 forwarders for hauling the RL. Therefore, the number of operators necessary to produce forest chips from LR and stem wood, using stationary chippers, is higher than that required for supply chains utilising only stem wood. When comparing the relative changes of the number of operators between the scenarios it is possible to see that the supply chains have different effects on employment. The biggest relative growth (+94% to scenario *Recent*) could be achieved under the *Potential* scenario using the supply chains based on mobile chippers. However, comparison of the absolute figures shows that the biggest number of new working places (94) would be created by the supply chains based on stationary chippers and KAMAZ log trucks.

**Table 16.** The total calculated number of machines and their operators by scenario (the relative change of the total number of operators compared to scenario *Recent* is shown in parentheses).

| Machines | Machines and operators by scenario, items | | | | | |
|---|---|---|---|---|---|---|
| | Recent | | Available | | Potential | |
| | Machines | Operators | Machines | Operators | Machines | Operators |
| **Energy wood supply chains based on a mobile chipper** | | | | | | |
| Mobile chipper | 6 | 12 | 10 | 20 | 12 | 24 |
| SCANIA chip truck | 11 | 22 | 17 | 34 | 21 | 42 |
| Total | 17 | 34 | 27 | 54 (59%) | 33 | 66 (94%) |
| **Energy wood supply chains based on a stationary chipper** | | | | | | |
| Bundler | 2 | 6 | 3 | 9 | 3 | 9 |
| Forwarder RL | 2 | 6 | 3 | 9 | 3 | 9 |
| KAMAZ log truck | 15 | 30 | 23 | 46 | 29 | 58 |
| SCANIA log truck | 8 | 16 | 13 | 26 | 16 | 32 |
| Stationary chipper | 3 | 9 | 5 | 15 | 6 | 18 |
| Total if KAMAZ log trucks are used | 22 | 51 | 34 | 79 (55%) | 41 | 94 (84%) |
| Total if SCANIA log trucks are used | 15 | 37 | 24 | 59 (22%) | 28 | 68 (84%) |

## 3.6.  Cost competitiveness of forest chips at the local fuel market

Cost calculations were done for five logging methods, taking into account the productivity of energy wood supply in the conditions of the study area and the local costs related to the supply operations. In total, 13 supply chain combinations were analysed from the viewpoint of cost-efficiency (Goltsev et al. 2010) to find a supply chain with the least cost per 1 m$^3$ of forest chips.

Figure 5 shows the comparison of the most cost-efficient energy wood supply chains for the 1$^{st}$ and 2$^{nd}$ commercial thinnings and final fellings.
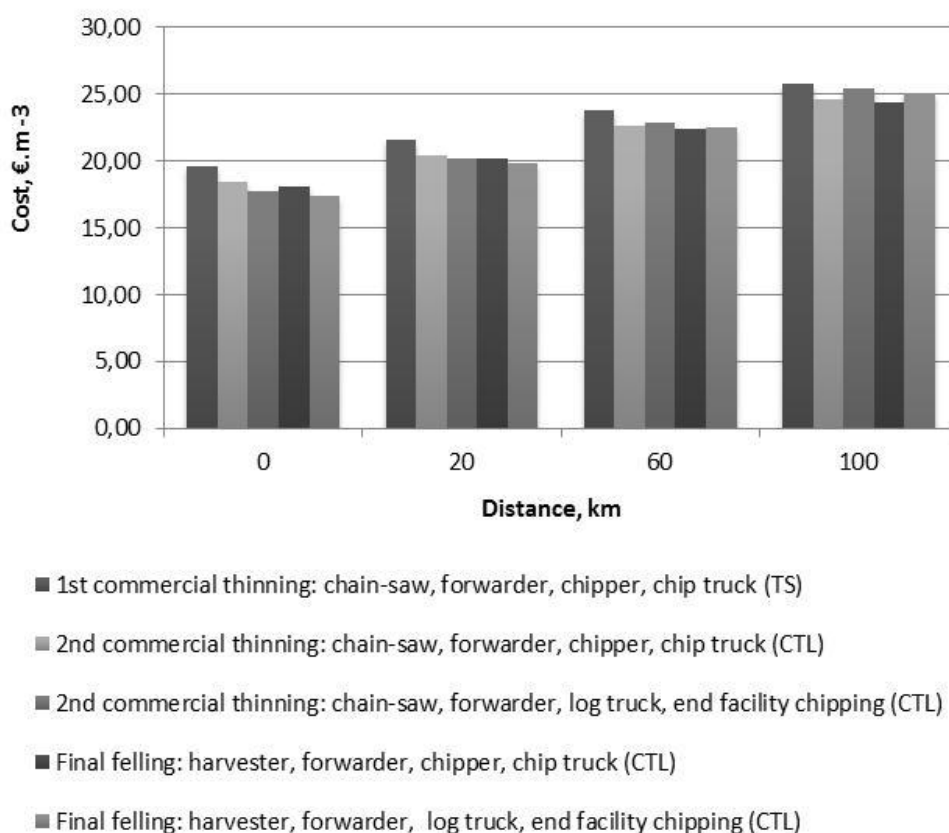
**Figure 5.** The most cost-efficient energy wood supply chains for the 1st and 2nd commercial thinnings and final fellings up to 100 km transportation distance.

In the conditions of the study area, the supply chains based on manual felling were preferable for commercial thinnings compared with fully-mechanised supply chains. Despite the higher productivity of harvesters in thinnings, manual felling provided lower total cost of energy wood supply due to the lower capital and labour costs. However, the difference in costs between partly-mechanised and fully-mechanised CTL supply chains in the 2nd commercial thinning was smaller compared with that of the 1st commercial thinnings, because productivity of the harvester increases more than the productivity of a lumberjack. In final fellings, the fully-mechanised CTL method became more cost-efficient for energy wood supply than the TL or FT methods with manual felling. The 1st commercial thinning provided the most expensive energy wood among the considered fellings, because of the small average stem volume of the felled trees, which caused low productivity of the felling and subsequent operations. In the 2nd commercial thinning, the productivity of logging operations increased due to the bigger average stem volume, which

resulted in lower supply costs (1.0 € m$^{-3}$ less compared with the 1$^{st}$ commercial thinning). There was almost no difference between the supply costs provided by the fully-mechanised CTL method in final felling and the supply chains utilising manual felling in the 2$^{nd}$ commercial thinning.

Figure 5 shows a small difference between the costs of energy wood supply from different types of fellings. This was due to the higher cost of wood resources (forest rent) designated for final fellings compared with stumpage paid for wood from thinnings. The difference was about 1.50 € m$^{-3}$. In addition, the low productivity of harvesters and low costs of manual work in Russia reduced the difference between the fully- and partly-mechanised logging methods and the different types of fellings.

Cost competitiveness of wood fuels is one of the most important factors affecting decision making on bioenergy development on all spatial levels. Without such analysis, a biomass assessment has little practical value (Smeets et al. 2010b). The calculated costs of forest chips produced from energy wood available in the study area were compared with the average prices of conventional energy sources used in the Leningrad region of Russia (MPERF, 2006; Värri et al. 2007).

In Figure 6, the calculated supply costs of forest chips are compared with the average local market price of conventional primary energy sources. Regarding forest chips, the conversion of volume units (m$^{3}$) to energy units (MWh$^{-1}$) was done based on primary energy content of air dried forest chips (Alakangas 2010). The supply costs of forest chips from final fellings represent the lower cost limit and the supply costs of forest chips from the 1$^{st}$ commercial thinnings show the upper cost limit.
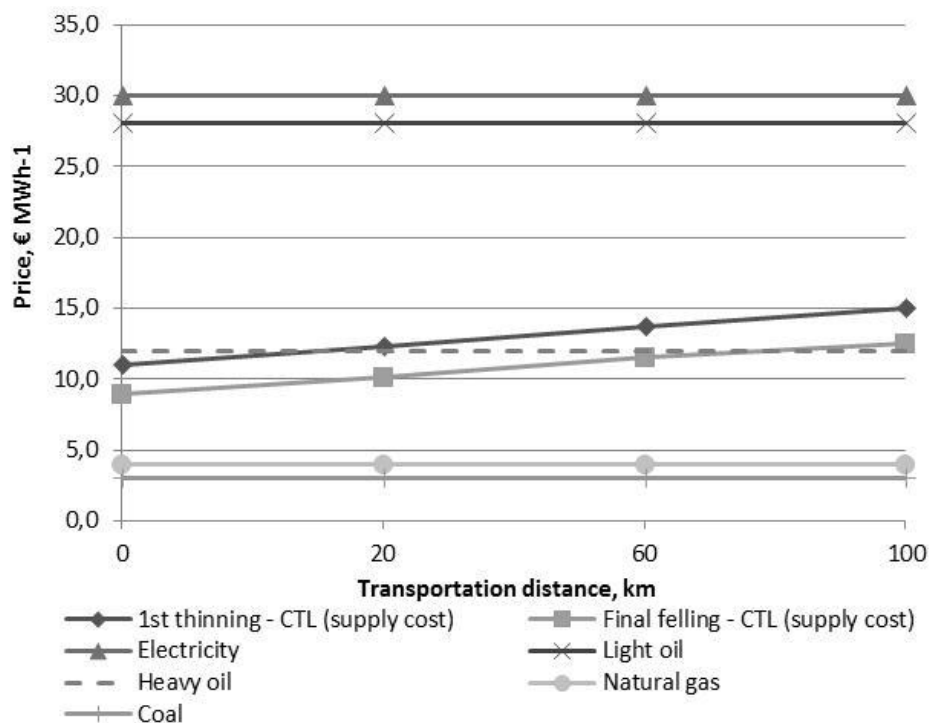
**Figure 6.** Comparison of the calculated costs of forest chips with the average local market prices of conventional primary energy sources.

Natural gas and coal were the cheapest energy sources in the study area. Forest chips were 2–3 times more expensive compared with natural gas and coal and therefore, could not act as a substitute for them from an economic viewpoint. Forest chips could compete in terms of costs with heavy oil if the transportation distance was less than 60 km and forest chips were supplied from final fellings done using the fully-mechanised CTL method. The analysis showed that costs of forest chips supplied by the considered chains were below or at the same level as the price of heavy oil if transportation distance was shorter than 50 km. Light oil and electricity are not cost competitive compared with forest chips within the whole range of forest chip transportation.

## 3.7. Impact of climate on technical accessibility of forests in the study area and characteristics of the identified winter felling forests

One of the factors limiting the estimated potential of energy wood of the study area is the technical accessibility of forests, which strongly depends on the duration of the winter felling season. Soil conditions and the lack of forest roads that can be used by heavy log trucks throughout the year make some forests inaccessible during the non-frosty season. Therefore, an economically feasible supply of wood might not be technically realised if
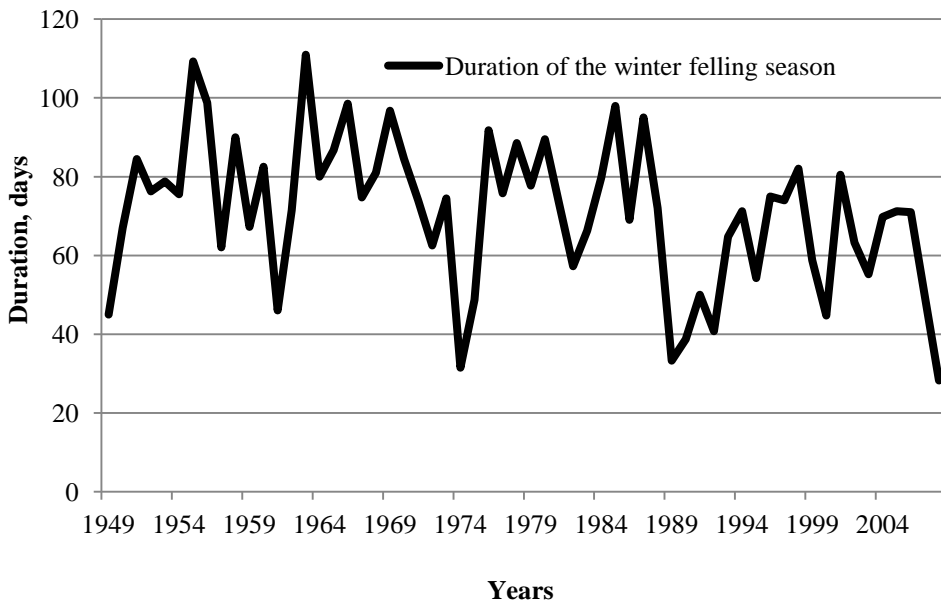
**Figure 7.** The calculated duration of the winter felling seasons in the period 1949–2008

climatic conditions do not allow construction and exploitation of winter roads, or if there is no available machinery to fully utilise accessible felling sites. Such situations could be avoided by predicting the duration of the winter felling season, which would allow proper planning of road construction and logging operations. In this study, the retrospective duration of the winter felling season was calculated (Figure 7) using historical (1949–2008) daily air temperature measurements from four local meteorological stations (Goltsev and Lopatin, 2011).

The trend in Figure 7 shows how the calculated duration of the winter felling season changed in time. The duration of the winter felling season was unstable during the entire timeframe. The longest winter felling season (126 days) in 1955 was almost three months longer than shortest winter felling seasons in 1974 and 2008 (38 and 39 days, respectively). The gradual increase in the duration of the winter felling season was followed by a drastic shortening.

The duration of the winter felling season in the future was predicted by extrapolating the historical trend up to 2099. Figure 8 shows the predicted duration of the winter felling season up to 2095.
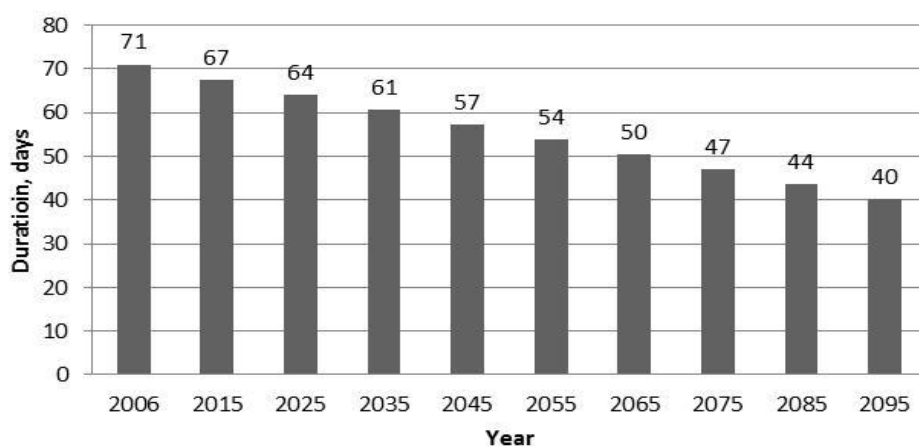
**Figure 8.** Duration of winter felling season in the future compared with 2006.

The average duration of the winter felling season will steadily decrease if the current tendency of increasing air temperature continues. On first inspection, the changes do not appear to be that drastic. The average duration of the winter felling season in 2030–40, 2060–70 and 2090–2100 will be 86%, 70% and 53% of the duration of the winter felling season of 2006, respectively. This means that for each decade, the duration of the winter felling season will become 3–4 days shorter.

The decreasing duration of the winter felling season increases the value of information about location and characteristics of those felling sites that are technically accessible only during the winter felling season. Identification of winter felling forests allowed the estimation of their standing volume and areas and the calculation of the volumes of industrial and energy wood represented by these forests. The characteristics of the identified winter felling forests are shown in Table 17.

**Table 17.** Characteristics of the identified winter felling forests.

| Age | Coniferous winter felling forest | | | Deciduous winter felling forests | | |
|---|---|---|---|---|---|---|
| | Standing volume, $m^3$ | Area, ha | Mean volume, $m^3$ $ha^{-1}$ | Standing volume, $m^3$ | Area, ha | Mean volume, $m^3$ $ha^{-1}$ |
| 21–40 | - | - | - | 172521 | 2050 | 84 |
| 41–60 | 205365 | 1505 | 136 | 755982 | 4047 | 187 |
| 61–80 | 660578 | 2864 | 231 | 2294878 | 9832 | 233 |
| 81–100 | 1296147 | 4996 | 259 | 2503155 | 9466 | 264 |
| 101–120 | 2339955 | 8335 | 281 | 925041 | 3453 | 268 |
| 121–> | 1595631 | 5930 | 269 | - | - | - |
| Total | 6097676 | 23630 | | 6651577 | 28848 | - |

Table 17 shows that no coniferous forests of the age class 21–40 years were identified as winter felling forests. Young coniferous forests in the study area were created mainly by the artificial regeneration of felling sites that connect to all-season roads. At the same time, there are young deciduous stands classified as accessible only during winter. In fact, these stands are the result of natural regeneration of clear cut sites that have been left without any artificial reforestation activities and consequent treatments. These sites were left for natural regeneration due to their low accessibility and a lack of money.

The identified winter felling forests represent in some age classes a significant share of the total forest area (Figure 9). The share of the coniferous winter felling forests in the total area of coniferous forests of the study area varies from 10% to 28%. The highest share of the coniferous winter felling forests is represented by forests of age classes exceeding 81 years. The situation is even worse in the case of deciduous forests. About 52% of all deciduous forests older than 60 years were classified as accessible only during winter. These forests have reached the age of final felling and represent a significant part of the resource base of the local logging companies. This means that the supply of wood in the district, both for industrial and energy use is vulnerable to the duration of the winter felling season. However, regarding coniferous forests, it is possible to say that the impact of shorter
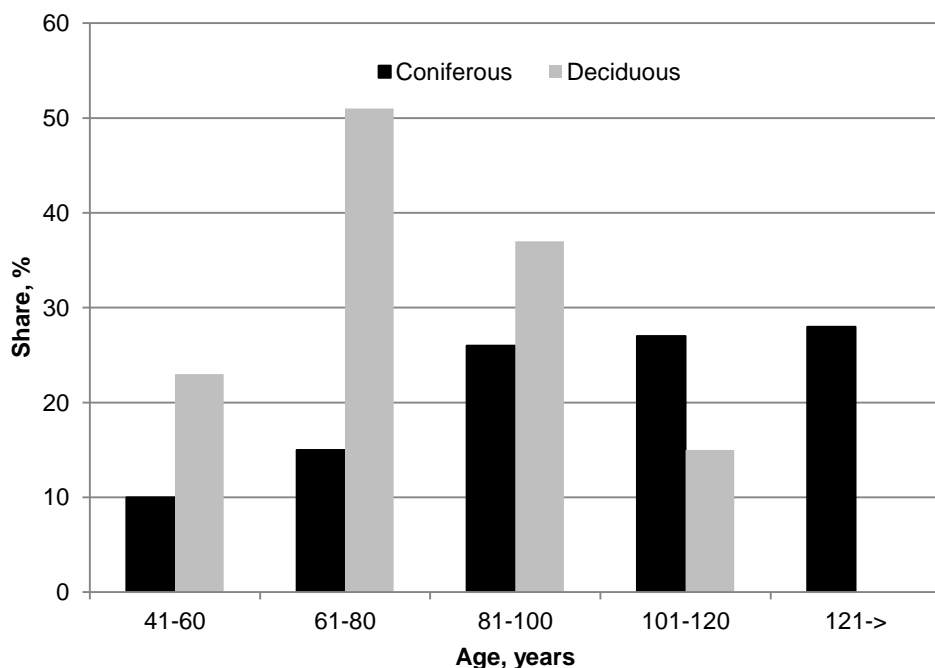


**Figure 9.** The share of the coniferous and deciduous winter felling forests compared with the total area of the coniferous and deciduous forests, respectively

**Table 18.** The total harvestable volume of energy wood in the winter felling forests of the Tikhvin district, 1000 $m^3$.

| Type of forest | Age, years | Total area, ha | Industrial wood | Harvestable energy wood | | | Sustainable annual cut | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Stem wood | Crown biomass | Total | Industrial wood | Energy wood | Total |
| Coniferous | 81> | 23630 | 3662 | 1914 | 520 | 2434 | 45 | 30 | 75 |
| Deciduous | 51> | 28848 | 3050 | 3433 | 375 | 3808 | 60 | 74 | 134 |
| Total | | 52478 | 6712 | 5347 | 895 | 6242 | 105 | 104 | 209 |

winters on the accessibility of these forests will become weaker in the future, because the share of winter felling forests is decreasing among maturing and middle-aged coniferous forests.

The total volumes of industrial and energy wood of the identified winter felling forests are shown in Table 18. The assessment showed (Table 18) that the total harvestable volume of energy wood in the identified winter felling forests is more than 6 million $m^3$. Taking into account rotation periods, annually in the winter felling forests 105 000 $m^3$ of industrial wood and 104 000 $m^3$ of energy wood could be harvested. Deciduous winter felling forests have more biomass for industrial and energy uses compared with the coniferous winter felling forests, because of their large area and shorter rotation period. It has to be noted that many felling sites that could be cut in summer time are actually cut in winter, because the logging companies do not have the financial resources to invest in construction of all-season forest roads and prefer to build cheap winter roads. Having in mind the future duration of the winter felling season, it is quite simple to calculate what such a decrease in the winter felling season means for a logging company that annually harvests a total of 200 000 $m^3$ of industrial and energy wood. In the region of about 80% of all fellings are done during the winter felling season. Thus, in 2006, the company should cut[8] 160 000 $m^3$ of wood during the winter felling season, or about 2253 $m^3$ of wood per day. In nine years' time, the company will have four fewer days during which to cut the same volume of wood. If the company does not prepare for a shorter winter felling season it will be unable to harvest about 9012 $m^3$ of wood. Assuming that in 2015 1 $m^3$ of wood will cost 40 € $m^{-3}$, the market value of the lost volume of wood will be about 360 480 €. In the case of extreme short winters the losses will be even worse.

The results show that logging companies should take into account the decreasing duration of the winter felling season when planning logging operations and keep in mind the probability of extreme short winters.

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[8] including also fellings outside of the study area

# 4.  DISCUSSION AND CONCLUSIONS

The methodology proposed in this study allows the estimation of energy wood availability at regional and local levels taking into account several factors that affect the various dimensions of the resource potential. These factors include the influence of intensification of forest management on energy wood availability and the impact of climate change on the technical accessibility of forests. In addition, using the proposed methods, the economic and social aspects related to the production of forest chips from the available energy wood can be analysed and quantified. The methodology could be used at regional level for whole north-western Russia. When applying the methods at district level, it is recommended that local data will be used taking into account the local fluctuations in productivity of supply operations, different mean crown-to-stem wood ratios and climatic differences.

The proposed methodology was tested at the regional level (in the Leningrad region of the north-western Russia) and at the local level (in Boksitogorsk, Shugozersky and Tikhvinsky districts of the Leningrad region). The study revealed the availability of significant volumes of energy wood in the region. In 2004, fellings produced more than 3.5 Mm$^3$ of energy wood, of which, deciduous energy wood represents about 62% and coniferous 38% of the total energy wood potential from logging. In addition, sawmills generated about 600 000 m$^3$ of wood by-products. Currently, energy wood from central processing yards and by-products from big sawmills are usually already utilised, e.g., for satisfying their own energy needs. Some smaller sawmills often dump their residues because they do not have the money to build boiler houses and utilise their own by-products (Ilavský et al., 2007).

The study showed that it is possible to intensify the utilisation of forest resources in the Leningrad region and thereby, also to increase the availability of energy wood. Utilisation of the whole annual allowable cut and intensification of thinnings would increase the energy wood potential of the region by 2.5 times compared with 2004. However, intensification of forest management would not provide the same results in all FMUs of the region. There were two FMUs (Rozhinsky and Severo-Zapadny) in which the harvesting of industrial wood cannot be intensified due to an overcut in 2004 (Table 9).

It has to be mentioned that the study might underestimate the energy wood potential. In fact, the energy wood potential of the region could be even higher, because current forest inventory practise in Russia tends to underestimate increment and sustainable annual cut (Niskanen et al. 2003; Pisarenko, 2004). Full utilisation of allowable cut and thinnings requires more investment in infrastructure and the development of the forest road network. Although intensification of forest management based on the CTL method would increase the availability of energy wood, this would also change the points of energy wood accumulation from the roadside and central processing yards, to cutting sites. This would complicate the collection of energy wood, especially in the case of logging residues. This problem could be solved by utilising the most effective technologies and methods for supply of energy wood (Röser, 2012).

The assessment of the energy wood potential in the Leningrad region was done using a resource-focused approach. On the one hand, it means a straightforward calculation methodology; however, on the other hand, the demand for energy wood was neglected due to the methodological features of this approach. The reliability of the results obtained at the regional level depends on several factors. The first factor is the accuracy of the input data,

especially in relation to the volume of the actual cut. Forest inventory data in Russia are often outdated and lacking in accuracy. According to Kinnunen et al. (2007), the average error of standing volume estimations in the Novgorod region of north-western Russia was 32.4%. The actual annual cut could be higher because of unreported volumes of illegal fellings (Johansson, 2010). Another important factor is the assumption about the volume of LR, which can be used as energy wood. Based on the literature (Matunin, 1985; Korobov and Rushnov, 1991), it was assumed that the volume of harvestable LR corresponds to 5.2% of the total wood harvest. Depending on soil conditions, all logging residues might be used for strip road improvements but in winter time, all logging residues could be available for energy use. Therefore, within the region, a large variation of logging residue availability exists, which could not be accounted for when estimating energy wood potential at the regional level. There is a similar problem with aspen wood. Some of the logging companies in the region use aspen stem wood for road construction. This decreases the available volume of energy wood, because often in the region, there is no other use for aspen wood except for road construction and the production of fuel wood. There was no data available at the regional level about the use of aspen wood for road construction. Therefore, at the regional level, it was not possible to estimate how the use of aspen wood for road construction decreases the available volume of energy wood.

A more detailed assessment of energy wood availability was carried out at the local level in three FMUs of the Leningrad region of Russia (Boksitogorsk, Shugozersky, Tikhvinsky). At this level, it was possible to avoid inconsistencies of input data related to the availability of logging residues and the use of aspen wood for road construction. Close cooperation with several logging companies operating in the study area provided reliable input data. For example, the share of collectable LR was estimated based on the data reported by the companies. In this case, the share of collectable LR was 60% of the total volume of crown biomass, which is higher than the ratio used in paper I. This explains the small difference between the results of estimates of energy wood potential obtained in papers I and II. Also the detailed input data allow reliable analyses of economic and social implications of the production of forest chips from the available energy wood.

The study area had good resource potential for the production of wood fuels. According to the scenario *Recent* in 2004, fellings in the region allowed an accumulation of 424 000 $m^3$ $yr^{-1}$ of energy wood at felling sites and central processing yards. In the *Allowable* scenario, the full utilisation of the annual allowable cut would increase the availability of energy wood by up to 637 000 $m^3$ $yr^{-1}$ or +50% relative to scenario *Recent*. Intensification of thinnings and utilisation of the entire annual allowable cut would allow a harvest of 774 000 $m^3$ $yr^{-1}$ (scenario *Potential*) or +83% of the actual available volume. In scenario *Allowable*, the relative increase of energy wood availability for the study area is almost the same as the average increase in the entire Leningrad region, +50% and +54%, respectively. The difference is bigger for scenario *Potential*, +83% and +106%, respectively, because the smaller proportion of middle-aged forests in the study area did not provide the same effect from intensification of thinnings.

The study showed that to harvest the available volumes of energy wood, the harvesting of industrial wood could be intensified; however, this would be possible only if there were a demand for it. Analysis of the development of the wood market in the study area was beyond the scope of this study. Proximity of the region to the European Union and the fact that Russia recently joined the World Trade Organisation could facilitate realisation of the scenarios. However, it was not possible to say when the considered scenarios of energy

wood availability might be realised in practise. There is the need for a follow-up study in order to answer this question.

The study revealed big differences in the average productivity between supply stages of the CTL and TL methods applied by the logging companies in the region. In final felling, the average productivity of harvesting and forwarding was 13 m$^3$ h$^{-1}$ and 10 m$^3$ h$^{-1}$, respectively, and productivity of felling, delimbing and skidding was 4 m$^3$ h$^{-1}$. In addition, the study showed that those logging companies that utilised the fully-mechanised CTL method were far from reaching the productivity limits of this logging method. The average productivity of harvesters and forwarders reported by the companies for final fellings was on average 20% to 30% lower than the average productivity of similar machines working in Finland in comparable conditions (in terms of landscape and stem volumes). The harvester operators of the local companies had less than three years of work experience that also affects the productivity.

The companies did not perform thinnings and therefore productivity data and functions for Finland and the calculated productivity reduction coefficient were used to estimate productivity for commercial thinnings in the study area. This straight forward approach introduces uncertainties to the obtained results, because all possible factors influencing productivity cannot be taken into account when estimating the reduction coefficient. The operational environment is also a very important factor which affects productivity. Röser (2012) showed that business models and working practices strongly influence productivity of forest chip supply chains. These important factors were not analysed in the given thesis and should be covered by future studies. It could be expected that the productivity of the CTL method in the study area would increase with the improvement of skills and experience of the operators.

Without intensification of forest management, the CTL method could have a negative impact on employment, because fewer machines would be needed to supply the same volume of energy wood. It was also found that log trucks from the Nordic countries have higher productivity than the log trucks manufactured in Russia and used by the local companies. The difference in some cases was twice as big. However, there are many forest roads, which due to their poor condition are not suitable for logging trucks produced in the European Union. This limited the applicability of these efficient trucks in the study area. This was one of the reasons why the logging companies could not completely utilise their wood supply capacities. Moreover, currently unutilised energy wood could be supplied only if the quantity of harvesters, forwarders and especially, trucks and chippers, were to be increased.

There is no clear opinion of how the development of bioenergy affects employment; there are both positive and negative consequences. Simola et al. (2010) concluding on results of modelling bioenergy development in Finland reported about its modest negative impact on GDP and employment in general. The reason is the transfer to more productive technologies and the costs that should be paid by the country to cut down its carbon emissions. In contrast, scenario modelling in Germany (Dürrschmidt and van Mark, 2006) and a case study in Finland (Ahonen, 2004) showed that bioenergy development would produce positive employment. Bioenergy development might have negative or positive employment effects that depend on numerous specific factors, especially on: the existence of state support, the availability of biomass for energy use, the demand for bioenergy and available technologies. The results of the study showed that intensification of forest management achieved by the utilisation of the energy wood potential of the study area could provide associated social gains. The number of machines and operators necessary to

supply the available volumes of energy wood grow depending on the scenario. The considered supply chains have different employment capacities defined by their productivity and the structure of the chain. The total requirements in the *Recent* scenario vary from 17 machines and 34 operators for the supply chains based on the mobile chipper, to 22 machines and 51 operators if KAMAZ log trucks and stationary chippers were used. Scenario *Potential* requires the highest quantity of machines to utilise the available volume of energy wood; up to 41 machines and 94 operators for the stationary chipping systems utilising KAMAZ log trucks. The employment effects could be even higher if the utilisation of the available energy wood volumes were to be done using supply chains based on manual felling. This case was not analysed in the study due to the decreasing share of manual fellings in Russia.

The energy wood supply chains comprising SCANIA log trucks and stationary chippers had higher productivity than the other considered chains. When this chain does not use LR, it requires fewer machines and operators to utilise the same volume of stem energy wood than other chains and therefore, the supply is easier to organise and manage. However, this chain has several disadvantages. It is based on the most expensive machinery and its maintenance is more complicated. The supply chain requires fewer operators due to the high productivity of the machinery, which could cause a negative impact on employment in rural areas if such a supply chain replaces less productive chains.

Several reviews (Berndes et al. 2003; Smeets et al. 2010b) of recently implemented assessments of energy wood potentials have shown that despite the large number of such studies, the economic implications of energy wood supply are not sufficiently well understood. The analysis of the economic feasibility of energy wood supply showed that supply chains in thinning based on manual felling provided lower cost forest chips compared with those supply chains utilising harvesters. However, the use of a harvester equipped with an accumulating harvesting head for early thinnings could decrease harvesting costs (Laitila 2012). Utilisation of harvesters becomes more economically feasible in final felling. In final fellings, the use of the fully-mechanised CTL method for forest chip supply was more efficient than the partly-mechanised FT and TL methods. The supply of forest chips from the $1^{st}$ commercial thinnings was the least cost-efficient among the considered fellings; the supply costs were between 18.8 and 25.8 € m$^{-3}$, depending on the transportation distance. The costs of energy wood from the $2^{nd}$ commercial thinning were lower; between 17.8 and 24.6 € m$^{-3}$. Final felling was the cheapest source of energy wood providing supply costs of 17.4 to 24.4 € m$^{-3}$, or from 11.0 to 17.8 € m$^{-3}$ when the costs of harvesting and forwarding of energy wood were allocated to industrial wood.

The comparative cost analysis showed that forest chips were cheaper than electricity and light oil as primary energy sources for warming up buildings. When calculating the costs of forest chip supply, the investment costs were taken into account and included costs of new machines and road construction but did not include costs of operators' training. The substitution of heavy oil by forest chips was economically feasible if a distance of forest chip transportation was less than 50 km and the forest chips supplied from final fellings only. Energy wood cannot be considered as an alternative fuel for coal and natural gas because of their low market cost. Factors such as high costs of building pipelines to remote areas (about 65 000–185 000 € km$^{-1}$ (REA, 2012a)) and the obligations to reduce greenhouse gas emissions could improve the competitiveness of forest chips against coal and natural gas.

Power generation in Russia has been based mainly on fossil fuels due to the vast resources of fossil fuels and now there is a lack of knowledge about the utilisation of

energy wood on an industrial scale (Pelkonen et al., 2004). The costs of energy wood supply could be lowered significantly, as has been proven by the development of nationwide supply of forest chips, e.g., in Finland, Sweden and Austria (Kopetz, 2003). Therefore, learning from the experience of countries like Finland, which successfully utilise wood fuels, is extremely important for the economic optimisation of energy wood supply in Russia. Hakkila (2005) presented several solutions that facilitated the use of energy wood in Finland and that made it economically more feasible: full mechanisation of logging, increasing the full weight of log and chip trucks up to 60 tonnes and intensive research and development activities.

By analysing the obtained results, it is possible to conclude that full mechanisation of thinnings in the study area would not immediately lead to a reduction in energy wood supply costs because of the low productivity of harvesting. The use of trucks with higher payloads would certainly lower energy wood transportation costs; however, the total allowable weight of a truck in Russia is 38 tonnes and significant efforts would be needed to change the transport legislation.

In addition to the economic constraints, the potential of industrial and energy wood in the study area is limited by climatic factors. About 80% of all fellings in the region were done during the winter felling season (Bolmat, 2007). The study showed that due to global warming, the average duration of the winter felling season could decrease by 3–4 days per decade. Therefore, in 2040–2050, the average duration of the winter felling season could be two weeks shorter compared with that of 2006 and by the end of the century, it could be up to one month shorter compared with 2006. These changes are not drastic because they stretch over a long time period. However, the logging companies in the study area should adapt their operations to the changing climate conditions. Without adaptation measures, the biggest logging companies could face significant losses of wood due to their inability to access the forests. For each day that the duration of the winter felling season is reduced, any of the biggest regional logging companies could lose more than 2000 m$^3$ of stem wood (including industrial and energy wood). A simple method for the identification of those forests that are accessible only during the winter felling season was elaborated in order to help the logging companies develop their adaptation measures.

The analysis of the forests within the study area showed that the share of winter felling forests, depending on the age class, varied from 10% to 28% and from 15% to 52% of the total area of coniferous and deciduous forests, respectively (Figure 9). This share is decreasing within the younger age classes, which means that the technical accessibility of the forests in the district will improve over time. However, this could have a negative impact, because an increased share of summer fellings also means increased risk of root infections due to root damage, especially in spruce forests. The identified winter felling forests could provide annually about 105 000 m$^3$ of industrial wood or 38% of the annual allowable cut. This highlights the importance of the winter felling forests for the local logging companies, especially if the high utilisation ratio of the district's forest is taken into account. In the case of warm winters, all the volume of industrial wood available in the winter felling forest cannot be compensated by the all-season accessible forest. At the same time, the total energy wood harvesting compared with the total industrial wood harvesting is relatively low; about 170 000 m$^3$. Thereby, the identified summer felling forests could satisfy the annual demand for energy wood. Considering these figures, one might presume that the impact of climate change (in the form of shorter winters) on the accessibility of energy wood would not be remarkable, because all the energy wood could be cut in the forests that are accessible all year round. However, local conditions have to be taken into

account. The density of the forest road network in the Tikhvin district is low, as it is in many regions of Russia. In order to procure wood from forests, logging companies are forced to build roads; it is their obligation as forest leasers according to the forest code (FFAR, 2006). During the winter season, low-cost temporary winter roads can be built, which means that the logging companies in the region attempt to harvest as much wood as possible during the winter, even in forests where fellings are possible in the summertime. Therefore, in the Leningrad region, currently about 80% of the annual cut is harvested during winter. This means that almost all the required volume of energy wood is harvested during winter. The harvested energy wood has to be collected and transported close to all-season roads during short time to ensure on-demand availability of the energy wood during all year round. This requires machinery for transportation and large areas for storing of wood. In addition to logistic issues, there are quality issues. Energy wood harvested during winter is relatively dry, but during spring energy wood without properly organised storing will absorb moisture from melting snow and rains.

The changes in the average duration of the winter fellings season in the future are not very remarkable; 3–4 days per decade. The logging companies in the district can adapt to this if they invest in the construction of all-season roads. However, it has to be kept in mind that between 1949 and 2008 the difference between the longest and the shortest duration of the winter felling season was three-fold. Assuming that the duration of extreme long and short winter felling seasons will follow the same shortening tendency, in 2030–40 the shortest felling season might be only 30–32 days. In such winters, organisation of felling operations will be problematic due to limited capacity of supply chains and complexity of logistics. It is difficult to estimate how much of the average annual winter cut could be compensated for by increasing the intensity of summer fellings. Thereby, the most harmful impact of climate change on the technical accessibility of wood in the study area is the decrease in the duration of the extreme short winters or increasing frequency. The change in the average duration of the winter felling season is less harmful. In the case of several successive extreme short winters the logging companies could face serious problems. The prediction of the probability of extreme long and short winter felling seasons would help the logging companies prepare realistic harvesting plans.

The assumption of an even age distribution of the forests was taken to simplify the estimation of the standing volumes of ageing forests. This assumption introduces some uncertainties into the results of the study because forests in the district are unevenly aged with a dominance of mature forests. This means that the difference between the results of this study regarding the harvestable volumes of wood and reality would increase in the future. Moreover, the impact of changing growing conditions (due to climate change) on the dynamics of growing stock and harvestable volumes of energy wood, should be taken into account in future studies, to better predict the availability of biomass for energy use. On the one hand, the growing duration of the vegetation period and increased share of carbon in the atmosphere could boost growth of the forests in the region, improving the availability of biomass. On the other hand, climate change could result in the increased occurrence of storms and droughts (Donner and Large, 2008) that could reduce the available volumes of wood. When using the proposed method in practice, at the level of a single logging company, it would be possible to get more consistent results, because the total volume of wood and the harvestable volume of energy wood could be calculated not for all mature and over mature winter felling forests but only for forest sites allocated by the logging company for final fellings. In this case, the amount of data to be processed would be reduced, enabling the use of site-specific inventory data and exact age and

species-specific conversion ratios. Therefore, the impact of climate change on the technical accessibility of forests would be predicted more precisely in terms of wood volumes.

The method used to estimate the duration of the winter felling season is not applicable for annual prognoses, due to the strong annual variation of the duration of the winter felling season. Here, the main aim was to show that climate change might affect the technical accessibility of forests and to attract more attention to this issue. However, this method could help logging companies evaluate long-term risks (for 10 and more years) related to the shortening of the winter felling season and to estimate the costs of mitigating actions (investments in construction of all-season roads and new machinery).

The assessment showed that the Leningrad region is a promising area from the view point of bioenergy development. Large volumes of energy wood are currently not utilised and intensification of forestry could increase the supply of energy wood from recent levels of 4.1 $Mm^3$ up to 9.2 $Mm^3$ (including round wood, logging residues and by-products of mechanical processing of wood). The detailed study at the level of a single FMU showed that the effect of intensification of forestry depends on the utilisation ratio of the annual allowable cut and the intensity of thinnings. The relatively high utilisation ratio in the Tikhvinsky FMU limits the potential of intensification of forestry. In this FMU, the available volume of energy wood could be increased only by 21% compared with the Shugozersky FMU, where the potential increase was 169%, due to the low utilisation of the annual allowable cut. The intensification of energy wood supply in the study area could have positive effects on employment and on the local market of forest machines. In the best case, up to 94 (+84%) new working places could be created. Realisation of the *Potential* scenario will require depending on the supply chain from 28 to 41 machines compared to 15-22 machines in the *Recent* scenario. The comparative cost analysis showed that costs of forest chips in comparison with market costs of natural gas and coal are too high and would not allow substitution of these fossil fuels by forest chips. However, if transportation distance is shorter than 60 km, forest chips have lower supply costs compared with the market costs of heavy oil. The harvestable volumes of industrial and energy wood in the study area are affected by climate change, due to the high share of winter fellings in the region (up to 80% by volume). In the case of extreme short winters, when volumes of winter fellings cannot be compensated during the summer without investments in road construction and machinery, a typical big logging company in the study area could lose about 360 000 euro.

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