Dissertationes Forestales 393

The role of forest chips in the electrification of the Finnish energy system and challenges for energy wood procurement from young thinning stands

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Academic dissertation
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ABSTRACT

Forest chips have become an important energy source in Finland in recent decades, largely driven by policies to increase renewable energy. In the 2020s, the expansion of alternative renewable energy technologies has affected the energy system. Meanwhile, criticism of forest chip use has grown, especially regarding climate and biodiversity impacts.

This dissertation investigates the future role of forest chips in Finland over the next decade and examines the operational environment of energy wood procurement. It also analyses harvesting conditions in young thinning stands with neglected management. The study combines survey data, forest inventory data, and harvesting simulations.

According to the findings, forest chip consumption is expected to decrease in heat-only and combined heat and power (CHP) plants by 2033, while remaining at a relatively high level. Forest chips will be increasingly used as a source of balancing power, extending energy wood storage times and intensifying terminal use. Most of the energy wood delivered in 2023 was domestic and sourced within 100 km of the consumer plant. A significant proportion of the supplied volume also consisted of roundwood suitable for industrial processing. Several of the analysed young thinning stands with neglected management were potential harvesting sites for delimbed energy stemwood and in some cases for pulpwood. High estimated harvesting costs resulted from the small average size of the removed stems and the low harvested volume.

Fluctuations in forest chip consumption, together with political uncertainty, should be recognised as undermining the operational environment of energy wood suppliers and posing a risk to security of supply. In stands where the removal consists of small-diameter stems, whole-tree harvesting may increase profitability if the stand is suitable for this method. Enhancing procurement and use of whole-tree chips is therefore important to improve forest management activities and prevent the use of industrial roundwood for energy.

Keywords: Energy policy, Renewable energy, Forest energy, Young forests, Forest management

Niinistö, T. (2026) Metsähakkeen rooli Suomen energiajärjestelmän sähköistymisessä ja energiapuun hankinnan haasteet nuorista harvennusmetsiköistä. Dissertationes Forestales 393. 49 p. https://doi.org/10.14214/df.393

TIIVISTELMÄ

Metsähakkeesta on tullut tärkeä energianlähde Suomessa viime vuosikymmenten aikana erityisesti uusiutuvan energian lisäämiseen tähdänneiden poliittisten toimien seurauksena. 2020-luvulla vaihtoehtoisten uusiutuvan energian teknologioiden yleistyminen on kuitenkin vaikuttanut energiajärjestelmään. Samanaikaisesti erityisesti ilmasto- ja luontovaikutuksiin perustuva kritiikki metsähakkeen käyttöä kohtaan on voimistunut.

Tämä väitöskirja tarkastelee metsähakkeen tulevaa roolia Suomessa seuraavan vuosikymmenen aikana sekä energiapuun hankintaketjujen toimintaympäristöä. Lisäksi se analysoi hoitamatta jääneiden nuorten harvennusmetsien korjuuolosuhteita. Tutkimuksessa yhdistyvät kyselytutkimusaineistot, metsänmittausaineistot sekä hakkuusimulaatiot.

Tulosten mukaan metsähakkeen kulutuksen lämpö- ja voimalaitoksissa odotetaan laskevan vuoteen 2033 mennessä, mutta pysyvän kuitenkin edelleen suhteellisen korkealla tasolla. Metsähaketta tullaan käyttämään aiempaa enemmän säätövoiman lähteenä, mikä pidentää energiapuun varastointiaikoja ja lisää terminaalivarastointia. Suurin osa vuonna 2023 toimitetusta energiapuusta oli kotimaista ja hankittu enintään sadan kilometrin etäisyydeltä laitoksesta. Merkittävä osa puusta oli metsäteollisuudelle jalostuskelpoista ainespuuta. Useat tutkituista hoitamatta jääneistä nuorista harvennusmetsistä olivat potentiaalisia karsitun energiarangan ja joissain tapauksissa myös kuitupuun hakkuukohteita. Korkeiksi arvioidut korjuukustannukset johtuivat poistettavien runkojen pienestä keskimääräisestä koosta ja pienestä hakkuukertymästä.

Metsähakkeen käyttömäärän vaihtelut ja poliittinen epävarmuus tulisi tunnistaa tekijöiksi, jotka heikentävät energiapuun hankintaketjujen toimintaympäristöä ja aiheuttavat riskin toimitusvarmuudelle. Metsiköissä, joissa hakkuupoistuma koostuu pieniläpimittaisista rungoista, kokopuun korjuu voi parantaa korjuun kannattavuutta, mikäli kohde on sille soveltuva. Kokopuun hankinnan ja hyödyntämisen edistäminen on siksi tarpeen metsänhoidon toimien tehostamiseksi sekä ainespuun energiakäytön ehkäisemiseksi.

Avainsanat: Energiapolitiikka, Uusiutuva energia, Metsäenergia, Nuoret metsät, Metsänhoito

ACKNOWLEDGEMENTS

"Seizing an opportunity" aptly describes both my doctoral journey and the motivation behind it. During my studies and after graduating with a Master of Science in Forestry, pursuing a doctoral degree or an academic career was not among my primary objectives. My interests were primarily focused on wood procurement and supply chains in the forest industry. This orientation stemmed not only from having grown up in an agricultural and forestry environment but also from my studies and work experience. However, my career path took an unexpected turn that ultimately led me towards research.

In December 2020, I began working at Natural Resources Institute Finland (Luke) as a Senior Statistician responsible for statistics on wood consumption and forest protection. This work offered a unique vantage point from which to follow current issues and developments within the forest sector. Working in a knowledgeable and supportive forest statistics team provided excellent opportunities for learning and exchanging ideas. In particular, my understanding of wood-based bioenergy and its central role in the Finnish energy system deepened significantly. At the same time, this work highlighted current information needs that provided the motivation for this dissertation.

The beginning of my research career at Luke in February 2024 would not have been possible without the support of many individuals. I would like to express my special thanks to my colleagues at Luke who contributed to developing the project idea, securing funding, and managing its implementation. Without their contributions, the REPower project, which provided the broader framework for my doctoral research within the context of Finland's energy transition, would not have come into existence, and this dissertation would not have been possible. I would also like to thank the European Union for funding the project. Warm thanks are also due to my employer, Luke, for the opportunity to pursue doctoral research alongside my regular work duties.

The University of Eastern Finland has played a central role in my doctoral journey. I would like to thank Professor Kalle Kärhä, the main supervisor of my dissertation, for his strong and consistent support throughout the process. I would also like to extend my warm thanks to my two other supervisors from Luke, Johanna Routa and Lauri Sikanen, for their guidance and encouragement. Without the trust and commitment shown by all of you, this dissertation would not have been completed.

I am grateful to all the co-authors of the articles included in this dissertation and to my colleagues at Luke for the excellent collaboration and encouraging working atmosphere during my doctoral research. I would especially like to thank Perttu Anttila and Juha Laitila for their key roles in the planning and implementation of the studies. Likewise, my friend and colleague Lauri Männistö has provided invaluable support and assistance in solving problems, even during the most challenging phases of the work. I also warmly thank Fulvio Di Fulvio and Helmer Belbo, the pre-examiners of this dissertation, for their valuable work.

Finally, I would like to express my warmest thanks to my family and close friends for their patience, encouragement, and understanding throughout this process. Special thanks go to my life partner, Marika, whose support and encouragement have been invaluable during the various stages of my doctoral journey.

Helsinki, 5 May 2026

Tuomas Niinistö

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman numerals **I–III** in the text.

I Niinistö T, Anttila P, Sikanen L, Kärhä K, Routa J (2025) Estimating future consumption of forest chips based on insights from energy producers: a case study for Finland. Scandinavian Journal of Forest Research 40(2): 95–106. https://doi.org/10.1080/02827581.2025.2491450.

II Niinistö T, Anttila P, Kaseva J, Sikanen L, Kärhä K, Routa J (2025) Energy wood flows and the operational environment of supply chains in Finland: insights from a supplier survey. Silva Fenn 59(3): 25011. https://doi.org/10.14214/sf.25011.

III Niinistö T, Anttila P, Laitila J, Männistö L, Pietilä V, Ahola A, Kärhä K, Sikanen L, Korhonen KT, Routa J (2026) Harvesting Conditions of Young Thinning Stands with Neglected Management Identified in the Finnish National Forest Inventories. Manuscript submitted.

Tuomas Niinistö is entirely responsible for this doctoral thesis, and his contribution to the studies is as follows:

I Tuomas Niinistö (TN) was the main author. TN, Perttu Anttila (PA), Lauri Sikanen (LS), Kalle Kärhä (KK), and Johanna Routa (JR) conceptualised the study and data collection, and contributed to the methodology. TN was primarily responsible for the data analysis with additional contributions from PA. LS, KK, and JR supervised the study.

II TN was the main author. TN, PA, LS, KK, and JR conceptualised the study and data collection. TN, PA, LS, KK, JR, and Janne Kaseva (JK) contributed to the methodology. TN was primarily responsible for the analysis, with additional contributions from PA and JK. LS, KK, and JR supervised the study.

III TN was the main author. TN, PA, LS, JR, KK, Juha Laitila (JL), Lauri Männistö (LM), Kari T. Korhonen (KTK), Arto Ahola (AA), and Ville Pietilä (VP) conceptualised the study and data collection. TN, PA, JL, LM, and KK contributed to the methodology. TN was primarily responsible for the data analysis with additional contributions from PA, JL, and LM. LS, KK, and JR supervised the study.

TABLE OF CONTENTS

ABBREVIATIONS AND DEFINITIONS

BECCS	Bioenergy with carbon capture and storage
BECCU	Bioenergy with carbon capture and utilisation
Cascade principle	Prioritising the highest added-value use of wood
CHP	Combined heat and power (plant)
DBH	Diameter at breast height
Delimbed stemwood	Stemwood from which branches have been removed
ECHE	Energy companies and heat entrepreneurs (Study **II)**
EHT	Energy wood harvesters and traders (Study **II)**
Energy wood	Roundwood, logging residues, and stumps
ETD	The Energy Taxation Directive 2003/96/EC
ETS	EU Emissions trading system
EU	European Union
EUDR	Regulation (EU) 2023/1115 on deforestation-free products
EW	Delimbed energy stemwood harvesting scenario (Study **III)**
FIC	Forest industry companies (Study **II)**
Forest chip	Chips made from energy wood
GLMM	Generalised linear mixed model
Industrial roundwood	Wood with industrial quality and dimensional requirements
IR5	Pulpwood harvesting scenario (Study **III)**
IR8	Pulpwood harvesting scenario (Study **III)**
KEMERA	Time-limited Funding for Sustainable Forestry
METKA	Temporary Forestry Incentive Scheme
m^3	Cubic metre (solid over bark)
NFI	National Forest Inventory
PMH_{15}	Productive machine hour including time delays <15 min
RED I	Renewable Energy Directive 2009/28
RED III	Renewable Energy Directive 2023/2413
Roundwood	Delimbed stemwood and whole trees
SAF	Sustainable aviation fuel
Whole tree	Stemwood, top, and branches harvested without delimbing
Young thinning stand	A thinning-stage stand at least 11 years old at breast height

INTRODUCTION

Political drivers of wood energy use

Wood energy constitutes a substantial component of the Finnish energy system, and wood is widely utilised in both heat and power generation (Official Statistics of Finland 2025a; 2025b). Although the use of non-combustion-based renewable energy such as wind and solar power has increased over the last ten years, wood-based energy still accounts for more than half of the country's renewable energy (Official Statistics of Finland 2025b). Moreover, wood fuel consumption is relatively high in Finland compared with many other European countries (United Nations 2018; Eurostat 2026).

The substantial consumption of wood energy has been driven by policy objectives to increase the share of renewable energy. Since the late 1990s, these objectives have been set primarily at the EU level. In 1997, the European Commission's strategy for future energy sources aimed to increase the share of renewable energy sources to 12% by 2010 (European Commission 1997). In 2001, a target was set for the share of renewable energy in electricity production (2001/77/EC), and in 2003, for the share of biofuels in transport (2003/30/EC) (European Parliament and Council 2001; European Parliament and Council 2003a). In 2003, the reduction of fossil fuel use was further promoted by establishing an emissions trading system (2003/87/EC, ETS), which was launched in 2005 (European Parliament and Council 2003b). The first Renewable Energy Directive (2009/28/EC, RED I), adopted in 2009, established a binding target for Member States to increase the share of renewable energy in the EU to 20% by 2020 (European Parliament and Council 2009). The directive has since been revised twice and the latest revision of the directive (2023/2413/EC, RED III) raised this target to 42.5% by 2030 (European Parliament and Council 2023a).

In Finland, wood fuels have represented a natural means of meeting these objectives due to the substantial supply potential arising from forestry and forest industry side streams. The political objectives have focused particularly on forest chips, that is, chips produced from delimbed stemwood, whole trees, logging residues, and stumps sourced directly from forests for energy generation. In 2008, the National Energy and Climate Strategy (2008) included a target of increasing the annual consumption of forest chips to 12 million m^3 (solid over bark) in heat-only and combined heat and power (CHP) plants. In 2013, this objective was raised to 25 TWh, equivalent to 13 million m^3 (Finnish Council of State 2013).

Among renewable-energy-related objectives, promoting forest chip use has been closely linked to forest policy. In Finnish silviculture, the relatively high proportion of young thinning stands with neglected management has been a longstanding challenge (Figure 1). In the Finnish National Forest Strategy 2025, the collection of small-diameter wood for use as forest chips was promoted to increase the profitability of management activities in young commercial forests (Ministry of Agriculture and Forestry of Finland 2015a). Subsidies for forest management measures have been found to play a decisive role in improving the economic viability of management activities (Petty and Kärhä 2011). Therefore, the collection of small-sized wood for energy is supported by the Temporary Forestry Incentive Scheme 71/2023 (METKA) (2023a) and was previously supported by the Act on Time-limited Funding for Sustainable Forestry 34/2015 (KEMERA) (2015b).

Figure 1. An example of a young thinning stand with neglected management on peatland in southern Finland. The number of stems is high, and the average diameter at breast height (DBH) is low due to delayed precommercial thinning. Photograph by Tuomas Niinistö.

Forest chip supply and consumption

Driven by policy measures such as higher emission allowance prices, the consumption of forest chips has risen substantially in Finnish heat-only and CHP plants since 2000 (Figure 2) (Official Statistics of Finland 2025c; European Energy Agency AG (EEX) 2026). Between 2000 and 2024, consumption has increased from less than one million m^3 to more than ten million m^3 (Official Statistics of Finland 2025c). Currently, forest chips constitute approximately a fifth of total wood fuel consumption in Finland (Official Statistics of Finland

2025b). In addition to political measures, the development has also been influenced by market-based factors such as rising prices of fossil fuels (Official Statistics of Finland 2025d). The heat-only and CHP plants are particularly utilised in district heating production, where predominantly wood-biomass-based fuels accounted for 51% of energy sources in 2025, with forest chips representing 29% of the total (Finnish Energy Association 2026). Correspondingly, the proportion of fossil fuels and energy peat consumed in district heating production in 2025 was only 13%, whereas it was 77% in 2010. The increase in renewable energy use has therefore been relatively rapid.

Figure 2. The Iiksenvaara combined heat and power (CHP) plant in Joensuu, operated by Savon Voima Oyj, is one of the largest in Finland. The plant's fuel mix consists mainly of solid wood fuels such as forest chips. Piles of sawdust and bark, generated as by-products of forest industry production, are visible in front of the plant. Photograph by Tuomas Niinistö.

A significant share of forest chips is made from forestry wood residues, which consist mainly of logging residues and a small proportion of stumps (Official Statistics of Finland 2025c). In addition, the majority of the forest chip volume used consists of roundwood, the consumption of which has increased particularly in recent years (Figure 3). The recorded roundwood used for energy includes delimbed stemwood and whole trees. However, harvesting statistics indicate that the proportion of delimbed energy stemwood is substantially higher than that of whole trees (Official Statistics of Finland 2026a).

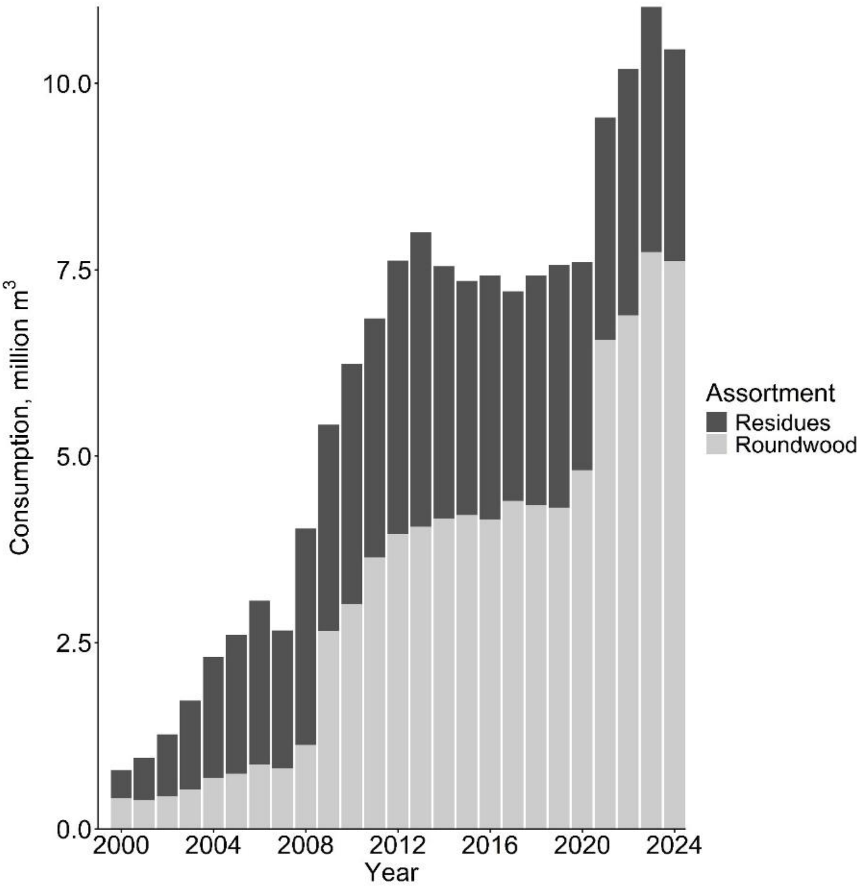

Figure 3. Forest chip consumption in Finnish heat-only and combined heat and power (CHP) plants between 2000 and 2024 (Official Statistics of Finland 2025c). Forest chip consumption increased notably during the twenty-first century, and this increase has been driven primarily by the increased use of roundwood in recent years. The recorded roundwood used for energy includes delimbed energy stemwood and whole trees.

However, the increase in forest chip consumption and energy wood utilisation has not led to the desired increase in forest management activity in young thinning stands. According to the 13th/14th National Forest Inventory (NFI) of Finland (2024), only 27% of such stands were identified as being in good forest management condition. In contrast, until 2022, approximately one fifth of the forest chips consumed in Finland was imported, mainly from Russia (Official Statistics of Finland 2023). The use of imported wood for energy has since decreased substantially due to the Russian invasion of Ukraine and the cessation of wood imports (Official Statistics of Finland 2025c). At the same time, the substantial increase in energy wood and forest chip prices has enhanced the cost-competitiveness of stands with higher harvesting costs for energy wood procurement (Official Statistics of Finland 2025d; 2026b). Nevertheless, the increased demand for domestic energy wood has been partly covered by roundwood that would otherwise have been suitable for processing by the forest industry in terms of dimensions and quality, that is, industrial roundwood (Viitanen et al. 2023). However, as the results of Kurki et al. (2012) indicated, some volume of industrial roundwood had previously been used as forest chips. This contradicts the cascade principle, which prioritises the use of wood based on its highest added value (European Commission 2016; European Parliament and Council 2023a).

Among the factors contributing to the higher consumption volumes of domestic energy wood, the increased use of roundwood (Figure 3) has been linked to the growing utilisation of terminal storage. Terminal-based energy wood supply chains are mainly based on delimbed stemwood (Figure 4) due to logistical benefits and lower biomass losses during storage compared with whole trees (Figure 5) and logging residues (Laitila and Väätäinen 2011; Routa et al. 2015). Correspondingly, the latest data available from 2020 indicated an increasing reliance on terminal-based supply chains (Strandström 2021). However, forest chip consumption has since risen substantially (Official Statistics of Finland 2025c).

Figure 4. Delimbed stemwood stored at a terminal site as raw material for forest chips. The pile contains some volumes of decayed large-sized roundwood. Additionally, in terms of diameter, a significant proportion of the wood may have been suitable for processing by the forest industry. However, the visible end of the woodpile provides insufficient information to quantify the proportion of industrial roundwood, that is, wood meeting the dimensional and quality requirements for forest industry production. Photograph by Tuomas Niinistö.

Figure 5. A covered pile of whole trees at a roadside storage site for use as forest chips in heat-only and combined heat and power (CHP) plants. Whole trees include stemwood, tops, and branches. The diameter distribution of the whole trees in the pile is broad. Photograph by Tuomas Niinistö.

Drivers of energy sector transformation in Finland

The development of the Finnish energy sector has been rapid in recent years and has also affected forest chip consumption. Alongside the decreasing consumption of fossil fuels and energy peat, the production of renewable electricity such as wind and solar power has increased substantially (Official Statistics of Finland 2025b; Finnish Energy Association 2026). Wind power capacity increased more than ninefold between 2015 and 2025, reaching nine terawatt-hours (TWh) (Renewables Finland 2026a). Similarly, solar power capacity has grown, although it remained below half a terawatt-hour in 2025 (Renewables Finland 2026b).

This development has also been in line with the policy objectives established in the Government Programme of Petteri Orpo (2023b).

The increased production of renewable electricity has also created opportunities for electrification in heat production, where wood fuels have previously offered one of the key solutions for mitigating emissions (Weiss et al. 2021; Hiltunen et al. 2025; Finnish Energy Association 2026). Along with the electrification of heat production, the warm winter in 2024 caused a decline in forest chip consumption (Viitanen et al. 2025; Official Statistics of Finland 2025c). However, the increasing proportion of weather-dependent renewable energy requires balancing power, which is still largely provided by CHP plants using wood-based fuels (Miettinen and Holttinen 2019; Joronen et al. 2025; Finnish Energy Association 2026). In addition, electricity consumption is expected to increase substantially (Fingrid Oyj 2025). Concurrently, the role of energy peat and fossil fuels continues to decline. This leaves only a few options other than wood-based fuels for balancing the energy system (Official Statistics of Finland 2025b).

Meanwhile, views on the utilisation of forest chips vary. These discussions have been influenced by concerns related to the climate and biodiversity impacts of wood harvesting and the carbon dioxide released during combustion (e.g., Soimakallio et al. 2016; Pihlainen et al. 2023). This applies particularly to roundwood, whose climate benefits are smaller than those of logging residues, because logging residues decay much faster than roundwood left in the forest (Jåstad et al. 2020). In this context, reducing wood combustion and allocating wood more extensively to forest industry production have been proposed as a measure to decrease harvesting volumes and increase forest carbon sinks (e.g., The Finnish Climate Change Panel 2023; 2025; Seppälä et al. 2026). Similarly, the recently updated National Energy and Climate Strategy (2026) set the objective of reducing combustion-based energy production. Meanwhile, according to the findings of Ghani et al. (2025), the impacts of harvesting logging residues or pre-commercial thinning on the forest carbon balance are relatively small. These impacts therefore do not significantly diminish the climate benefits achieved through the use of such forest biomass as a substitute for fossil fuels.

To support the reduction of harvesting volumes and to direct wood towards purposes other than burning, measures such as taxing the use of forest chips for energy have been proposed (e.g., Pihlainen et al. 2023; Seppälä et al. 2025; Lintunen et al. 2026). The removal of tax exemptions for all solid biofuels consumed in larger heat-only and CHP plants was also proposed in the initial draft of the revision of the Energy Taxation Directive 2003/96/EC (ETD) by the Commission (2021). For sustainable biomass, the proposed tax rate would have been lower. These restrictions on the supply and use of woody biomass were introduced in the RED III Directive (European Parliament and Council 2023a). If implemented, taxation of solid wood fuels would be expected to substantially undermine the cost-competitiveness of these fuels in energy generation, reducing their consumption (Muilu et al. 2024). However, the revision of the ETD is still in progress, and solid biomass taxation has been removed from the latest proposals (Council of the European Union 2025).

Objectives

This dissertation aims to investigate the future role of forest chips as part of the Finnish energy system. It examines expected changes in consumption volumes and utilisation to construct a future outlook on their development within the rapidly transforming energy sector. As forest chips are a significant component of the current Finnish energy system, the study also seeks to support preparedness for forthcoming changes by analysing the operational environment of energy wood procurement. A further objective is to analyse ways to promote a sustainable energy wood supply, particularly from the perspective of the cascade principle. To this end, the study analyses the origin and quality of the energy wood consumed. It also examines the harvesting conditions of young thinning stands with neglected management, where energy wood harvesting can support the economic viability of forest management. In addition to their potential for delimbed energy stemwood harvesting, these stands are assessed as a source of pulpwood from a cascade-use perspective. The main research question of this dissertation is how the role of forest chips develops in the Finnish energy system and how the security of supply and sustainability of energy wood procurement can be promoted in a changing operational environment. The dissertation consists of Studies **I**, **II**, and **III**, and the study-specific research questions are listed in Figure 6.

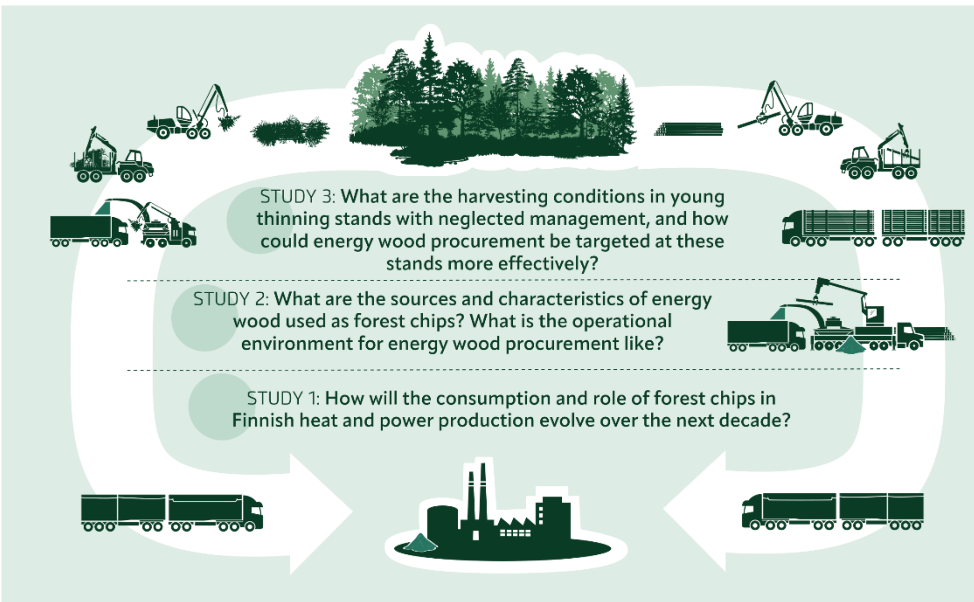

Figure 6. The overall framework of the dissertation and the study-specific research questions.

MATERIALS AND METHODS

Overview of the data and methods

In this section, the main principles of data collection and analysis are described for each of the three studies. However, more detailed information can be found in the original articles.

In Study **I**, the estimated national forest chip consumption volumes and analysis were based on a research survey conducted among energy producers. Additionally, another nationwide research survey was utilised to analyse the operational environment of energy wood supply chains in Study **II**. In Study **III**, the harvesting conditions of young thinning stands with neglected management — considered as a potential source of energy wood — were analysed based on field measurement data and harvesting simulations.

Study I

Data collection

In Study **I**, the research survey for estimating the future use of forest chips in heat-only and CHP plants was conducted in April and May 2024. The survey respondents, the consumer plants, and the consumption baseline were identified based on the statistics of Wood in Energy Generation in 2023 (Official Statistics of Finland 2024).

In the survey, respondents were asked to estimate the annual consumption of forest chips, other solid wood fuels, and energy peat at the plant level in 2026 and 2033. The year 2026 was selected to represent the influence of current investments in energy generation technologies such as electric boilers, waste heat recovery, and improvements in energy efficiency. Moreover, the replacement of energy peat use has occurred particularly in recent years and will also affect the use of wood energy. Correspondingly, the effect of planned investments in bioenergy with carbon capture and utilisation (BECCU) or storage (BECCS) was expected to be particularly visible in 2033.

In addition to consumption volumes, respondents were asked to identify other potential changes in forest chip consumption, such as changes in the proportions of different energy wood assortments compared with the current state in 2023. Respondents were also asked to report new investments and other potential factors influencing the consumption and development of energy generation.

Analysis

The development of forest chip use was analysed for plants for which the consumption estimates were available for both 2026 and 2033, based on survey responses. The analysis was conducted at the national level and across four major regions (Figure 7). Additionally, the total consumption of forest chips in Finnish heat-only and CHP plants was estimated. For plants with missing consumption estimates, values were imputed using linear regression analysis. Separate linear regression models were fitted for 2026 and 2033. In each model, the response variable was forest chip consumption in the target year. The explanatory variables were recorded forest chip consumption in 2023 and the change in consumption between 2023 and the target year, based on data from the respondent plants.

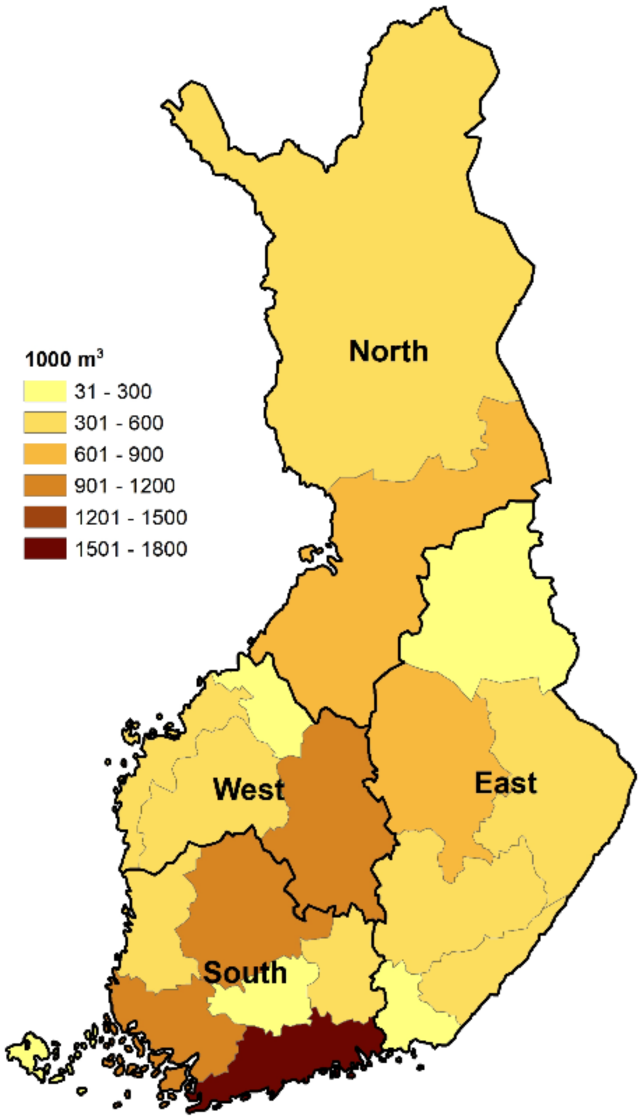

Figure 7. Forest chip consumption in Finnish heat-only and combined heat and power (CHP) plants in 2023 and the classification of the four major regions used in the analyses of Studies Ⅰ and Ⅱ. The regional differences in consumption volumes are substantial.

The analysis was supplemented by examining the factors affecting forest chip use. The development of energy peat consumption was analysed for plants with available consumption estimates for 2026 and 2033. Additionally, the perspectives expressed in responses to qualitative questions, such as new investments, were analysed, and the prevalence of different aspects in the data was counted.

Study II

Data collection

The data for Study **II** were collected in April and May 2024. The research survey on deliveries of energy wood for heat-only and CHP plants was targeted at energy wood suppliers. The group of suppliers was selected from public data sources, and the aim of the data collection was to reach as many suppliers as possible.

In the survey, respondents were asked to report volumes of delivered forest chips and different energy wood assortments used as forest chips. Respondents were asked to report the volumes at the level of the end consumer's plants or terminals. In addition, the respondents were asked to allocate delivery volumes, as percentages, to transport distance categories in relation to the consumer plant location to analyse energy wood procurement areas.

Furthermore, respondents were asked to report the proportions of different energy wood assortments in the delivered energy wood. The assortment classification resembled that used in the data collection of the Wood in Energy Generation 2023 statistics (Official Statistics of Finland 2024). This classification included a category for wood with dimensions and quality suitable for processing by the forest industry. It was also requested that the proportions of imported wood and wood sourced from land-use change areas be reported.

To analyse the operational environment of supply chains, suppliers were asked about the potential effects of currently relevant EU policy measures, namely, the updated Renewable Energy Directive 2023/2413 (RED III) and Regulation on Deforestation-free products 2023/1115 (EUDR). The security of energy wood supply was assessed by requesting information on the terminal storage capacity and storage volumes in the autumn of 2023.

Analysis

The analysis of Study **II** focused on the data provided by those respondents who had supplied energy wood or forest chips in 2023. However, some responses were incomplete and were utilised solely in analyses where the data were usable. The coverage of the data therefore varied between questions.

Based on the data provided, the amount and origin of procured energy wood and different assortments were identified. Moreover, energy wood procurement areas were analysed using generalised linear mixed models (GLMMs). A beta distribution with a logit link was employed based on the provided transport distance proportions. In the procurement-area model developed, the effects of the transport distance category, forest chip consumption category, and their interaction were used as fixed effects. The random effects of municipality, region, and Finland's four major regions (Figure 7) were also tested.

The effects of policy objectives on the operational environment were analysed using responses based on qualitative and quantitative measures. Additionally, the suppliers' terminal capacity, the characteristics of terminals, and their utilisation rate were identified.

Study III

Data collection

In Study **III**, the 60 young thinning stands analysed were selected from the sample plots and surrounding stands of the 13th NFI in Finland (Figure 8) (Korhonen et al. 2024). These stands were defined as being in the thinning stage, with a breast-height age of at least 11 years. The selected plots were within 80 km of the cities of Tampere and Jyväskylä, and were measured between 2019 and 2023. For each NFI plot, neglected pre-commercial thinning or first thinning was identified, and these stands were considered likely to still be unmanaged based on the absence of forest-use declarations or delineations of KEMERA or METKA subsidies. The selected stands were analysed using field measurements in October 2025, following the 13th NFI's field measurement instructions (Korhonen et al. 2024). However, the analysed area was limited to a maximum of two hectares located around the NFI plot, even if the total area of the stand was larger.

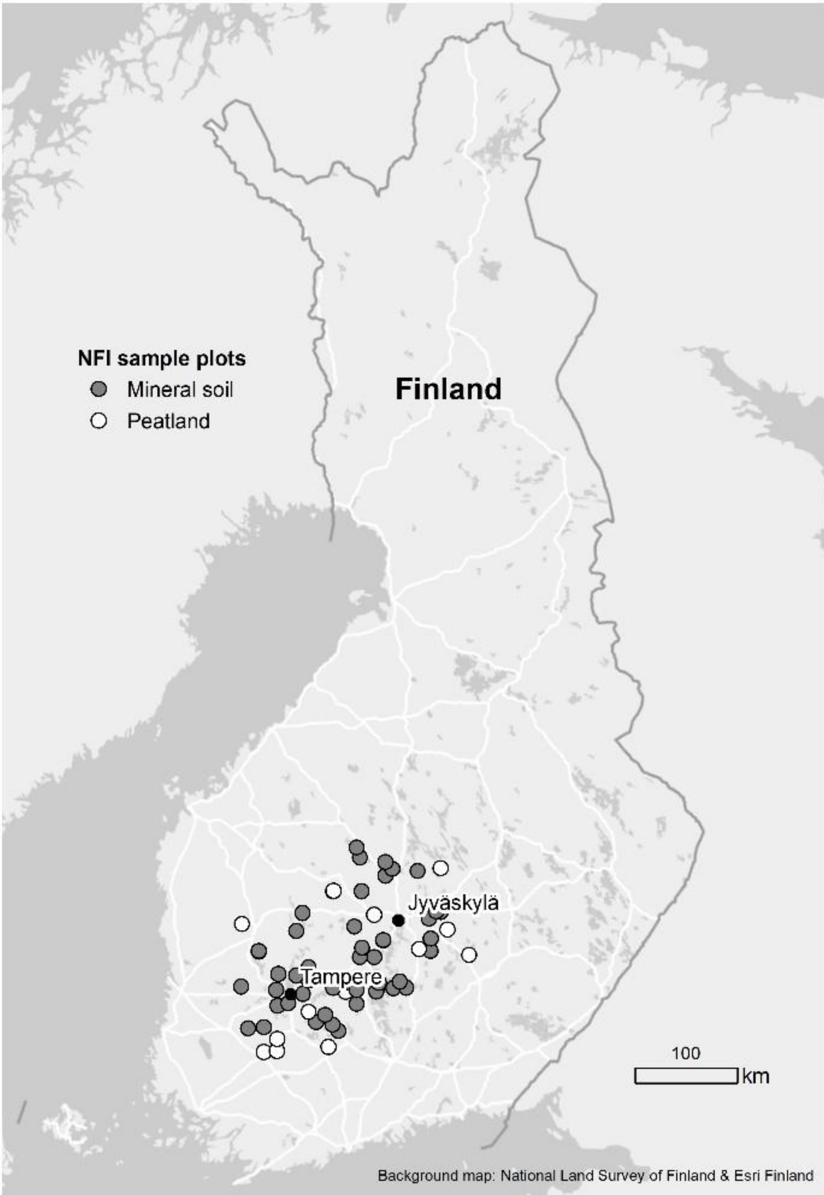

Figure 8. The 60 selected sample plots of the 13th National Forest Inventory (NFI) used in the analysis of Study III and their spatial distribution within 80 km of the cities of Tampere and Jyväskylä.

For each stand, habitat characteristics and other possible features were determined. A total of three to six circular sample plots were placed in each stand, the number of which depended on the variability of stand structure and the stand's total area. The radius of the sample plots varied depending on the trees' diameter at breast height (DBH). In each of the sample plots, every tally tree with a DBH of at least 4.5 cm was measured. Additionally, a representative number of height-sample trees was measured for Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), and deciduous tree species, mainly consisting of silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrh.). Missing heights for tally trees were estimated using the functions by Veltheim (1987), adjusted using the measured height of sample trees. Trees below a DBH of 4.5 cm were considered understorey, and only average DBH and height were estimated.

Harvesting simulations

First, the need for pre-harvest clearing was estimated for each stand. For the pre-harvest clearing, a threshold value of 2000 understorey trees (DBH <4.5 cm) per hectare was set. If this threshold was exceeded, the pre-harvest clearing costs were estimated using the working productivity model by Kaila et al. (1999) and the general hourly wages from the Collective Agreement of the Forest Sector (2024).

For each stand, a thinning-from-below harvesting operation was simulated using the Motti simulator platform using data of trees with a DBH of at least 4.5 cm (Salminen et al. 2005; Siipilehto et al. 2014). Three different harvesting scenarios were compared based on harvesting volumes and costs: delimbed energy stemwood harvesting with a minimum top diameter of 3 cm (EW); pulpwood harvesting with minimum top diameters of 5 cm (IR5) and 8 cm (IR8) and a 3-metre minimum bolt length requirement. The minimum top diameter of 3 cm for delimbed energy stemwood was applied as a technical threshold, as stems smaller than this threshold typically break during delimbing. Additionally, the two different minimum top diameter limits for pulpwood were selected to represent the effect of dimensional requirements, which may vary depending on market conditions and other operational factors.

The cost-competitiveness of each stand and scenario was estimated by calculating the roadside cost for harvested wood, the most important component of which was harvesting cost. This cost consisted of cutting and forwarding costs. The cutting cost was estimated using productivity models by Perho (2012): one for single-tree cutting productivity for pulpwood; one for integrated pulpwood and small-diameter stemwood, applied in delimbed energy stemwood harvesting. The forwarding work productivity was calculated using fixed values for a 600 m ha^{-1} strip road network, 300 m empty and loaded driving distances, and an 11 m^3 average payload size using the model by Kärhä et al. (2006). The cutting and forwarding work productivities were converted to operating productivity, including time delays of up to 15 min (PMH_{15}). The cutting and forwarding costs were calculated with hourly costs of €131.3 for a harvester and €96.2 for a forwarder (Pesonen et al. 2025). In addition, the roadside cost included the average wood procurement overhead cost (€2.0 m^{-3}) allocated to the harvesting and pre-harvest clearing cost where required (Strandström 2025).

Finally, cost-competitiveness was estimated by comparing roadside costs with the average delivery sale prices of delimbed energy stemwood and pulpwood in the Keski-Suomi price region in 2025 (Official Statistics of Finland 2026b; 2026c). Under this purchasing method, wood is purchased as a stacked pile at roadside storage.

RESULTS

This section gathers the main findings of Studies **I, II,** and **III**. A more detailed description of the results can be found in the original articles.

The role of forest chips in Finland's future energy generation

In Study **I**, the analysed survey data included forest chip consumption estimates for 325 plants. Of these, 244 plants consumed forest chips in 2023, together accounting for 79% of total forest chip consumption in Finnish heat-only and CHP plants in 2023. Based on the survey-based and modelled estimates for the remaining plants, total forest chip consumption in Finnish heat-only and CHP plants is projected to increase slightly by 2026 (Figure 9). However, consumption is expected to decline by 2033, although it is anticipated to remain relatively close to the current consumption volume.

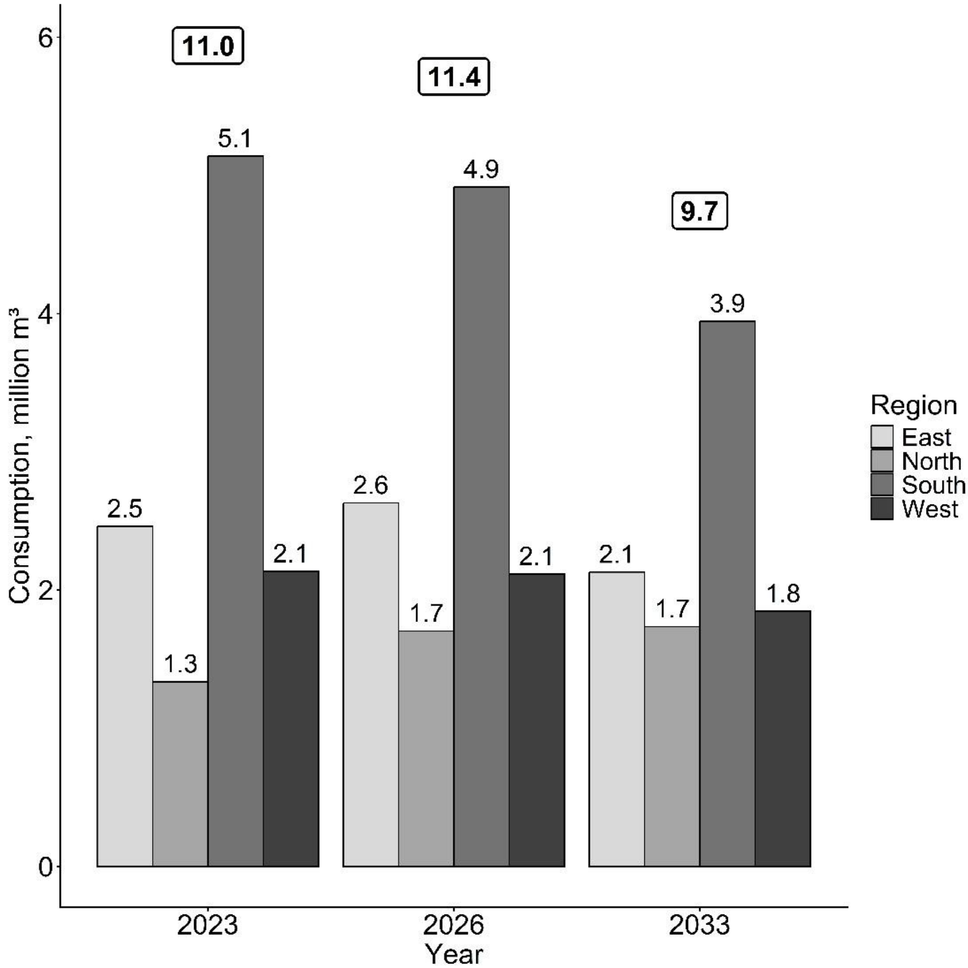

Figure 9. Forest chip consumption in Study **I** by region. The circled box presents the total consumption for the whole country. In relation to consumption in 2023, 79% of the estimates were based on the responses to the survey for Study **I,** while estimates for the remaining plants were modelled using linear regression analysis.

Regional differences in consumption were substantial, and they were particularly caused by differences in energy peat consumption. The analysed data covered 58% of total energy peat consumption in 2023 and included 109 consumer plants. In the East and North regions, where energy peat consumption was at the highest level, it was expected that forest chip consumption would increase between 2023 and 2026, mainly due to the replacement of energy peat. By contrast, in the South region, where energy peat consumption in 2023 was at the lowest level, it was projected that forest chip consumption would decrease by 2026. However, the results of Study **I** indicate that energy peat consumption is expected to halve between 2023 and 2026, and to be almost completely phased out by 2033, especially in larger plants throughout the country.

The regional differences in the development of forest chip consumption were also explained by varying strategic approaches to the development of energy generation. While 18 respondents reported plans to build new heat-only or CHP plants, most of these were intended to replace existing plant capacity. Similarly, 11 respondents indicated plans to decommission their current plant capacity. By contrast, most of the reported investment plans focused on measures to improve energy efficiency or build alternative energy generation technologies. For example, 37 respondents identified scrubbers as a target for potential or already implemented investments; 24 respondents mentioned heat pumps. Twenty-six respondents mentioned investment plans for electric boilers.

Respondents reported that alternative electricity-based energy generation technologies are expected to cause fluctuations in forest chip consumption, while wood is increasingly used as a source of balancing power. This trend was also identified as a potential factor that could increase the share of roundwood used as forest chips due to its better preservation during storage. However, from a longer-term perspective, the investment plans for BECCU may have a substantial impact on forest chip and wood fuel consumption. Several respondents mentioned these plans. If BECCU investments are realised, waste heat recovery from hydrogen electrolysers may replace wood energy. However, BECCU depends on the availability of biogenic carbon, and the potentially high profitability of BECCU was highlighted as a factor that could increase wood combustion's economic viability.

Operational environment of energy wood supply

In Study **II**, the analysed data from the survey covered 6.058 million m^3 of energy wood and forest chips delivered in 2023 by 65 suppliers in Finland. Of this volume, 4.553 million m^3 was delivered to plants, and 1.506 million m^3 to end consumers' terminals. Additionally, the average delivery volume of individual operators was substantially higher among Forest Industry Companies (FIC) and Energy Companies and Heat Entrepreneurs (ECHE) than among Energy Wood Harvesters and Traders (EHT) (Table 1).

Table 1. Finnish energy wood suppliers and their total, average, and median supply volumes in 2023, presented by company type based on the analysed survey data on energy wood deliveries (Study Ⅱ).

Type of supplier	Number of suppliers	Annual supply volume, 1000 m^3	Average supply volume by supplier, 1000 m^3	Median supply volume by supplier, 1000 m^3
Energy wood harvesters and traders (EHT)	36	1 984	55	39
Energy companies and heat entrepreneurs (ECHE)	14	1 824	130	12
Forest industry companies (FIC)	15	2 251	150	22
Total	65	6 058	93	30

The volume of delivered energy wood consisted of industrial roundwood (976 000 m^3), other roundwood (3.003 million m^3), logging residues (2.048 million m^3), and stumps (32 000 m^3). However, the proportions of energy wood assortments varied among supplier types (Figure 10).

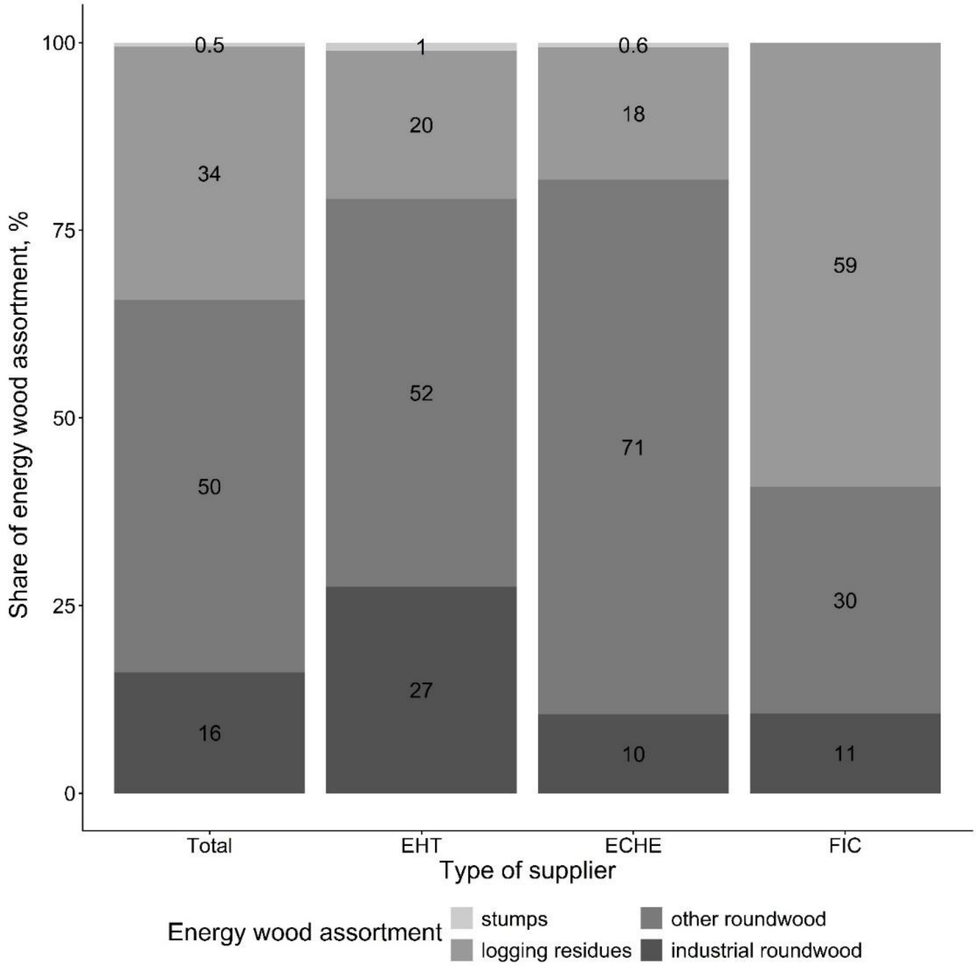

Figure 10. The proportions of energy wood assortments varied by supplier type in the survey data on energy wood deliveries in 2023 (Study Ⅱ). In total, the data included information from 65 Finnish energy wood suppliers who delivered 6.058 million m^3 of energy wood. The total delivery volumes were 1.984 million m^3 for energy wood harvesters and traders (EHT; 36 operators), 1.824 million m^3 for energy companies and heat entrepreneurs (ECHE; 14 operators), and 2.251 million m^3 for forest industry companies (FIC; 15 operators).

The supplied energy wood was mainly sourced from domestic forests. Only three suppliers reported delivery volumes of imported energy wood, totalling 94 000 m^3. Of this volume, 84% consisted of roundwood unsuitable for processing by the forest industry. Imported wood accounted for 5% of the total delivery volume of these suppliers. Additionally, 16 respondents reported that they had delivered energy wood sourced from land-use change areas in 2023. The volume of that wood accounted for 148 000 m^3 and represented 8% of the wood supplied by these respondents.

The plant-level energy wood transport distances and procurement areas were modelled based on the data from 4.216 million m^3 of energy wood delivered. These volumes were delivered to the plants and to end-user's terminals located within 15 km of the presumed consumer plant. The differences among forest chip consumption categories ($F_{2,891} = 9.4$, $p < 0.001$), transport distance categories ($F_{5,767} = 52.2$, $p < 0.001$), and their interaction ($F_{10,765} = 7.6$, $p < 0.001$) were identified. The model's explanatory power was 37% (Figure 11). Additionally, the results of the analysis showed the differences in transport distances between supplier types. The distances were shorter on average for the EHT group than for the ECHEs and FICs.

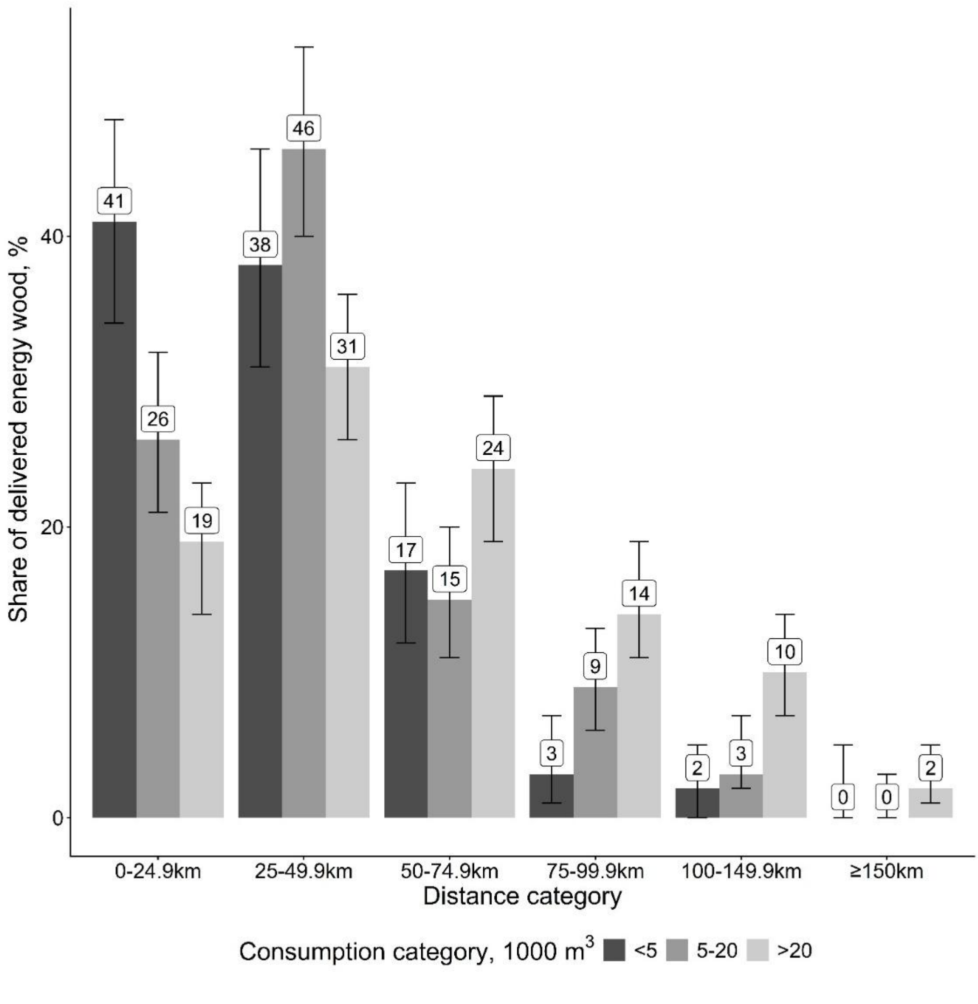

Figure 11. The model for energy wood transport distances and procurement areas in Finland. The model is based on survey data covering 4.216 million m^3 of energy wood delivered in Finland in 2023. The figure presents the 95% confidence interval for each estimate. Full parameter estimates for the fixed effects (logit scale) are provided in supplementary file 2 of Study Ⅱ.

Only 36 suppliers reported having their own terminals. The total terminal area of these suppliers was 312 hectares. Of this area, 78 hectares were asphalted, making them particularly suitable for storing chipped wood. In the autumn of 2023, before the heating season, 849 000 m^3 of forest chips and energy wood assortments used as forest chips were stored in these terminals.

Regarding policy measures, most respondents felt uncertain about their impact on the operational environment for energy wood procurement and had not prepared for their effects. A total of 13 respondents reported preparing for the effects of the RED III directive, and of whom six considered the potential implications to be minor. A total of 14 respondents had prepared for the EUDR, and five assessed its impacts as minor. However, five respondents also criticised the increasing regulation and bureaucracy caused by these measures.

Harvesting conditions of young thinning stands with neglected management

In Study **III**, a total of 52 young thinning stands of the 60 selected stands were ultimately measured. Eight stands were rejected based on the field inventory because they did not meet the criteria for selection as research stands. The stand and habitat characteristics of the measured stands varied (Table 2; Table 3). Based on the criteria selected for pre-harvest clearing, the need for such clearing was identified in 25 stands. The average pre-harvest clearing cost for these stands was €220 ha^{-1}.

Table 2. Habitat characteristics of the 52 measured young thinning stands with neglected management (Study Ⅲ). The other category includes one grove (Norway spruce-dominated) and one rocky site (Scots pine-dominated).

Forest stand type on mineral soil or nutrient-equivalent peatland	Number of stands by main tree species and site type							
	Mineral soil				Peatland			
	Scots pine	Norway spruce	Silver birch	Downy birch	Scots pine	Norway spruce	Silver birch	Downy birch
Herb-rich heath forest	-	9	2	1	-	-	-	5
Mesic heath forest	8	8	-	-	4	2	-	1
Sub-xeric heath forest	6	-	-	1	1	-	-	-
Xeric heath forest	1	-	-	-	1	-	-	-
Other	1	1	-	-	-	-	-	-

Table 3. Main characteristics of measured 52 young thinning stands with neglected management (Study Ⅲ). DBH refers to diameter at breast height.

	Total number of trees, N ha^{-1}	Trees DBH ≥4.5 cm				
		Number of trees, N ha^{-1}	Basal area, m^2 ha^{-1}	Average DBH, cm	Average height of trees, m	Standard deviation of DBH at the stand level, cm
Mean	5 103	2 591	25.9	14.1	14.0	4.2
Median	4 257	2 498	27.3	13.9	14.4	4.2
Min	1 512	1 375	11.1	9.4	9.3	2.6
Max	12 247	5 199	39.2	19.8	19.6	6.3

Harvesting simulations showed that harvesting volumes varied substantially among the stands and scenarios (Table 4). In the EW scenario, the harvesting volume per hectare was 9% higher on average than in the IR5 scenario. Between the EW and IR8 scenarios, the corresponding difference was 38%. The impact of unmerchantable trees on harvesting volumes was minor. Unmerchantable trees occurred in 18 stands and accounted for an average of 3% of the harvested volume in those stands. These trees consisted mainly of grey alder (*Alnus incana*) and black alder (*Alnus glutinosa*).

Table 4. Simulated harvesting volumes of the 52 measured young thinning stands with neglected management (Study Ⅲ). The EW scenario represented harvesting of delimbed energy stemwood with a 3 cm minimum top diameter. The other two scenarios were pulpwood harvesting with a requirement of a 3-metre minimum bolt length and minimum top diameters of 5 cm (IR5) and 8 cm (IR8).

	Density of removal, n ha^{-1}	Diameter at breast height (DBH) of removals, cm	Harvesting volumes, m^3 ha^{-1}		
			EW	IR5	IR8
Mean	1 465	9.9	79.9	73.4	57.8
Median	1 392	9.4	85.2	79.9	61.5
Min	247	7.3	20.7	17.1	9.6
Max	4 091	13.6	154.2	147.8	123.4

The simulated harvesting cost varied substantially among stands and depended heavily on the average volume of stems removed in the harvesting operation (Figure 12). Moreover, differences in dimensional requirements for harvested wood among the three scenarios had a substantial impact on costs, particularly in stands with a lower average volume of removed stems.

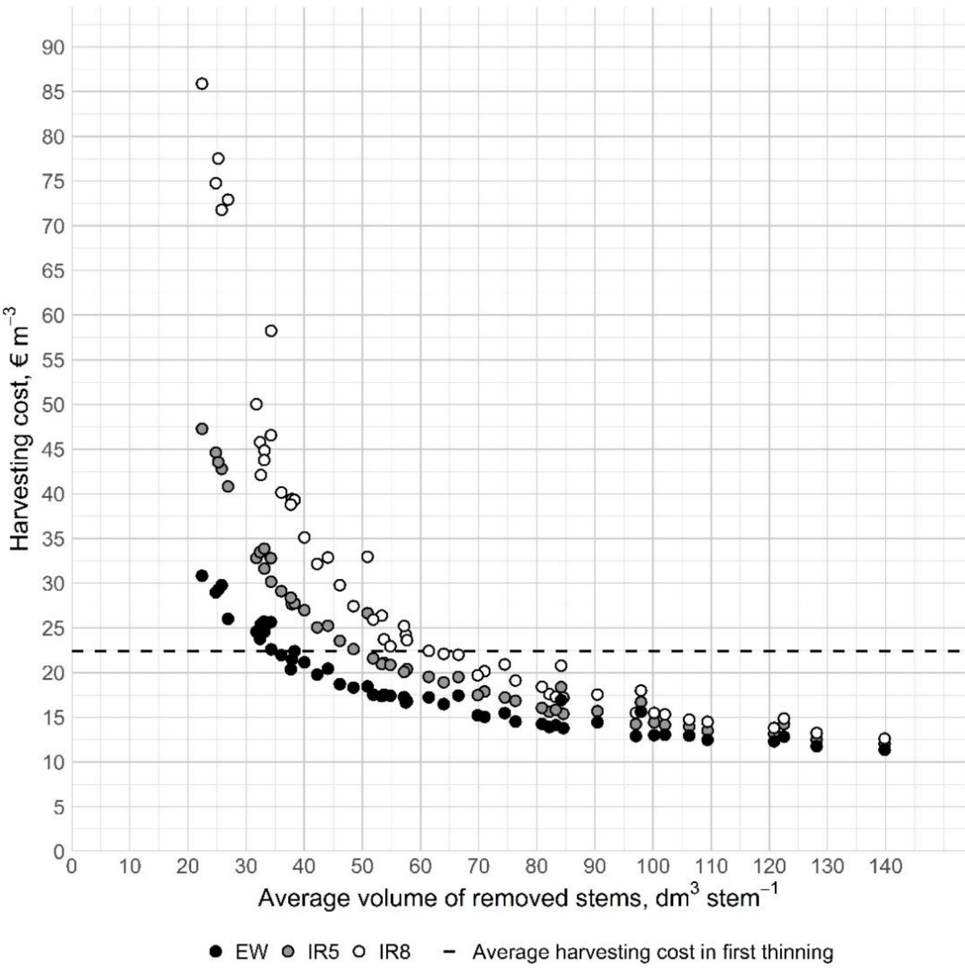

Figure 12. Harvesting costs of the 52 measured forest stands, including cutting and forwarding costs (Study Ⅲ). Harvesting costs strongly depended on the average total stem volume of removed trees. The EW scenario represented delimbed energy stemwood harvesting with a 3 cm minimum top diameter. The IR5 and IR8 scenarios represented pulpwood harvesting with minimum top diameters of 5 cm and 8 cm, and with a 3-metre minimum bolt length requirement. The horizontal line indicates the recorded average first thinning harvesting cost (€22.4 m^{-3}) in 2024 (Strandström 2025).

Estimated roadside costs varied among stands and scenarios (Figure 13). This was largely caused by the considerable variation in cutting productivity and costs. Based on the results, the roadside cost for each stand in the EW scenario was lower than the average delivery sale price of delimbed energy stemwood in 2025. However, in the IR5 scenario, the roadside cost exceeded the average delivery sale price of pulpwood in 2025 in four stands (8%) and in 12 stands in the IR8 scenario (23%).

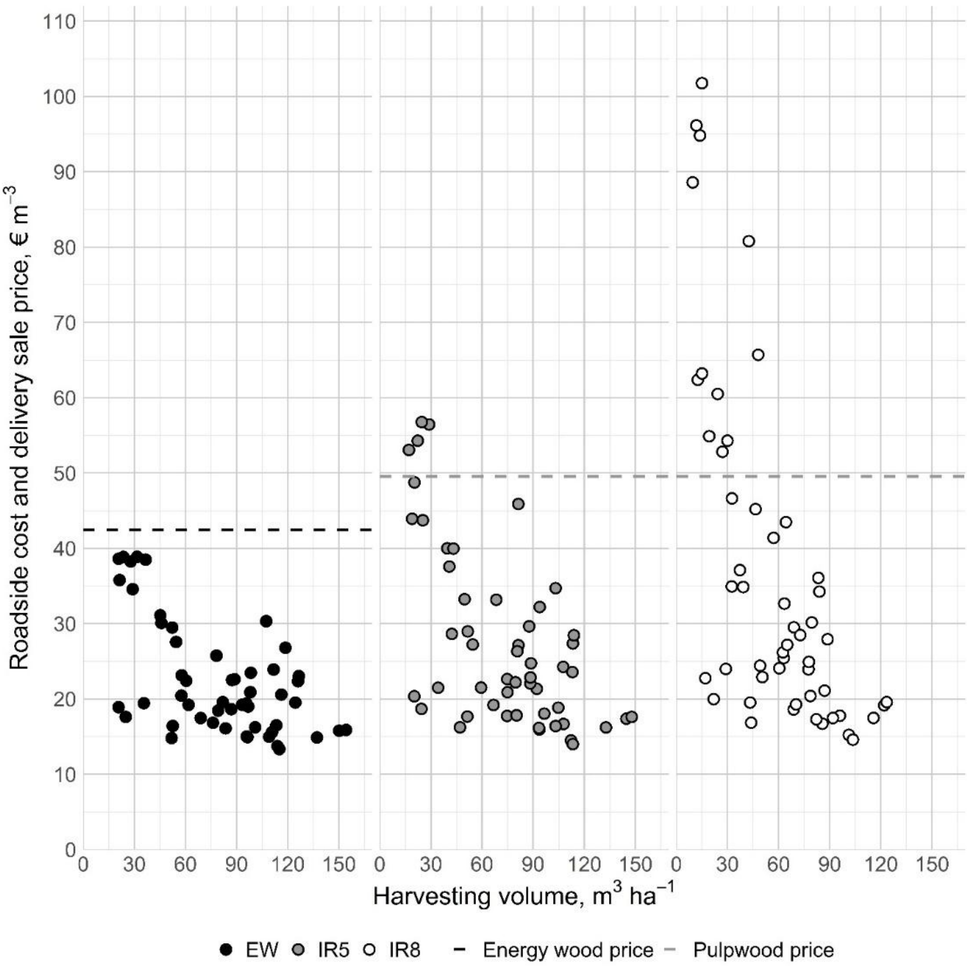

Figure 13. Roadside costs and estimated harvesting volumes (m^3 ha^{-1}) for three thinning-from-below harvesting scenarios in 52 measured forest stands (Study III). The costs include harvesting, pre-clearing where required, and the harvesting share of average wood procurement overhead costs of €2.0 m^{-3} according to Strandström (2025). The EW scenario represented harvesting of delimbed energy stemwood with a 3 cm minimum top diameter. The other two scenarios were pulpwood harvesting, with a requirement of a 3-metre minimum bolt length and minimum top diameters of 5 cm (IR5) and 8 cm (IR8). The average energy wood and pulpwood prices are based on Official Statistics of Finland (2026b; 2026c).

DISCUSSION

Bioenergy as an important part of the future energy system

Biomass-based fuels are essential for replacing fossil fuels and achieving climate objectives both in Finland and globally (Zappa et al. 2019). When combined with BECCS in particular, the climate benefits of bioenergy are substantial (Alvarado Cummings et al. 2025). In addition, it has been estimated that achieving the EU's 2040 climate target and reaching climate neutrality by 2050 will require substantial use of wood biomass for energy (European Commission 2024). These perspectives effectively highlight the divergence in views and interpretations concerning bioenergy. Instead of viewing bioenergy as part of the solution to mitigate climate change, for example, Seppälä et al. (2025; 2026) have taken a different position. They have argued that the use of forest chips should be reduced to decrease harvesting volumes and thereby increase forest carbon sequestration.

However, in the future, the use of bioenergy is likely to shift to more advanced biofuels. This shift is likely to involve fuels used in marine and aviation transport rather than increased combustion of solid biomass (Börjesson Hagberg et al. 2016; International Energy Agency 2021). This development is guided by policy objectives such as the targets for the share of sustainable aviation fuels (SAF) in the EU, as set out in Regulation (EU) 2023/2405 (European Parliament and Council 2023b).

The growing role of wood energy as a source of balancing power

The electrification of district heating systems has been considered a potential solution for the decarbonisation of the heating sector. Technologies such as electric boilers can be utilised during periods of low electricity prices. This can reduce the consumption of fossil fuels and biomass in district heat production (Weiss et al. 2021; Hiltunen et al. 2025). This development is in line with the results of Study **I**, which indicated a decrease in forest chip consumption by 2033.

At the same time, the proportion of weather-dependent electricity generation such as wind power is increasing in the energy system. Therefore, the need for renewable balancing power is becoming more substantial (Miettinen and Holttinen 2019). This can also be seen in the results of Study **I** as the estimated forest chip consumption remained at a relatively high level. Additionally, these results are consistent with those of Koljonen et al. (2025), for example, which predict that the use of forest chips will remain relatively high over the next ten years.

However, it should also be noted that although the survey dataset collected in Study **I** was comprehensive, some plants were nevertheless excluded. For these plants, consumption estimates were obtained by modelling. Moreover, the modelling could not incorporate all potential explanatory variables, such as the influence of energy peat consumption. It is likewise important to note the uncertainty caused by unpredictable weather conditions.

In the longer term, widespread use of technologies such as heat storage systems and the introduction of various mechanisms for flexible demand will help maintain the energy system's balance (Child et al. 2017; Olkkonen et al. 2018). Additionally, hydrogen may offer substantial potential as a form of seasonal storage for renewable energy (Elberry et al. 2021). It should also be noted, however, that the wider electrification of the energy system requires substantial investments in Finland's main grid (Fingrid Oyj 2025). As the results of Rinne and Syri (2015) show, the energy system's stability can also be effectively managed by a CHP plant connected to heat storage. A significant advantage of using CHP plants for balancing power is that their capacity is already widely available.

Future development and challenges for wood energy

In recent years, the profitability of CHP production has suffered from the rapid increase in fuel prices (Official Statistics of Finland 2025d). Its economic viability also strongly depends on electricity prices (Jääskeläinen et al. 2018). The increased fluctuations in electricity prices caused by weather-dependent electricity production are therefore likely to decrease CHP production (Mikola 2025). Additional challenges for CHP production may arise from policy measures like taxes on the use of solid wood fuels or forest chips. Such measures would substantially weaken the competitiveness of wood-based energy (Muilu et al. 2024). In this context, the taxation of forest chip consumption, as proposed, for example, by Seppälä et al. (2025) and Lintunen et al. (2026), may be an effective measure for steering wood consumption and harvesting volumes in line with forest carbon sequestration objectives (The Finnish Climate Change Panel 2025; Seppälä et al. 2026). In other words, the potential climate benefits of such taxation would pertain to forest carbon sinks, whereas the negative economic impacts would fall on the energy sector. Nevertheless, the overall impact of these measures should be comprehensively considered.

As the results of Forsström et al. (2022) demonstrate, a forest chip tax would increase district heating prices over the next decade. However, the impacts of rapidly declining forest chip use as a result of policy measures could pose greater risk to energy security. As the results of Joronen et al. (2025) show, combustion-based energy production is required during cold weather, when electricity supply is insufficient to meet demand. For example, in January 2026, CHP electricity production was at a high level, constituting a significant proportion of the electricity generated in Finland (Fingrid Oyj 2026a; 2026b). Similarly, the utilisation rate of electric boilers was low (Fingrid Oyj 2026c).

For the longer-term future of wood energy and forest chips, the key question concerns the kinds of solutions that will be used to replace the current plants at the end of their life cycle. As the development of forest chip consumption clearly indicates, many of the currently operating plants were built in the 2010s (Official Statistics of Finland 2025c). Many of these plants will therefore reach the end of their life cycle by the end of the 2030s. Based on the results of Study **I**, over the next ten years, replacement investments will probably mainly involve solutions other than new plants that consume solid wood fuels. Only a few investments in new plants consuming solid wood fuels were identified. Other investments related to wood burning were focused on improving energy efficiency. However, if investments in BECCU or BECCS in particular are realised, the role of wood energy may change substantially as a source of biogenic carbon dioxide.

It must be noted that the survey underpinning Study **I** was conducted in the spring of 2024. Several new investment plans have since been made that may affect forest chip consumption. Therefore, the consumption of forest chips may decline more sharply than anticipated, as indicated by the recorded consumption of 9.1 million m^3 in 2025 (Official Statistics of Finland 2026d). Nevertheless, the investments in BECCU and BECCS are characterised by substantial uncertainty (Kujanpää et al. 2023). Likewise, as Fingrid (2025) identifies, electricity demand is expected to increase along with the weather-dependent electricity production, which may have implications for the functioning of electricity markets. In addition, if the current relatively high prices of wood fuels and forest chips begin to decline, which is likely if consumption declines, this could improve the cost-competitiveness of wood-based energy generation (Official Statistics of Finland 2025d). Similarly, BECCS and BECCU could enhance the profitability of wood-based bioenergy. It is therefore necessary to assess energy generation development trends as comprehensively as possible to improve preparedness for the changes they may bring. Such assessments are also necessary to enable the comprehensive monitoring of policy impacts.

Ensuring energy wood supply

As noted in Study **I,** the more fluctuating future use of forest chips will be a significant challenge for energy wood procurement and supply chains due to the reduced ability to anticipate forest chip consumption. As the results of Väätäinen et al. (2017) indicate, fluctuations in energy wood supply can be managed by terminal-based energy wood supply chains. Based on the results of Study **II**, the current terminal capacity of energy wood suppliers seems sufficient to manage a higher terminal storage utilisation rate. However, it is important to recognise that the data analysed represented only part of the energy wood suppliers operating in Finland. In addition to energy wood suppliers, some energy wood end users have their own terminal capacity. However, the results of Niskanen (2025) indicate regional variation in total terminal capacity.

Increasing use of terminals, however, leads to higher supply costs than direct supply from roadside storage to the plant (Kärhä 2011; Väätäinen et al. 2017). Moreover, the stored energy wood ties up a significant amount of capital. In addition to the variable utilisation rate of machinery and labour, this poses a challenge for the economic viability of energy wood suppliers, whose revenue is based on the supplied volumes. This problem may be addressed by implementing pricing models that would also allow suppliers to receive income from storage. Nevertheless, the supply chains' economic viability may become difficult to maintain if the baseline volume of forest chip supply and consumption falls sufficiently low as a result of the energy system's electrification or policy measures such as taxation of solid biomass fuels. Long-term supply contracts that specify a minimum delivery volume of energy wood could therefore offer an option to mitigate these impacts. Moreover, increasing the predictability of policy measures could further enhance the stability of the operational environment for energy-wood suppliers and support long-term investment decisions. These issues related to energy wood supply chains may otherwise pose risks to security of supply, particularly as long as forest chips and wood energy retain a critical role as a source of balancing power.

In addition, changes in energy wood consumption and supply chains are likely to affect the procurement areas and transport distances of energy wood. These changes should be taken into account, as they influence the use of forest resources at a time when most of the wood consumed is procured from domestic forests. As demonstrated by the results of Study **II**, most of the energy wood is sourced from areas relatively close to the plants, despite the increased price of energy wood (Official Statistics of Finland 2026). The average transport distance for energy wood is considerably shorter than the average transport distances for industrial roundwood for processing by the forest industry (Strandström 2025). Additionally, the harvesting of energy wood enhances the profitability of young-forest management (Petty and Kärhä 2011; Ministry of Agriculture and Forestry of Finland 2015a). The emergence of regions with insufficient energy wood demand as a result of declining consumption would therefore be detrimental to the profitability of young forest management.

The context-dependent definition of industrial roundwood

Among the changes in the operational environment, Study **II** indicated that a significant volume of industrial roundwood was used as forest chips for energy purposes. Based on these results, the estimated volume of burned industrial roundwood may have been around 1.9–2.6 million m^3 in 2023. Nonetheless, the analysed data covered 55% of the energy wood supply in 2023, and the proportion of industrial roundwood varied among respondents. However, these findings run counter to the general aim of preventing the burning of industrial roundwood to utilise the wood in the highest-value use possible (European Parliament and Council 2023a; Lintunen et al. 2026; Seppälä et al. 2026).

However, a decrease in forest chip consumption may not prevent the burning of industrial roundwood. Based on the results of Laitila and Väätäinen (2011) and Routa et al. (2015), delimbed energy stemwood is particularly suitable for terminal-based supply chains. Other assortments, such as logging residues and small-diameter whole trees, are typically chipped directly at roadside storage sites and transported as chips for use at plants. This is due to the high costs of transporting them unchipped and the substantial dry-matter losses during terminal storage. Moreover, it should be noted that the characteristics of different woody biomass fractions influence their suitability as fuel. Smaller boilers generally require fuels with lower moisture content, and delimbed energy stemwood typically has a higher energy content than forest chips produced from logging residues or whole trees (Alakangas et al. 2016). In particular, energy content is relevant for the use of forest chips in balancing power production, as energy demand is substantial during periods of severe cold. Against this background, further research is necessary to improve the utilisation, storability, and economic viability of terminal-based supply chains for logging residues and whole trees.

Moreover, as the simulation results of Study **III** indicate, the volume of energy wood burned depends strongly on the dimensional and quality requirements of industrial roundwood. These results are in line with Pasanen et al. (2014). For example, increasing the minimum top diameter from 5 cm to 8 cm alone reduced the harvesting volume of pulpwood by 21% in the simulation results for thinning-from-below operations in the 52 analysed young thinning stands. However, the harvesting costs of industrial roundwood are higher than those of energy wood (Figure 12) due to lower harvesting volumes and lower cutting productivity, as the results of Perho (2012) show. According to the cascade principle, wood should be allocated to its highest-value use. In light of the results of Study **III,** this evaluation should be based on techno-economic aspects rather than solely on dimensional and quality requirements. Some volume of industrial roundwood could be harvested, even from poorly managed young thinning stands with small-diameter removed stems. However, these harvesting operations would not be economical.

Wood supply from young thinning stands with neglected management

Young thinning stands with neglected forest management are generally considered a potential and sustainable source of energy wood. However, the results of Study **III** show varying harvesting conditions and cost-competitiveness of these stands. Although the average delivery sale price of energy wood in 2025, used as a reference for analysing harvesting cost-competitiveness, was relatively high, many of the estimated roadside costs for delimbed energy stemwood were close to that level. In practice, these results mean that the economic value of energy wood harvested from these stands is limited, as most of its value is absorbed by harvesting costs. Moreover, cost-competitiveness deteriorates further if the market price of energy wood decreases.

The Finnish state provides subsidies to non-industrial private forest owners for the management of young thinning stands and the collection of small-diameter wood for energy under the METKA incentive scheme (2023a). However, it was found that the importance of these subsidies for enabling first thinning in such young thinning stands with neglected management was limited. Only three of the 52 stands analysed in Study **III** met the current requirements for stand characteristics after the harvesting operation (Ministry of Agriculture and Forestry of Finland 2026). Based on these criteria, subsidies are targeted more at the management of sapling stands than of young thinning stands. Furthermore, this effect is accentuated with thinning-from-below operations. For example, if the remaining trees include old seed trees, these trees increase the average size of the remaining trees.

When interpreting the cost-competitiveness results of Study **III**, several limitations should be taken into account. In addition to energy wood prices, the applied cutting and forwarding productivity models, the assumed hourly costs of machinery, and the threshold value and costs of pre-harvest clearing exert an influence on the outcomes. In addition, Study **III** examined only the harvesting of delimbed energy stemwood and pulpwood, for which market demand is comparatively stronger. However, harvesting profitability in stands where harvesting removals consists of small-diameter stems may be improved by implementing whole-tree harvesting, as shown in a previous study by Laitila et al. (2010). In addition to preventing the burning of industrial roundwood, promoting the management of young thinning stands is another important reason for improving the competitiveness of whole-tree use for energy. Nevertheless, it should be acknowledged that whole-tree harvesting is not suitable for all forest stand types. The removal of crown biomass leads to nutrient losses in the soil, and the impact is particularly substantial when harvesting spruce and birch (Palviainen and Finér 2012).

Finally, forest owners' objectives for their forests vary considerably. The proportion of owners who prioritise considerations other than economic ones is also substantial (Karppinen et al. 2020). Nevertheless, the Finnish Forest Act 1093/1996, revised in 2014, does not include an obligation concerning the management of young forests once a new stand has been established after regeneration felling (Ministry of Agriculture and Forestry of Finland 1996). In interpreting the results of Study **III**, it is therefore important to recognise that neglected forest management may also reflect the forest owner's own choice rather than poor harvesting cost-competitiveness. From these perspectives, further research is required to understand better the phenomenon and its underlying causes, as the management of young forests is important for the sustainable economic utilisation of forest resources, and these management activities are also supported by the state.

CONCLUSIONS

This dissertation examines the role of wood energy, particularly forest chips in the electrification of the Finnish energy system. The results identify expected changes in both forest chip use and the operational environment of energy wood supply chains. Furthermore, the analysis reveals factors that hinder the targeting of energy wood procurement at young thinning stands with neglected forest management.

Forest chip consumption is expected to decrease by 2033 as alternative energy generation and technologies such as electric boilers and waste heat recovery become more widespread. However, consumption is likely to remain at a relatively high level due to declining use of fossil fuels and energy peat. In the medium term, wood fuels are increasingly utilised as a source of balancing power. This results in greater fluctuations in consumption, longer storage times for energy wood, and greater reliance on terminal storage.

In 2023, most of the energy wood was sourced within 100 km of the consuming plant, and the delivered assortments varied by supplier type. A notable share of the delivered volume consisted of industrial roundwood. In the future, industrial roundwood may still be used for energy, as extended storage times and greater reliance on terminal storage tend to favour the burning of delimbed energy stemwood instead of logging residues or whole trees. The existing terminal capacity of energy wood suppliers also enables broader use of terminal-based supply chains. Overall, suppliers' operational environment is affected by changes in forest chip use, while increasing regulatory measures add to uncertainty.

Young thinning stands with neglected management have substantial variation in cost-competitiveness as a source of energy wood. In the analysed stands, the effect of forest management subsidies proved limited, as stand characteristics exceeded eligibility thresholds. The procurement cost of delimbed energy stemwood was found to be high relative to its economic value despite relatively high energy wood prices in 2025. However, some stands were identified as suitable even for supplying pulpwood. The potential harvesting volume depended strongly on the dimensional requirements of the harvested wood assortments. In stands where the removal consists of small-diameter stems, whole-tree harvesting may improve harvesting profitability.

The results of this dissertation (Figure 14) contribute to a more comprehensive understanding of the evolving role of forest chips within the Finnish energy system, highlighting the interplay between technology, markets, and forest resources. The challenges that fluctuating forest chip consumption creates for energy wood procurement and economic viability should be recognised, particularly to ensure security of supply. In addition, proposed policy measures such as taxation of forest chip consumption may further exacerbate these challenges. To avoid the use of industrial roundwood for energy, the utilisation of lower-value assortments such as whole trees and their supply chains need to be improved. Strengthening these supply chains also enhances the potential of young thinning stands with neglected management as a source of energy wood. These insights provide a foundation for developing strategies that balance climate objectives, energy security, and sustainable forest management.

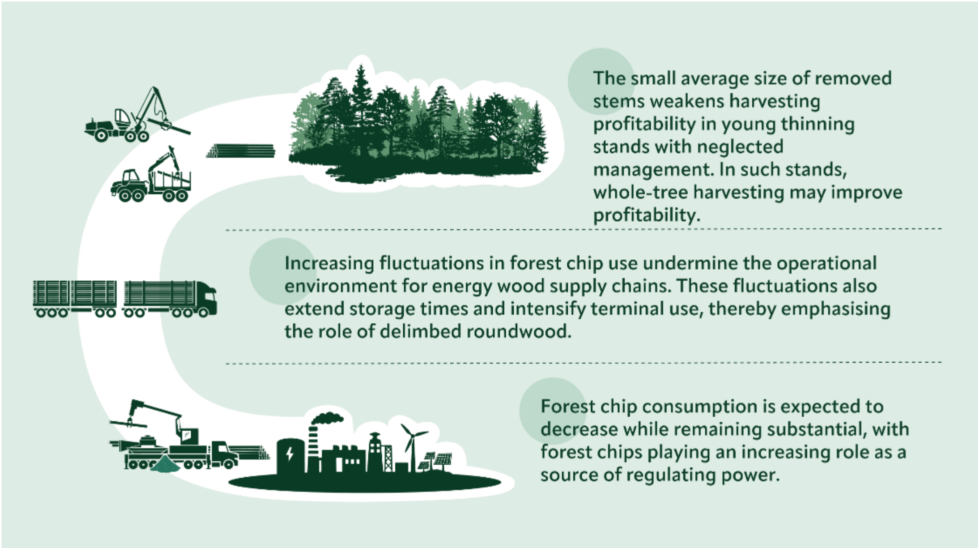

Figure 14. The results of this dissertation. The increasing role of wood as balancing power poses challenges for energy wood supply.

REFERENCES

Alakangas E, Hurskainen M, Laatikainen-Luntama J, Korhonen J (2016) Suomessa käytettävien polttoaineiden ominaisuuksia. [Characteristics of fuels used in Finland]. VTT Technology 258. https://publications.vtt.fi/pdf/technology/2016/T258.pdf. Accessed 5 March, 2026.

Alvarado Cummings S.C, Junginger M, Hanssen S.V, Van Der Hilst F, Duden A.S (2025) Comparing GHG Emissions of Residue-Based BECCS to Alternative Biomass Uses. GCB Bioenergy 17(12):e70089. https://doi.org/10.1111/gcbb.70089.

Börjesson Hagberg M, Pettersson K, Ahlgren E.O (2016) Bioenergy futures in Sweden – Modelling integration scenarios for biofuel production. Energy 109:1026–1039. https://doi.org/10.1016/j.energy.2016.04.044.

Child M, Haukkala T, Breyer C (2017) The Role of Solar Photovoltaics and Energy Storage Solutions in a 100% Renewable Energy System for Finland in 2050. Sustainability 9(8):1358. https://doi.org/10.3390/su9081358.

Council of the European Union (2025) Draft Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast) - Presidency compromise text. https://data.consilium.europa.eu/doc/document/ST-9008-2025-INIT/en/pdf. Accessed March 2, 2026.

Elberry AM, Thakur J, Veysey J (2021) Seasonal hydrogen storage for sustainable renewable energy integration in the electricity sector: A case study of Finland. J Energy Storage 44:103474. https://doi.org/10.1016/j.est.2021.103474.

European Commission (1997) Energy for the Future: Renewable Sources of Energy - White Paper for a Community strategy and action plan. Communication from the Commission. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:51997DC0599. Accessed 25 February, 2026.

European Commission (2016) CASCADES – Study on the optimised cascading use of wood. https://data.europa.eu/doi/10.2873/827106.

European Commission (2021) Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0563. Accessed 27 February, 2026.

European Commission (2024) Securing our future – Europe's 2040 climate target and path to climate neutrality by 2050: building a sustainable, just and prosperous society. Commission Staff Working Document Part 3. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024SC0063. Accessed 28 February, 2026.

European Energy Agency AG (EEX) (2026) EU ETS auction market data. https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions. Accessed 27 February, 2026.

European Parliament and Council (2001) Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market. https://eur-lex.europa.eu/eli/dir/2001/77/oj.

European Parliament and Council (2003a) Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport. http://data.europa.eu/eli/dir/2003/30/oj.

European Parliament and Council (2003b) Directive 2003/87/EC of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. http://data.europa.eu/eli/dir/2003/87/2024-03-01.

European Parliament and Council (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. http://data.europa.eu/eli/dir/2009/28/oj.

European Parliament and Council (2023a) Directive (EU) 2023/2413 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. http://data.europa.eu/eli/dir/2023/2413/oj.

European Parliament and Council (2023b) Regulation (EU) 2023/2405 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). http://data.europa.eu/eli/reg/2023/2405/oj.

Eurostat (2026) Production of electricity and derived heat by type of fuel 2024. https://doi.org/10.2908/NRG_BAL_PEH. Accessed 25 February, 2026.

Fingrid Oyj (2025) Fingridin sähköjärjestelmävisio vuodelle 2040. [Electricity system vision 2040]. https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/sahkojarjestelmavisio-2025/fingrid-sahkojarjestelmavisio-2040.-loppuraportti-10_2025.pdf. Accessed 4 March, 2026.

Fingrid Oyj (2026a) Cogeneration of district heating - real-time data. https://data.fingrid.fi/en/datasets/201. Accessed 20 February, 2026.

Fingrid Oyj (2026b) Industrial cogeneration - real-time data. https://data.fingrid.fi/en/datasets/202. Accessed 20 February, 2026.

Fingrid Oyj (2026c) Electric boiler consumption sum - real-time data. https://data.fingrid.fi/en/datasets/371. Accessed 20 February, 2026.

The Finnish Climate Change Panel (2023) Suuntaviivoja Suomen ilmastotoimien tehostamiseen. [Guidelines for Strengthening Finland's Climate Action]. Suomen ilmastopaneelin julkaisuja 1/2023. https://doi.org/10.31885/9789527457177.

The Finnish Climate Change Panel (2025). Suomen hiilineutraaliuspolku – Arvio hiilineutraaliuden saavuttamisesta ja sen keinoista. [Finland's Path to Carbon Neutrality – An Assessment of Achieving Carbon Neutrality and the Means to Reach It]. Suomen ilmastopaneelin julkaisuja 1/2025. https://doi.org/10.31885/9789527457337.

Finnish Council of State (2008) Pitkän aikavälin ilmasto- ja energiastrategia – Valtioneuvoston selonteko eduskunnalle 6. päivänä marraskuuta 2008. [A long-term climate and energy strategy – Government report to Parliament of 6 November 2008]. https://tem.fi/documents/1410877/2627938/Selonteko+2008.pdf/f9b30f57-e51f-464c-ae7f-956b070a0f88/Selonteko+2008.pdf?t=1462791421000. Accessed 2 February, 2026.

Finnish Council of State (2013) Kansallinen energia- ja ilmastostrategia -Valtioneuvoston selonteko eduskunnalle 20. päivänä maaliskuuta 2013. [The National Energy and Climate Strategy – Government Report to Parliament of 20 March 2013]. https://tem.fi/documents/1410877/2626968/Energia-_ja_ilmastostrategia_2013.pdf/ce0e9b73-f907-454b-b52b-87fa9fa481d2/Energia-_ja_ilmastostrategia_2013.pdf.pdf. Accessed 2 February, 2026.

Finnish Energy Association (2026) District heating statistics 2025 (preliminary). https://energia.fi/tilastot/kaukolampotilastot/. Accessed 25 February, 2026.

Finnish Government (2023a) Valtioneuvoston asetus metsätalouden määräaikaisesta kannustejärjestelmästä 1021/2023. [The governmental decree on a temporary incentive scheme for forestry 1021/2023]. https://www.finlex.fi/fi/lainsaadanto/saadoskokoelma/2023/1021.

Finnish Government (2023b) A strong and committed Finland - Programme of Prime Minister Petteri Orpo's Government 20 June 2023. https://julkaisut.valtioneuvosto.fi/handle/10024/165044.

Forsström J, Koreneff G, Koljonen T, Lehtilä A (2022). Taustaselvitys Suomen energiaverotuksen kehitystyölle. [Background Study for the Development of Finland's Energy Taxation]. https://vm.fi/documents/10623/101263033/Energiaveroraportti.pdf/c1de27ac-ef3e-7219-da11-f1c62ad2d2e3/Energiaveroraportti.pdf?t=1649826668135. Accessed 3 March, 2026.

Ghani HU, Lehtilä A, Forssén A, Liu X, Leinonen I (2025). Evaluating the global warming potential of harvested wood due to the carbon stock changes under different forest management practices. Sustain Prod Consump 61:15–24. https://doi.org/10.1016/j.spc.2025.10.010.

Hiltunen P, Lindroos TJ, Rämä M (2025) The impact of electric boilers and heat storages in the Nordic power markets and district heating systems. Clean Eng Technol 27:101028. https://doi.org/10.1016/j.clet.2025.101028.

Huttunen R, Kuuva P, Kinnunen M, Lemström B, Hirvonen P (2026) Kansallinen energia- ja ilmastostrategia. [National Energy and Climate Strategy]. Publications of the Ministry of Economic Affairs and Employment 2026:4. https://urn.fi/URN:ISBN:978-952-327-952-0.

International Energy Agency (2021) Net Zero by 2050 - A Roadmap for the Global Energy Sector. IEA. https://www.iea.org/reports/net-zero-by-2050. Accessed 3 March, 2026.

Jääskeläinen J, Huhta K, Lehtomaki J (2018) Ensuring Generation Adequacy in Finland with Smart Energy Policy - How to save Finnish CHP Production? 15th International Conference on the European Energy Market (EEM), Lodz, Poland, 2018, pp. 1-5. https://doi.org/10.1109/EEM.2018.8469211.

Jåstad EO, Bolkesjø TF, Trømborg E, Rørstad PK (2020) The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. Appl Energy 274:115360. https://doi.org/10.1016/j.apenergy.2020.115360.

Joronen J, Salhoja P, Vähätiitto J (2025) Report on the transition to non-combustion-based and carbon-negative district heating. Tampereen Energia. https://www.tampereenenergia.fi/julkaisut/uusi-selvitys-polttoon-perustumattomaan-ja-hiilinegatiiviseen-kaukolampoon-siirtymisesta-2025/. Accessed 27 February, 2026.

Kaila S, Poikela A, Strandström M (1999) Raivaussahatyön tuottavuus ja palkanmääritys. [Productivity and wage determination in clearing saw work]. Metsätehon raportti 78. https://www.metsateho.fi/wp-content/uploads/2015/02/metsatehon_raportti_078.pdf. Accessed 15 December, 2025.

Kärhä K (2011) Industrial supply chains and production machinery of forest chips in Finland. Biomass Bioenergy 35(8):3404–3413. https://doi.org/10.1016/j.biombioe.2010.11.016.

Kärhä K, Keskinen S, Kallio T, Liikkanen R, Lindroos J (2006) Ennakkoraivaus osana ensiharvennuspuun korjuuta. [Pre-commercial thinning as a part of first thinning timber harvesting]. Metsätehon raportti 187. https://metsateho.fi/wp-content/uploads/2015/02/metsatehon_raportti_187.pdf. Accessed 25 November, 2025.

Karppinen H, Hänninen H, Horne P (2020) Suomalainen metsänomistaja 2020. [Finnish forest owner 2020]. Luonnonvara- ja biotalouden tutkimus 30/2020. https://urn.fi/URN:ISBN:978-952-326-961-3.

Koljonen T, Soimakallio S, Silfver T, Kivinen M, Aakkula J, Aittoniemi E, Arola T, Faehnle M, Forsberg T, Forsius M, Haakana M, Hirvelä H, Honkatukia J, Ikkala L, Karhinen S, Karvonen T, Karvosenoja N, Kivimaa P, Koreneff G, Koskivaara O, Lauhkonen A, Lehtilä A, Lehtonen H, Lounasheimo J, Mikola J, Mutanen A, Myllykangas J-P, Myllyviita T, Niemistö J, Ojala A, Paunu V-V, Rehunen A, Savolahti M, Savolainen H, Similä L, Sivonen M, Sokka L, Tirroniemi J, Vainio T, Viitanen J, Vikfors S, Vuori K-M, Vähäkuopus T (2025). Kansallisen energia- ja ilmastopolitiikan uudet toimet ja skenaariot (KEITO) – keskipitkän aikavälin vaikutusarviot. [New measures and scenarios of the National Energy and Climate Policy (KEITO) – medium-term impact assessment]. VTT Technology 442. https://doi.org/10.32040/2242-122X.2025.T442.

Korhonen KT, Räty M, Haakana H, Heikkinen J, Hotanen J-P, Kuronen M, Pitkänen J (2024) Forests of Finland 2019–2023 and their development 1921–2023. Silva Fenn 58(5):24045. https://doi.org/10.14214/sf.24045.

Kujanpää L, Koponen K, Linjala O, Mäkikouri S, Arasto A (2023) Opportunities provided by technological carbon sinks and the means for their advancement in Finland. The Finnish Climate Change Panel Report 7/2023. https://doi.org/10.31885/9789527457306.

Kurki P, Mutanen A, Anttila P (2012) Energiapuumarkkinat – käytännön kokemukset ja tilastointimahdollisuudet. [Energy wood markets - practical experience and statistical possibilities]. Working Papers of the Finnish Forest Research Institute 228. http://urn.fi/URN:ISBN:978-951-40-2358-3.

Laitila J, Heikkilä J, Anttila P (2010) Harvesting alternatives, accumulation and procurement cost of small-diameter thinning wood for fuel in Central Finland. Silva Fenn 44(3):143. https://doi.org/10.14214/sf.143.

Laitila J, Väätäinen K (2011) Kokopuun ja rangan autokuljetus ja haketustuottavuus. [Truck transport and chipping productivity of whole trees and delimbed energy stemwood]. Metsätieteen aikakauskirja 2011(2):6635. https://doi.org/10.14214/ma.6635.

Lintunen J, Pihlainen S, Assmuth A, Ahtikoski A, Artell J, Haikarainen S (2026) Katsaus toimiin ja ohjauskeinoihin metsien kestävyystavoitteiden saavuttamiseksi. [A review of measures and policy instruments for achieving forest sustainability goals]. Luonnonvara- ja biotalouden tutkimus 3/2026. https://urn.fi/URN:ISBN:978-952-419-149-4.

Miettinen J, Holttinen H (2019) Impacts of wind power forecast errors on the real-time balancing need: a Nordic case study. IET Renew Power Gener 13(2):227–233. https://doi.org/10.1049/iet-rpg.2018.5234.

Mikola I (2025) Modeling the impacts of district heat electrification and CHP decommissioning in Finland. Master's thesis, Aalto University. https://urn.fi/URN:NBN:fi:aalto-202505203932.

Ministry of Agriculture and Forestry of Finland (1996) Metsälaki 1093/1996. [The Finnish Forest Law 1093/1996]. https://www.finlex.fi/fi/lainsaadanto/1996/1093. Accessed 18 November, 2025.

Ministry of Agriculture and Forestry of Finland (2015a) National Forest Strategy 2025. http://urn.fi/URN:ISBN:978-952-366-006-9.

Ministry of Agriculture and Forestry of Finland (2015b) Kestävän metsätalouden määräaikainen rahoituslaki 34/2015. [Act on Time-Limited Funding for Sustainable Forestry 34/2015]. https://www.finlex.fi/eli?uri=http://data.finlex.fi/eli/sd/2015/34/ajantasa/2023-01-19/fin. Accessed 18 November, 2025.

Ministry of Agriculture and Forestry of Finland (2026) Valtioneuvoston asetus metsätalouden määräaikaisesta tukijärjestelmästä annetun valtioneuvoston asetuksen muuttamisesta MMM/2025/155. [Government decree amending the government decree on the temporary incentive scheme for forestry MMM/2025/155]. https://valtioneuvosto.fi/paatokset/paatos?decisionId=5374. Accessed 18 November, 2025.

Muilu I, Patronen J, Armila N, Lehtoranta I, Rautalin J (2024) Biomassan verotuksen laajentamisen mahdollisuudet ja haasteet. [Opportunities and challenges of extending biomass taxation]. Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2024:7. http://urn.fi/URN:ISBN:978-952-383-184-1.

National Forest Inventories (NFI) (2024) Forest resources by region. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/forest-resources/forest-resources-by-region-6. Accessed 11 January, 2026.

Niskanen J (2025) TIESIT-energiapuuterminaaliprojekti, loppuraportti. [The Final Report of TIESIT energy wood terminal project]. Finnish Forest Centre. https://www.metsakeskus.fi/sites/default/files/document/tiesit-energiapuuterminaaliprojekti-loppuraportti.pdf. Accessed 11 January, 2026.

Official Statistics of Finland (2023) Wood in energy generation 2022. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2022. Accessed 5 February, 2026.

Official Statistics of Finland (2024) Wood in energy generation 2023. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2023. Accessed 20 January, 2026.

Official Statistics of Finland (2025a) Production of heat and power 2024. Statistics Finland. https://stat.fi/en/publication/cm1hs1qfy32tf07w5nzls9o0b. Accessed 16 February, 2026.

Official Statistics of Finland (2025b) Energy supply and consumption 2024, quarters 1-4. Statistics Finland. https://stat.fi/en/publication/cm1kp28ercqo607vwpxnyxz5d. Accessed 16 February, 2026.

Official Statistics of Finland (2025c) Wood in energy generation 2024. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2024. Accessed 25 November, 2025.

Official Statistics of Finland (2025d) Energy prices 2025, 3rd quarter. Statistics Finland. https://stat.fi/en/publication/cm3my5sz5g6u307ugj629eypt. Accessed 16 January, 2026.

Official Statistics of Finland (2026a) Commercial fellings 2025 (provisional). Natural Resources Institute Finland. https://www.luke.fi/en/statistics/commercial-fellings/commercial-fellings-2025-provisional. Accessed 27 February, 2026.

Official Statistics of Finland (2026b) Trade of energywood, 4th quarter and year 2025. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/volumes-and-prices-in-energywood-trade/trade-of-energywood-4th-quarter-and-year-2025. Accessed 27 February, 2026.

Official Statistics of Finland (2026c) Volumes and prices in roundwood trade, 12/2025. Natural Resources Institute Finland. https://www.luke.fi/en/statistics/volumes-and-prices-in-industrial-roundwood-trade/volumes-and-prices-in-roundwood-trade-122025. Accessed 27 February, 2026.

Official Statistics of Finland (2026d) Wood in energy generation 2025 (provisional). Natural Resources Institute Finland. https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2025-provisional. Accessed 26 March, 2026.

Olkkonen V, Ekström J, Hast A, Syri S (2018) Utilising demand response in the future Finnish energy system with increased shares of baseload nuclear power and variable renewable energy. Energy 164:204–217. https://doi.org/10.1016/j.energy.2018.08.210.

Palviainen M, Finér L (2012) Estimation of nutrient removals in stem-only and whole-tree harvesting of Scots pine, Norway spruce, and birch stands with generalized nutrient equations. Eur J For Res 131(4):945–964. https://doi.org/10.1007/s10342-011-0567-4.

Pasanen K, Laitila J, Pykäläinen J, Anttila P (2014) Using the ComBio decision support system to assess whether energy wood and/or pulpwood should be harvested in young forests. Int J For Eng 25(1):51–65. https://doi.org/10.1080/14942119.2014.903614.

Perho A (2012) Joukkokäsittelyn hyödyntäminen kuitupuun sekä kuitu- ja rankapuun integroidussa hakkuussa. [Utilisation of Multi-Tree Handling in Integrated Harvesting of Pulpwood and Delimbed Energy Stemwood]. Master's thesis, University of Eastern Finland. http://urn.fi/urn:nbn:fi:uef-20121119.

Pesonen J, Rantala T, Prinz R, Ovaskainen H, Kauranen P, Poikela A, Kärhä K (2025) Reducing the idle times of forest machines: A scenario analysis with machine big data in Finland. Unpublished manuscript. Accessed 25 November, 2025.

Petty A, Kärhä K (2011) Effects of subsidies on the profitability of energy wood production of wood chips from early thinnings in Finland. For Policy Econ 13(7):575–581. https://doi.org/10.1016/j.forpol.2011.07.003.

Pihlainen S, Pohjola J, Piiroinen T, Pekkonen M, Kostamo K, Kautto P (2023) Ympäristölle haitalliset tuet Suomessa [Environmentally Harmful Subsidies in Finland]. Suomen ympäristökeskuksen raportteja 30/2023. http://hdl.handle.net/10138/565350.

Renewables Finland (2026a) Wind power statistics 2025. https://suomenuusiutuvat.fi/media/tuulivoima_vuositilastot-2025-1.pdf. Accessed 17 February, 2026.

Renewables Finland (2026b) Solar power statistics 2025. https://suomenuusiutuvat.fi/media/solar-power-2025_9.1.pdf. Accessed 17 February, 2026.

Rinne S, Syri S (2015) The possibilities of combined heat and power production balancing large amounts of wind power in Finland. Energy 82:1034–1046. https://doi.org/10.1016/j.energy.2015.02.002.

Routa J, Kolström M, Ruotsalainen J, Sikanen L (2015) Precision measurement of forest harvesting residue moisture change and dry matter losses by constant weight monitoring. Int J For Eng 26(1):71–83. https://doi.org/10.1080/14942119.2015.1012900.

Salminen H, Lehtonen M, Hynynen J (2005) Reusing legacy FORTRAN in the MOTTI growth and yield simulator. Comput Electron Agric 49(1):103–113. https://doi.org/10.1016/j.compag.2005.02.005.

Seppälä J, Ahlvik L, Arasto A, Halonen J, Kivimaa P, Koponen K, Kulovesi K, Kurnitski J, Lehtonen H, Liimatainen H, Mäkipää R, Soimakallio S, Soukka R, Toppinen A (2025) Keinoja kulun kuromiseksi – Suomen ilmastopaneelin politiikkasuositukset 2025. [Closing the Gap – Policy Recommendations of the Finnish Climate Change Panel 2025]. The Finnish Climate Change Panel. https://ilmastopaneeli.fi/hae-julkaisuja/keinoja-kuilun-kuromiseksi-suomen-ilmastopaneelin-politiikkasuositukset-2025/ Accessed 25 February, 2026.

Seppälä J, Karttunen M, Ollikainen M, Salo M, Soimakallio S, Weaver S, Vesala T, Pukkala T, Kotiaho J, Aalto J, Bäck J, Kallio KP, Koivula M, Kosenius A-K, Laine I, Oksanen E, Silfverberg O (2026) Metsien hakkuiden, ilmastotavoitteiden ja luonnon monimuotoisuuden suojelun yhteensovittaminen [Reconciling forest harvesting with climate objectives and biodiversity conservation]. Suomen ilmastopaneelin raportti 1/2026. https://ilmastopaneeli.fi/hae-julkaisuja/metsien-hakkuiden-ilmastotavoitteiden-ja-luonnon-monimuotoisuuden-suojelun-yhteensovittaminen/. Accessed 25 February, 2026.

Siipilehto J, Valkonen S, Ojansuu R, Hynynen J, Miina J, Saksa T (2014) Metsikön varhaiskehityksen kuvaus MOTTI-ohjelmistossa [Description of stand early development in the MOTTI simulation software]. Working Papers of the Finnish Forest Research Institute: 286. https://urn.fi/URN:ISBN:978-951-40-2463-4.

Soimakallio S, Saikku L, Valsta L, Pingoud K (2016) Climate Change Mitigation Challenge for Wood Utilization—The Case of Finland. Environ Sci Technol 50(10):5127–5134. https://doi.org/10.1021/acs.est.6b00122.

Strandström M (2021) Metsähakkeen tuotantoketjut Suomessa vuonna 2020 [The production chains of forest chips in Finland 2020]. Metsätehon tuloskalvosarja 8/2021. https://www.metsateho.fi/wp-content/uploads/Tuloskalvosarja-2021-08-Metsahakkeen-tuotantoketjut-Suomessa-vuonna-2020.pdf. Accessed 26 November, 2025.

Strandström M (2025) Puunkorjuu ja kaukokuljetus vuonna 2024 (Timber harvesting and long-distance transportation of roundwood in 2024). Metsätehon tuloskalvosarja 9/2025. https://www.metsateho.fi/wp-content/uploads/Tuloskalvosarja-9-2025-Puunkorjuu-ja-kaukokuljetus-vuonna-2024.pdf. Accessed 26 November, 2025.

The Rural Employers' Association, Finnish Forest Administration, Forest Services Employers, Private Forestry Employers, Industrial Union (2024) Metsäalan työehtosopimus 1.2.2024–31.1.2026 [Collective Agreement for the Forestry Sector, 1 February 2024 – 31 January 2026]. https://www.teollisuusliitto.fi/wp-content/uploads/2024/04/Metsaalan-tyoehtosopimus-2024%E2%80%932026.pdf. Accessed 23 November, 2025.

United Nations (2018) Wood Energy in the ECE Region. https://unece.org/fileadmin/DAM/timber/publications/SP-42-Interactive.pdf. Accessed 19 September, 2025.

Väätäinen K, Prinz R, Malinen J, Laitila J, Sikanen L (2017) Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. Global Change Biology Bioenergy 9(11):1657–1673. https://doi.org/10.1111/gcbb.12463.

Veltheim T (1987) Pituusmallit männylle, kuuselle ja koivulle [Tree height models for pine, spruce and birch]. Master's thesis, University of Helsinki.

Viitanen J, Mutanen A, Karvinen S, Härkönen K, Kallioniemi M, Kniivilä M, Leppänen J, Niinistö T, Routa J, Uotila E, Viitala E-J (2023) Metsäsektorin suhdannekatsaus 2023-2024. [Finnish Forest Sector Economic Outlook 2023-2024]. Natural Resources Institute Finland. http://urn.fi/URN:ISBN:978-952-380-795-2.

Viitanen J, Mutanen A, Kallioniemi M, Kilpeläinen H, Kniivilä M, Leppänen J, Niinistö T, Routa J, Toikka M, Viitala E-J (2025) Metsäsektorin suhdannekatsaus 2025-2026 [Finnish Forest Sector Economic Outlook 2025-2026]. Natural Resources Institute Finland. https://urn.fi/URN:ISBN:978-952-419-099-2.

Weiss R, Saastamoinen H, Ikäheimo J, Abdurafikov R, Sihvonen T, Shemeikka J (2021) Decarbonised District Heat, Electricity and Synthetic Renewable Gas in Wind- and Solar-Based District Energy Systems. Journal of Sustainable Development of Energy, Water and Environment Systems 9(2):1–22. https://doi.org/10.13044/j.sdewes.d8.0340.

Zappa W, Junginger M, van den Broek M (2019) Is a 100% renewable European power system feasible by 2050? Applied Energy 233–234:1027–1050. https://doi.org/10.1016/j.apenergy.2018.08.109.