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Improving the energy efficiency of wood harvesting in Finland

Hanna Haavikko
School of Forest Sciences
Faculty of Science and Forestry
University of Eastern Finland

Academic dissertation

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Author: Hanna Haavikko

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Thesis Supervisors:
Professor Teijo Palander
Department of Forest Sciences, University of Eastern Finland, Finland

Professor Kalle Kärhä
Department of Forest Sciences, University of Eastern Finland, Finland

Pre-examiners:
Professor Patrik Thollander
University of Linköping, Department of Management and Engineering (IEI), Linköping, Sweden

Lauri Sikanen, D.Sc. (For.)
Natural Resources Institute Finland, Joensuu, Finland

Opponent:
Risto Lauhanen, D.Sc. (For.)
Seinäjoki University of Applied Sciences, Seinäjoki, Finland

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ABSTRACT

To address the issue of climate change, the EU's climate and energy framework has set targets to improve energy efficiency. Reducing greenhouse gas (GHG) emissions requires higher energy efficiency in the wood supply of forest industries. The aim of the study was to clarify the energy-efficiency baseline for wood-harvesting operations, define useful measures and follow up the total fuel consumption and resulting emissions.

The results indicated that wood-harvesting entrepreneurs have a positive attitude towards energy efficiency. The fuel consumption of wood-harvesting machines was the lowest for the final fellings, while in first thinnings, the consumption was highest per cubic metre harvested. The average cubic metre-based fuel consumption and GHG emissions in respect of wood harvesting were more than double in the first thinning compared to the final felling. Better allocation of harvesting machines could reduce fuel consumption and GHG emissions while improving work efficiency. Hour-based fuel consumption is most affected by machines' engine power and wood-harvesting conditions of forest stands. Fuel consumption per cut cubic metre is affected by wood-harvesting conditions and machine units.

The calculated energy efficiency was highest in final fellings. A more significant factor than fuel consumption (input) is the amount of harvested wood (output) in the energy-efficiency equation. Energy efficiency can also be improved by operator education. Trucks which are used for harvesting-machine relocation have a significant impact on wood-harvesting operations' total fuel consumption and emissions. It is therefore essential to minimise the number of relocations and operational and resource planning should be developed. In the future, the examination of fuel consumption and GHG emissions should be extended to the entire wood-harvesting chain, including long-distance transportation and timber trade, and for example the effect of operator should be investigated in more detail.

Keywords: carbon dioxide equivalent (CO_2 eq.), forest machine, fuel consumption, greenhouse gas (GHG) emissions, machine operator, machine relocation

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Mikkeli, January 2023
Hanna Haavikko

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I–III. Articles I–II are reprints of previously published articles with the kind permission of the publishers, while study III is the author's version of the submitted manuscript.

I Haavikko H, Kärhä K, Hourula M, Palander T. (2019). Attitudes of Small and Medium-Sized Enterprises towards Energy Efficiency in Wood Procurement: A Case Study of Stora Enso in Finland. *Croatian Journal of Forest Engineering*, 40 (1): 107-123. http://www.crojfe.com/site/assets/files/4288/haavikko.pdf

II Haavikko H, Kärhä K, Poikela A, Korvenranta M, Palander T. (2022) Fuel Consumption, Greenhouse Gas Emissions, and Energy Efficiency of Wood-Harvesting Operations: A Case Study of Stora Enso in Finland. *Croatian Journal of Forest Engineering*, 43 (1): 79-97. http://doi.org/10.5552/crojfe.2022.1101

III Kärhä K, Haavikko H, Kääriäinen H, Palander T, Eliasson L, Roininen K. (2022) Fossil fuel consumption and CO_2 eq. emissions of cut-to-length (CTL) industrial roundwood logging operations in Finland.

In **Study I:** Hanna Haavikko was the main author. Hanna Haavikko, Kalle Kärhä and Teijo Palander completed the study design. Hanna Haavikko, Kalle Kärhä and Miikka Hourula carried out the data collection. Hanna Haavikko, Kalle Kärhä and Miikka Hourula had the main responsibility for the data analysis and interpretation of the results. Hanna Haavikko took the main responsibility for writing the article, with the help of co-authors Kalle Kärhä and Teijo Palander. In **Study II:** Hanna Haavikko was the main author. Hanna Haavikko, Kalle Kärhä and Teijo Palander completed the study design. Hanna Haavikko, Kalle Kärhä and Mika Korvenranta carried out the data collection. Asko Poikela supported the fuel consumption of relocation-truck calculations. Hanna Haavikko, Kalle Kärhä and Teijo Palander had the main responsibility for the data analysis and interpretation of the results. Hanna Haavikko took the main responsibility for writing the article, with the help of Kalle Kärhä and Teijo Palander. In **Study III:** KK, HK, KR, TP, and HH conceptualized the study. HK, KK, and KR collected field data. KK and HK performed statistical analyses. KK and LE were responsible for the interpretation of the results and wrote the manuscript. All authors commented the manuscript.

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LIST OF ABBREVIATIONS

CH_4	methane
CO	carbon oxide
CO_2	carbon dioxide
CTL	cut-to-length
eq	equivalent
EJ	exajoule
g	gram
GHG	greenhouse gas
h	hour
HC	hydrocarbon
kg	kilogram
km	kilometre
kW	kilowatt
kWh	kilowatt hour
L	litre
LFO	light fuel oil
LIPASTO	Finland’s traffic exhaust emissions and energy consumption calculation system
m	metre
m^2	square metre
m^3	cubic metre
MJ	megajoule
ML	million litres
MWh	megawatt hour
N_2O	nitrous oxide
NO_x	nitrogen oxides
PM	particulate matter
RES	renewable energy source
SO_2	sulphur dioxide po. sulphur dioxide
t	tonne
toe	tonnes of oil equivalent
TYKO	Finland’s emission model for machinery

1 INTRODUCTION

1.1 Background of the study

Over the last decade, climate change has become an increasingly concrete threat to humanity. According to an IPCC report, global warming and especially carbon dioxide (CO_2) emissions have continued to grow strongly and were the largest in the whole reporting history between 2010 and 2019 (IPCC 2022). In 2018, the IPCC estimated that the average global temperature will rise by 1.5 degrees between 2030 and 2052 if the current rate of increase continues (IPCC 2018). However, since then, the IPCC's progress report has found that the set targets cannot be met at the current rate, with global average temperatures projected to rise by 2.7 degrees by the end of the century, leading to a dramatic change in global living conditions (United Nations Environment Programme 2021). The impact of global warming can already be seen, especially in sensitive forest ecosystems, which have changed and may disappear with the rise in temperature and the associated side effects, such as the increase in forest fires (IPCC 2018). Moreover, global warming will change sea temperatures and water levels, affecting ecosystems, food production and water balance (IPCC 2021). The consequences of global warming will become a part of the global ecosystem. To avoid an undesirable scenario, global agreements and targets have been set to reduce greenhouse gas (GHG) emissions (CO, HC, CH_4, N_2O, SO_2, PM and NO_X). These measures have had small positive effects. Although CO_2 emissions have increased over the last decade, this increase has slowed (IPCC 2022). Achieving the targets, however, will require significant reductions in global emissions in the coming years, as well as efforts by all sectors to reduce energy consumption, produce cleaner energy and reduce GHG emissions (European Union 2012).

To avoid the worst-case climate-change scenario, the first UN Framework Convention on Climate Change was adopted in 1992 (United Nations 1992). In 2015, a legally binding agreement on climate change was signed in Paris with the aim of limiting the global average temperature rise to below 2°C and limiting the increase to 1.5°C (United Nations 2015). 1.5°C limit was confirmed again in 2021 in the conference of Glasgow (EU commission 2021). The key strategies for climate change in the European Union are the Climate and Energy Package 2030 and the Long-Term Climate Strategy 2050. At the highest level, these key strategies guide EU climate actions (European Union 2014). The 2030 EU Climate and Energy Framework has three aims: 1) to cut GHG emissions by 40% from the level of 1990; 2) to increase the renewable-energy share to at least 27%; and 3) to improve energy efficiency by at least 27%. In addition, in the long-term Climate Strategy for 2050, the EU presents the more ambitious target of cutting overall GHG emissions by 80% from the 1990 level. To achieve this target, two milestones have been set. By the year 2030, the aim is to reduce GHG emissions by 40% and, by the year 2040, the aim is to reduce emissions by 60% compared with the 1990 level (EU commission 2011). To reach these targets, all sectors need to take part and conduct actions to move towards a low-carbon society (European Union 2012). In

2020, the European Green Deal was adopted, the main goal of which is to make Europe carbon-neutral by 2050. To achieve this goal, GHG emissions must be reduced by 55% from 1990 levels by 2030. The agreement not only includes measures to curb emissions, but also includes a comprehensive program of measures to make the EU economy sustainable throughout the green transition (EU commission 2019). However, in Finland, the current governing coalition has set a much stricter target for achieving carbon neutrality as early as 2035 (Finnish government 2020).

In 2020, the total consumption of raw wood over-bark was 4,460 million cubic metres (m^3) worldwide, of which 2,262 million m^3 were used by industry and 2,198 million m^3 were used as wood fuel (FAO 2021). The share of forest-industry products in the value of Finnish gross exports in 2020 was 18%, while over 78.3 million m^3 of raw wood were used (Ministry of Agriculture and Forestry 2022). The amount of domestic roundwood felled was over 69 million m^3 (Natural Resources Institute Finland 2022a). In the future, the global market for forest-industry products is expected to continue to grow and by 2035, the value of the Finnish wood-production market is expected to reach EUR 715 billion (AFRY 2021). Stora Enso is a global manufacturer of renewable packaging, bio material, wood construction solutions and paper, with approximately 23,000 employees. In 2021, a total of over 42.9 million m^3 of wood (including raw wood, wood chips and sawdust) was delivered to Stora Enso's mills globally (Stora Enso 2022). The raw-wood volumes presented in this study were unified into over-bark quantities using the Hakkila et al. (2002) coefficient of 1.14.

1.2 Energy Efficiency

The primary energy supply has risen sharply worldwide since the 1970s (254 EJ), more than doubling (606 EJ) by the year 2019 (IEA 2021a). The industry sector is the biggest energy consumer, with a share of 38%. Energy-intensive sectors, such as pulp and paper, iron, steel, cement and aluminium, have continued to grow in recent years and, as a result, energy consumption in industry has increased annually by an average of 0.9% since 2010 (IEA 2022a). In 2019, fossil fuels accounted for more than 81% of the world's energy consumption. Coal accounted for a slight decline in total electricity production over the past decade, but its share was still the largest, at 37%. The share of oil in electricity production has also continued to decline, being less than 3%. The share of renewable energy sources in total production has gradually risen to 27%, having been less than 20% in the 1990s (IEA 2021b). However, the global Covid-19 pandemic temporarily reduced total energy consumption by 4%, especially in 2020, although in 2021, its rate of growth was already 4.6% higher than before the pandemic (IEA 2021c).

The definition of energy efficiency in the literature depends on the context. However, in general, it describes the relationship between the benefits obtained and the energy used, i.e., the relationship between production (output) and input in terms of energy (Irrek and Thomas 2008; Nylund et al. 2016). The Finnish Institute for Environmental and Energy Research has defined the goal of energy efficiency as the ability to perform the same activity with less energy consumption, which means reducing the inputs from the same production (EESI 2022). Jagemar (1996) defines energy efficiency as “a measure of the balance between the energy gained and the sacrifice necessary to bring about this gain”. Moreover, the EU’s energy efficiency directive (European Union 2012) gives the following definition: “Energy efficiency means the ratio of output of performance, service, good or energy, to input of energy.”

In addition, energy efficiency can be considered in terms of end-user energy efficiency, energy conversion, macroeconomics, or intermediate economy (Irrek and Thomas 2008). From a macroeconomic perspective, energy efficiency is energy intensity or energy productivity when the energy input is linked to monthly yield parameters, such as energy consumption per unit of GDP. Energy productivity usually starts from (actual) gross domestic production per primary energy input, where primary energy includes renewables, oil, natural gas, coal and nuclear energy. Energy-intensity parameters can be measured at the aggregate level as ratios of certain physical parameters, such as wood-supply fuel consumption per 100 km driving power or cutting m^3 (Irrek and Thomas 2008). Energy consumption can be divided into direct consumption, such as fuel consumption, or indirect, such as energy consumption from the production of inputs or tools (Nyholm et al. 2005; Mikkola and Ahokas 2009; Lauhanen et al. 2015). Moreover, Nylund et al. (2016) have suggested that approaches to improvements in energy efficiency by reducing CO_2 emissions from work machinery can be divided into four interdependent options: improving energy efficiency at both the engine and vehicle level; low-carbon fuels; and increasing work efficiency.

Energy efficiency is a relative quantity that is often examined using the energy unit, e.g., kWh or MWh (Palander et al. 2020; Thollander et al. 2020). Different metrics are used for energy efficiency. The traditional energy-efficiency measures are thermal energy efficiency and the energy-consumption intensity of appliances; however, the absolute amount of energy consumption and the diffusion rate can also be used between energy-efficient appliances. The challenge when comparing energy efficiency is determining the boundary between two objects if these objects are not structurally completely identical (Tanaka 2008). Thollander et al. (2020) defined energy-payback criteria for the forestry industry: “Energy payback index represents the potential saving per year divided by the embodied energy and thus results in a relation of how long it will take for the measure to save as much energy as it has required in production.” Research into energy efficiency has also been hampered by the operationalisation of concepts, i.e., the definition of measurable physical and analytical concepts (Paaso 2004). Moreover, it would be important to determine the energy consumption and efficiency of the entire wood supply chain, as optimising one area can have a detrimental effect on other areas (Kallionpää et al. 2010). In addition, instead of examining the energy efficiency of an individual product, company or activity, it is possible to determine the energy efficiency of a product throughout its life cycle, i.e., to use life-cycle energy-efficiency indicators (Tanaka 2008). Thollander and Ottosson (2010) showed that energy-management are not fully utilised in energy-intensive sectors and long-term energy strategies have not been developed. Energy efficiency and energy management can be improved through technological solutions, such as increasing artificial intelligence and robotics in all sectors and the use of low-emission technologies (Erbach 2015). In addition, improving energy efficiency requires research, implementation planning and practical action to achieve the set climate targets nationally and globally.

In this research energy efficiency is defined as follows. Article I: “Energy efficiency can be increased if overall energy consumption is reduced. Physically and mathematically, the lower value of consumed energy content indicates better energy efficiency. Thus, in wood procurement the energy efficiency is the ratio between the consumed energy content of a conversion process from fuels and indirect energy forms (kW L^{-1}, kW g^{-1}) as the input of the system and the produced energy content of wood as the output of the system (i.e. kW m^{-3} or kW kg^{-1} of cut, hauled, transported wood, or payload of wood or delivered unit of these). Improvement in energy efficiency can be achieved by reducing consumption of energy input with a constant level of energy output but also by enhancing output with constant energy consumption of inputs. It is also possible to develop both measures simultaneously with more complex systems.”

In Finland, the domestic procurement of raw wood for the forestry industry is largely based on wood trade with private forest owners, whose share is currently around 60% (Natural Resources Institute Finland, 2019). Wood procurement for organisations is mainly carried out by small harvesting and timber-trucking companies (Soirinsuo 2012; Hourunranta et al. 2013). In general, fuel and energy efficiency in small companies are not as advanced as in larger companies (Zhang 2016), as the challenge for small companies is often the financial investment required to take action and identify areas for development. The decision-making process related to energy efficiency has been found to improve as company size increases (Trianni et al., 2016). The importance of energy efficiency has been recognised in forestry operations and is expected to add value to companies in the future, as well as improving their competitive position (Nylund et al. 2016).

Energy efficiency has been identified as one way to reduce overall energy consumption. This has been successful in developed countries. In addition, investing in energy efficiency will reduce GHG emissions and the need for energy infrastructure, as well as increasing energy security (Tanaka 2008; Erbach 2015). In 2007, the Council of Europe identified energy efficiency as a key element of the climate-change and energy strategy. The goal was to reduce energy consumption by 20% by 2020 and to save 9% for end use by 2016. The National Energy Efficiency Action Plans were intended to ensure that the target was met (European Union 2012). In order to meet the 2030 EU Climate and Energy Framework targets, in 2012, the EU adopted the Energy Efficiency Directive, which aims to guide companies and organisations to take actions to improve energy efficiency at all stages of the energy chain, from energy distribution to final consumption (European Union 2012; EU commission 2013; Motiva 2018). However, in 2018, a new energy-efficiency directive set the energy-efficiency target of reducing energy consumption by at least 32.5% by 2030 compared to 2007. The implementation of the European Green Deal has also required reviewing and updating of energy-efficiency targets. With these updated climate targets, the obligation to save energy almost doubled. EU countries must work together to ensure a further 9% reduction in energy consumption by 2030 from the 2020 benchmark (Directive 2018/2002/EU; EU commission 2019).

EU countries are required to report on the state of energy efficiency. For example, in order to achieve the set energy-efficiency targets, the Energy Efficiency law came into force in Finland in 2014, which requires large companies to promote energy efficiency and to undergo an energy audit every four years or obtain an energy-efficiency certificate, such as the ISO 50001 energy management system standard (Energy Efficiency Act 2014; ISO 2011). According to the Energy Efficiency Act, large companies are defined as any natural or legal person with at least 250 employees or an annual turnover of more than EUR 50 million and a balance-sheet total of more than EUR 43 million. The company is released from its obligation to the law if it has a certified energy-management system or environmental-management system in accordance with section 7 of the Energy Efficiency Act (1429/2014), which includes an energy audit (Energiatehokkuuslaki 3.1§, 7§ and 8§).

Stora Enso has made a determined effort to improve its energy efficiency. In 2015, Stora Enso Wood Supply Finland (WSF) was certified with the ISO 50001 Energy Efficiency Management System standard and at the same time, the company set a target to improve its energy efficiency by 4% by 2020 (Stora Enso 2015). In addition, Stora Enso had an Energy and Carbon Policy whose targets were to reduce specific electricity and heat consumption per saleable tonne of pulp, paper and board production by 15% by the end of 2020 compared to the baseline year of 2010 and to reduce fossil CO_2 emissions per saleable tonne of pulp, paper and board by 35% by the end of 2025 from a 2006 baseline (Stora Enso 2017). Moreover, in 2019, the company set new, more ambitious targets that cover the entire value chain. Their aim is to reduce absolute GHG emissions by 50% by 2030 from the 2019 level. The long-term goal for 2050 is to strive to provide customers with 100% regenerative solutions (Stora Enso 2021).

Achieving the set climate, energy and sustainable-development goals requires an improvement in energy productivity. Energy efficiency can be used to influence industrial emissions together with process optimisation and technology development. Politically, CO_2 emissions can be controlled by the global-emissions trading scheme, which has existed in the EU since 2005. The price of a tonne of carbon dioxide has long been around EUR 5; however, in recent years it has started to rise, thereby limiting energy use (Sandbag 2022). After February 2022, the European Commission announced that it would sell carbon-emission permits to finance its disengagement from Russian energy (EU commission 2022a). At that time, the price of a ton of carbon was at its highest at EUR 102; currently, it is around EUR 80 per ton (Sandbag 2022). The European Commission has set the goal of disconnecting from Russian energy by 2027 (EU commission 2022a). In order to achieve this goal, the European Commission announced a budget of EUR 210 billion to support the transition towards sustainable energy (EU commission 2022a).

In the forestry sector, energy-efficiency research has been conducted, especially in the pulp and paper industries (e.g., Farla et al. 1997; de Beer et al. 1998; Martin et al. 2000; Kilponen et al. 2001; del Río González 2005; Joelsson and Gustavsson 2008; Thollander and Ottosson 2008; Fleiter et al. 2012; Fracaro at al. 2012; Peng et al. 2015; Hämäläinen and Hilmola 2017; Koreneff at al. 2019). Wood procurement and the overall roundwood industry have been studied much less (Lindholm and Berg 2005; Klvač and Skoupy 2009; Holzleitner et al. 2011a, 2011b; Palander 2016, 2017; Lijewski et al. 2017; Palander and Kärhä 2018; Palander et al. 2018; Prinz et al. 2018, 2019). Previous research focused on productivity, cost reduction, and operational efficiency and technical improvements in cutting and forwarding machines and transportation trucks. Instead, a more comprehensive review of energy efficiency would require a life-cycle analysis (LCA) and GHG emission calculations that would include, in addition to the cut-to-length (CTL) harvesting of industrial roundwood, the movement of operators by car and the relocation of machinery between harvesting sites. Obtaining this information requires a better understanding of the actions, but also up-to-date information on fuel consumption and GHG emissions at different stages (e.g., Väkevä et al. 2004; Handler et al. 2014; Han et al. 2015; de la Fuente et al. 2017; Abbas and Handler 2018). In addition to wood harvesting and transport, the LCA review should include information on the manufacture and maintenance of factories, the manufacture and processing of products and their use and the treatment of waste (Athanassiadis 2000; Mikkola and Ahokas 2009; Lauhanen et al. 2015).

As early as 1995, Frühwald and Solberg observed that there should be a common methodology in the forest industry in order to make LCA studies comparable. In 2000, Athanassiadis (2000) studied CTL fuel consumption and emissions in the life-cycle phases of wood harvesting and forwarding machines. The study also included energy consumption related to the manufacture of machinery, the procurement of raw materials, and the manufacture, assembly and transportation of equipments (Athanassiadis 2000). Nylund et al. (2016) also identified that LCA assessment should be developed for wood harvesting so that CO_2 emissions would be comparable for propulsion. Furthermore, Venäläinen et al. (2021) highlighted the need to develop the calculation of life-cycle impacts, as the current calculations are based only on emissions from use. Social policy instruments (laws, regulations, and directives) can make companies' operations more energy-efficient; however, in addition to these, training in working methods and increasing energy efficiency through knowledge should improve the energy-efficient thinking and operation of companies and the entire value chain (Väkevä et al. 2004).

The relative share of fuel costs in the total cost of timber transport is more than twice as high as that of harvester or forwarder machines (Statistics Finland 2022). During 2022, the price of crude oil rose by a record 64% to EUR 104.4 per barrel (Oilprice.com 2022). As a result, the share of fuel costs has risen by several percent in timber-trucking, to 35.1%, and in wood-harvesting, to 14 %; however, the relative difference in activity has remained unchanged (Statistics Finland 2022). It is clear that as the price of crude oil and, thus, the fuel costs of entrepreneurs increase, the development of energy efficiency becomes increasingly likely (Rohdin and Thollander 2006; Rohdin et al. 2007; Thollander and Ottosson 2008; Thollander et al. 2013; Brunke et al. 2014; Nylund et al. 2016; Ministry of the Environment 2022a). In addition, it is important to note that in cutting and forwarding, machines are still able to use less taxable light fuel oil, which in turn reduces harvesting entrepreneurs' fuel costs compared to timber-trucking (Fuel Tax Act 1472/1994). In addition, EU-level requirements have been set for heavy-duty vehicles, which require the determination of the fuel consumption and CO_2 emissions of new commercial vehicles (EU regulations 2017/2400). As a result of these factors, truck manufacturers have adopted technology to improve fuel efficiency. So far, the costs of wood-supply companies have been closely tied to the price of crude oil and alternative forms of energy have been available for little. However, the development of alternative fuels, such as biogas and biofuels, has accelerated. An example of this is the Finnish government's goal of halving the GHG emissions from transport by 2030 compared to 2005 (Huttunen 2017). This change is further accelerated by the European Commission's decision in October 2022, according to which all new cars and vans registered in Europe must be zero-emission by 2035 (EU commission 2022b). Emissions from work machines (industrial machinery) constitute 5% of Finland's total emissions (Statistics Center 2022), 9% of which came from harvester machines and 4% from forwarding machines in 2020 (VTT Technical Research Centre of Finland 2021). In order to reduce the emissions of work machines, efforts have been made to increase fuel taxation and, thus, demand; moreover, information on the emissions of work machines has been developed by improving the quality of VTT's TYKO model of the output data for emission calculations. In order to reduce the emissions of work machines, the obligation to distribute biofuels can also be increased and the electrification of the machine fleet can be encouraged. In addition, information management can improve the knowledge base on the means of reducing emissions. In the case of work machines, replacing oil with alternative energy sources has proven to be a challenge and, currently, there are hardly any electrically powered machines available. However, it is possible to achieve emission reductions by combining different actions, such as by improving the energy efficiency of work machines and their methods of use, as well as developing operations and automation (Ministry of the Environment 2022a). In Finland, in the national energy and climate strategy for 2030, there is a 10% mixing obligation for the planned biofuels to reduce greenhouse gases for work machines. In addition, expanding regulation to energy efficiency and CO_2 emissions would promote the adoption of new technological solutions (Huttunen 2017).

1.3 Fuel consumption

Generally, energy efficiency has long been politically focused on curbing energy consumption, specifically in terms of electricity consumption rather than fuel efficiency (Zhang 2016). Although there are no large-scale studies on the energy efficiency of wood harvesting, the productivity of wood supply and fuel consumption have been studied extensively (e.g., Koskinen and Pennanen 1986; Brunberg 2000, 2005, 2007, 2012, and 2013; Brunberg et al. 2004 and 2017; Rieppo and Örn 2003; Örn 2003; Väkevä et al. 2004; Suvinen 2006; Jönsson, 2007; Tikkanen et al., 2008; Klvač and Skoupy, 2009; Holzleitner et al., 2011a and 2011b; Klvač et al. 2013; Manner et al. 2016; Nordfjell et al. 2003; Ackerman et al. 2017; Lijewski et al. 2017; Magagnotti et al. 2017; Ghaffariyan et al. 2018; Prinz et al. 2018; Jylhä et al. 2019). However, it should be noted that in Finland, no comprehensive follow-up study has been conducted on the fuel consumption of cutting and forwarding machines for almost 20 years (Rieppo and Örn 2003). Moreover, previous studies investigated how to increase the productivity of wood supply, reducing costs and improving the technical efficiency of harvesting machines and the functional efficiency of working methods (e.g., Carter and Cubbage 1995; Mäkinen 1997; LeBel and Stuart 1998; Bonhomme and LeBel 2003; Penttinen et al. 2009; Cacot et al. 2010; Drolet and LeBel 2010; Leon and Benjamin 2012; Soirinsuo 2012; Hourunranta et al. 2013; Conrad IV et al. 2017; Obi and Visser 2017).

Rieppo and Örn (2003) sought to develop methods for measuring fuel consumption in wood harvesting. They found that the average fuel consumption per hour was 12.2 L for cutting machines and 10.5 L for forwarding machines, while the average cubic-based fuel consumption values for over-bark were 0.87 L m^{-3} for cutting and 0.65 L m^{-3} for forwarding. In the same year, Nordfjell et al. (2003) found that the average fuel consumption per hour for over-bark was between 9.4–10.2 L, depending on the harvesting-machine model and timber (sawlogs or pulpwood), which is similar to Rieppo and Örn (2003)'s results. More than 15 years later, Jylhä et al. (2019) found, in a long-term follow-up study, that cutting machine average fuel consumption had increased to 0.9 L m^{-3}. Brunberg (2007, 2013) presented a similar finding in his own research comparing average fuel consumption between 2006 and 2012, when fuel consumption by cutting machines increased by an average of 9%. According to Brunberg's results, the average fuel consumption for wood-harvesting was 1.43 L m^{-3} over a year. Nevertheless, compared to the mid-1980s, fuel consumption per m^{-3} has decreased by almost one litre as harvesting-machine performance has improved (Brunberg 2013).

Brunberg et al. (2004), Brunberg (2007, 2013) and Holzleitner et al. (2011b) showed that fuel consumption when using the CTL method is affected by harvesting machine size and engine power (kW). However, several studies have found that fuel consumption is not directly proportional to engine power because many other factors, such as harvesting-machine characteristics (e.g., tracks, engine power, payload, adjustments and set-ups), harvesting-machine operators (e.g., machine operators' education and skills) and harvesting conditions (e.g., stem size, cutting method, tree species, number of timber assortments, hectare-based amount of wood-harvesting, driving distance, depth of snow cover) affect the total fuel consumption (e.g., Rieppo and Örn 2003; Klvač and Skoypy 2009; Holzleitner et al. 2011b; Brunberg 2013; Kenny et al. 2014, Ghaffariyan and Apolit 2015; Lijewski et al. 2017; Magagnotti et al. 2017; Prinz et al. 2018; Jylhä et al. 2019; Spinelli and de Arruda Moura 2019). In addition, Ghaffariyan et al. (2018) found that harvesting-machine design (i.e., the size and weight of the machine) has an effect on fuel consumption and Murtonen (2004) found that fuel quality (density differences between different fuel grades) also affects fuel consumption. Furthermore, Jylhä et al. (2019) emphasised that different sizes of harvesting machines should be used as optimally as possible in relation to the average stem size of the trees harvested. Several studies (Rieppo and Örn 2003; Jylhä et al. 2019) have found that the fuel consumption of a cutting machine is significantly affected by the cutting methods.

The average stem size of the trees in the stand increases the hour-based fuel consumption in both cutting and forwarding machines. However, as the stem size increases, the productivity of the harvesting machine increases faster than the fuel consumption, which means that the fuel consumption per cubic metre decreases as the average stem size increases (Rieppo and Örn 2003). Although hour-based fuel consumption was highest in final felling (Rieppo and Örn 2003), at the same time, the average fuel consumption per m^3 was 58%

lower in final felling compared to thinning (Jylhä et al. 2019). Nordfjell et al. (2003) also found, in their forwarding study, that productivity is strongly correlated with fuel consumption per cubic metre. As the forwarding distance increases, the productivity of the forwarding machines decreases and the fuel consumption per fixed metre increases. However, since the forwarding distance does not significantly affect the hourly fuel consumption of forwarding machines, the fuel consumption during driving is similar to the consumption of other work phases (Rieppo and Örn 2003). Instead, the harvesting conditions, the number of tree species, the cutting method, the harvesting machine characteristics and the soil, as well as the operator, also have a significant impact on the forwarders' total consumption of light fuel oil (e.g., Nordfjell et al. 2003; Rieppo and Örn 2003; Holzleitner et al. 2011b; Brunberg 2013; Kenny et al. 2014; Ghaffariyan and Apolit 2015; Oyier and Visser 2016; Pandur et al. 2019).

The relocation of harvesting machines also has a significant impact on the total wood-harvesting light-fuel-oil consumption, GHG emissions and energy-efficiency models (Palander et al. 2018). A few studies have been conducted on the relocation trucks used in cutting- and forwarding-machine relocation (Wildmark 2014; Kuitto et al. 1994; Kärhä et al. 2007; Väätäinen et al. 2006, 2008, 2019; Kauppinen 2010). There is significant variation in the average relocation distance of the harvesting machines from one harvest area to another between different studies. In studies carried out in Finland, the average transport distance between harvest areas has been measured at 30 km (Kuitto et al. 1994; Kärhä et al. 2007; Väätäinen et al. 2006, 2008, 2019; Kauppinen 2010), while in Sweden, it has been found to be less than half as long, at only 14 km (Wildmark 2014). However, there are only a few older studies on the fuel consumption of relocation trucks. In Kauppinen (2010)'s study, the average fuel consumption per harvesting machine was 50 L 100 km^{-1} for a loaded relocation truck and 29 L 100 km^{-1} when the trucks were empty.

1.4 Greenhouse-gas emissions

The largest share of GHG emissions comprises carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases. The most significant of these is CO_2, which accounts for as much as 80% of total GHG emissions (IPCC, 2014). With the help of the global warming potential (GWP) coefficient, the climatic effects of different greenhouse gas emissions can be converted into comparable carbon-dioxide equivalents. The coefficients of other greenhouse-gas emissions have been determined by comparing the radiative forcing caused by the emission of one kilogram of these emissions to the corresponding radiative forcing of the carbon dioxide on the Earth's surface. The GWP value of CO_2 is 1, that of CH_4 is 28 and that of N_2O is 265 (Statistics Finland 2019). Globally, human GHG emissions comprise over 36.3 billion tonnes of carbon-dioxide equivalent (CO_2 eq.) (IEA 2022b). In addition, 93% of these CO_2 emissions arise from the use of fossil fuels (Ge et al. 2021). The majority of global CO_2 emissions are generated by electricity and heat production (44%), followed by transport (26%) and industry (20%) (IEA 2019). Economic growth has long been based on increasing the use of fossil fuels, leading to increased GHG emissions (Caporale et al. 2021). However, in 2021, the growth of CO_2 emissions was 6% compared to the previous year (IEA 2022b). At the same time, the gross domestic product increased by 6.1% globally and, in China, increased by as much as 8.1% (World Economic and Financial Survey 2022). This relationship between the economy and GHG emissions requires complete decoupling if the all set climate targets are to be met. In addition, the circulation of all materials (biological and technical materials) should be improved to meet the 2050 targets (Ellen MacArthur Foundation 2019). To ensure this, the European Union (EU) has successfully introduced various policy instruments to encourage companies to switch to cleaner energy sources and technologies (Vaden et al. 2019). The carbon-balance method, according to which the combustion of 1 kg of diesel produces 2.77 kg of CO_2 (Eq. 1) (EPA 2016), is approved by the United States Environmental Protection Agency for determining fuel consumption and CO_2 emissions.

$$Emissions = Fuel \times CC \times 44/12 \tag{1}$$

where

Emissions = Mass of CO_2 emitted
Fuel = Volume of fuel combusted
CC = Fuel carbon content, in units of mass of carbon per volume of fuel
44/12 = ratio of molecular weights of CO_2 and carbon

This means that as fuel consumption increases, CO_2 emissions increase by a constant value. GHG emissions from work machines have been at the same level since 1980 in Finland, as measured using the TYKO model (Markkanen and Lauhkonen 2021). Work-machine emissions in Europe have been regulated by the EURO classification since 1993. Exhaust emissions from work-machine engines are regulated by the Stage rating, which is proportional to the Tier emission standards used in the United States (IARC 2014). The purpose of these classifications is to set the acceptable level of requirements of exhaust-emission regulations for work machinery (Motiva 2022). EURO VI is currently in force for the EURO class and Stage V was valid for the Stage classification in 2020 (EU regulations 2019/1242; EU regulations 2021/1068). According to a study based on the TYKO model and conducted by the VTT in 2020, the GHG emissions of work machines (including cutting and forwarding machines) in Finland were 2.4 Mt CO_2 eq. Of this total, harvesting machines accounted for about 13% (319,958 t CO_2 eq 2020) and 121.3 million litres (ML) of light fuel oil were generated. This TYKO model did not take into account the stages related to wood-harvesting, such as relocation machines or trips by machine operators to harvest areas or related to maintenance (Technical Research Centre of Finland 2021). According to a study conducted by Venäläinen et al. (2019), emissions from wood harvesting were 292,000 t CO_2 eq. In addition to the TYKO model, Venäläinen et al. (2019) used the LIPASTO model. In Finland, the construction-equipment industry has also agreed on a voluntary Green Deal agreement (2019), the aim of which is to reduce carbon-dioxide emissions from the entire industry (Green Deal 2019).

GHG emissions from wood harvesting have previously been investigated by Athanassiadis (2000), Berg and Karjalainen (2003), Klvač and Skoupy (2009), Lijewski et al. (2017), Ackerman et al. (2017) and Venäläinen et al. (2019), among others. Since the 1990s, CO_2 emissions from wood harvesting have decreased by about 90% (Berg and Karjalainen, 2003). The most significant reasons for this are considered to be the development of motor technology and technology in relation to equipment, as well the renewal of working methods (Berg and Karjalainen 2003). The results of previous studies on CO_2 emissions from wood harvesting have some variation. In Lijewski et al. (2013), cutting machine CO_2 emissions for over-bark were 1.59 kg m^{-3}. Furthermore, Ackerman et al. (2017) found that CO_2 emissions from cutting machines for over-bark were 1.50 kg m^{-3}, and for forwarding machines emissions were 0.89 kg m^{-3}. However, in Venäläinen et al. (2019)'s study, the CO_2 emissions from harvesting (cutting and forwarding machines) were 4.58 kg m^{-3} for over-bark and these were parallel with Klvač and Skoupy (2009)'s results for over-bark of 2.61 kg m^{-3} for cutting machines and 3.54 kg m^{-3} for forwarding machines. The amount of emissions was significantly affected by the wood-harvesting method and the relationship between the average tree volume and the amount of harvesting (Lijewski et al., 2013). Productivity is higher in the final felling, resulting in lower emissions per cubic metre (Eriksson and Lindroos 2014). According to a study by Karjalainen and Asikainen (1996), CO_2 emissions from thinning in harvesting were 3.90 kg m^{-3} for over-bark, while they were 1.86 kg m^{-3} from final felling. Correspondingly, for forwarding-machine emissions, the differences were not as significant for thinnings of over-bark at 1.92 kg m^{-3} and for final felling at 1.42 kg m^{-3}. In addition, Berg and Karjalainen (2003) studied the GHG emissions from wood harvesting and included machine transportation in Sweden and Finland. The data collected from Sweden included all transport, but the Finnish data included only the emissions from the transfer of harvesting machines and not empty drive. The total CO_2 emissions from harvesting (including machinery transportation) over-bark were 3.23 kg m^{-3} in Finland and 5.61 kg m^{-3} in Sweden (Berg and Karjalainen 2003).

Venäläinen et al. (2021) found that the share of emissions in wood harvesting can be reduced by using, for example, biofuels or renewable fuels and digitalisation, increasing other modes of transport and developing infrastructure. According to a study by Nylund et al. (2016), significant CO_2 reductions can be achieved by developing the use of work machines, switching to biofuels, developing machine technology and improving the energy efficiency of the engine. However, currently, cutting machines and forwarding machines are powered by internal combustion engines (Markkanen and Laukonen 2021). In addition, it is noteworthy that alternative fuels do not directly reduce fuel consumption, which depends on the work machine and its use (Nylund et al. 2016). In addition, technology based on alternative engine technology is scarce, with only one machine manufacturer currently producing hybrid cutting machines (Markkanen and Laukonen 2021). It has been estimated that the power lines of harvesting machines electrify more slowly than those of other machines because the construction of charging infrastructure takes place in remote forest conditions and obtaining enough power for the relevant tasks is challenging (Moreda et al. 2016; Lajunen et al. 2018). With regard to harvesting machines, automation can be used to promote the electrification of machines in work that is repetitive and predictable (Lajunen et al. 2018).

1.5 Aims of the study

Significant energy-efficiency research has been conducted in the forestry industry. However, it has been studied much less in respect of the wood supply to the industry. The main aim of this thesis was to study the energy efficiency of the wood-harvesting operations, fuel consumption and GHG emissions of the CTL harvesting machinery in Finland. Indirect energy contributions, e.g., manual wood-harvesting and traveling by forestry experts, were excluded from the analysis. In the sub-publications of the thesis, the concept of energy efficiency was clarified in respect of wood supply, along with the indicators that can be used for analysing and reporting it. The baseline energy efficiency was determined by calculating the fuel consumption and emissions of harvesting machines and relocation trucks. In order to improve the energy efficiency of wood harvesting, the factors that have the greatest impact on the fuel consumption of cutting and forwarding machines were identified. More specifically, the aims of the Articles I–III were as follows:

(i) To clarify wood-harvesting entrepreneurs' attitudes towards energy efficiency and describe the future needs, measures and prospects of entrepreneurs relating to energy efficiency and its improvements (Article I).

(ii) To determine wood-harvesting operations' energy efficiency in relation to harvesting methods and machines' engine power, as well as to calculate the fuel consumption and GHG emissions caused by cutting, forwarding and the relocation of harvesting machines (Article II).

(iii) To describe and model the fuel consumption of CTL harvesting machines in cutting and forwarding as well as calculating the total annual fuel consumption and CO_2 eq. emissions. This was undertaken for the cutting and forwarding machines and trucks needed for relocations of harvesting machinery and travel by car by operators, harvesting managers and service and maintenance staff to the harvesting site. Finally, the significant factors that affect fuel consumption were suggested (Article III).

Table 1. Description of the articles.

	Article I	Article II	Article III
Name of the article	Attitudes of Small and Medium-Sized Enterprises towards Energy Efficiency in Wood Procurement: A Case Study of Stora Enso in Finland.	Fuel Consumption, Greenhouse Gas Emissions, and Energy Efficiency of Wood-Harvesting Operations: A Case Study of Stora Enso in Finland.	Fossil fuel consumption and CO_2 eq. emissions of cut-to-length (CTL) industrial roundwood logging operations in Finland.
Study question	What are entrepreneurs' attitudes towards energy efficiency and what is the baseline of energy efficiency?	What are the calculated fuel consumption, greenhouse gas emissions and energy efficiency of wood-harvesting methods for cutting, forwarding and machine relocations?	What is the actual fuel consumption of cutting and forwarding machines and which factors have the most significant influence on it?
Material	Interviews with entrepreneurs from Stora Enso Wood Supply Finland.	Stora Enso WSF's enterprise-resource-planning system (machine data). Annual amounts of wood-harvesting and harvesting-site information. Machine-technique information from Koneyrittäjät annual catalogue.	Stora Enso WSF's harvesting machines' fuel consumption follow-up with Piusi K-24 digital flow meter. Harvesting-site information produced by machine operators. Machine-technique information.
Method	Quantitative research. Interview. Case study.	Quantitative research. Case study. Interview.	Quantitative research. Follow-up study. Case study.

2 MATERIALS AND METHODS

2.1 Research layout

The thesis aims to clarify the energy efficiency and measurements and improve the overall energy efficiency of wood-harvesting operations. The thesis examines the energy efficiency of roundwood harvesting implemented using the CTL method. The reference framework of the study consisted of the different stages of wood harvesting and their energy-efficiency indicators (see Figure 1). The system included different stages, which made it possible to examine the energy efficiency of many different operations in the wood harvesting process. In this respect, the following delimitations were made for the study. The study examined the purchase of roundwood and did not include forest energy (i.e., forest chips, stumps and logging residues). In Article I, both harvesting operators and timber-trucking operators were contacted; otherwise, the survey did not examine long-distance transport from the forest to the mill. In Article II, relocations of cutting and forwarding machines were included and, in Article III, car trips by operators, harvesting managers and service and maintenance staff to the harvesting sites were added.

The survey of the entrepreneurs examined the energy efficiency of the machines through information, training, investment in machinery and components, company productivity, metrics, operating factors and visions for the future (Article I). The starting point for examining the energy efficiency of the harvesting machines was to model productivity on the basis of the fuel consumption of the machines and the technical data of the equipment used, particularly the engine power (kW) of the machines. In addition, GHG emissions were calculated based on fuel consumption (Articles II and III).

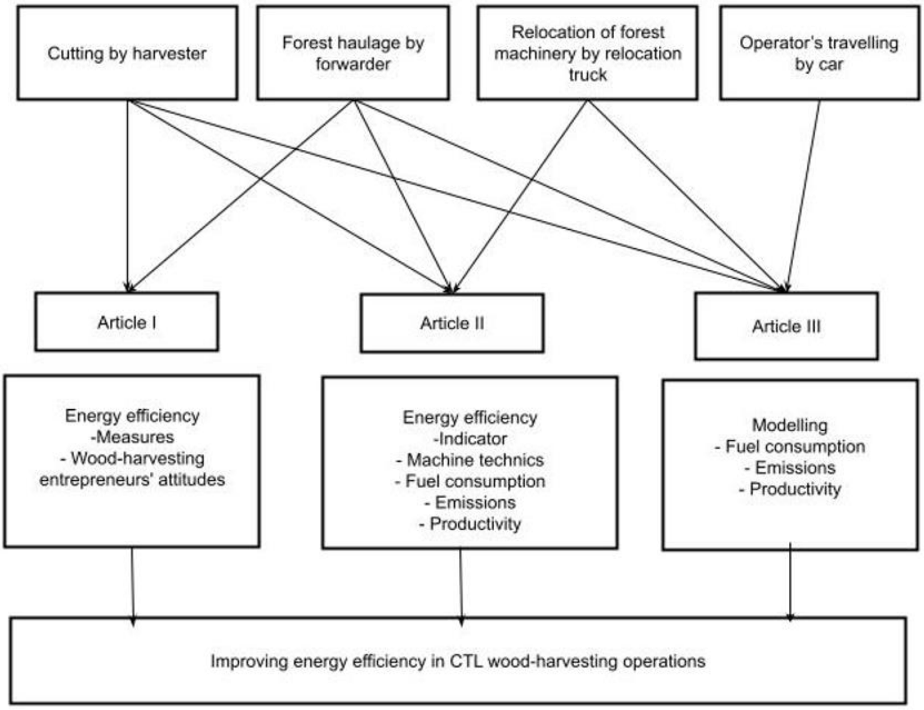

Figure 1. Schematic outline of the thesis and concepts for considering energy efficiency, fuel consumption and GHG emissions of wood-harvesting operations.

2.2 Study data

The study data in Article I were collected through a semi-structured interview and research material was added to determine the productivity modelling of a harvesting machine. The fuel consumption and energy efficiency of wood harvesting were calculated in Article II. In addition, follow-up research and additional machine-user data were used to determine the long-term fuel consumption and CO_2 eq. emissions in Article III. The harvesting-machine data were collected from the enterprise resource planning (ERP) system of Stora Enso WSF and they were verified by the contractors in the survey and enriched with accurate machine information and carrying capacity. The harvesting-machine relocations from one harvesting site to another were detected through the ERP system. The harvesting-machine information was mainly derived from the Koneyrittäjät Machine Catalogues, published annually by the Trade Association of Finnish Forestry and Earth Moving Contractors (1996–2016); some detailed machine information was also found and checked from the Internet pages and machine booklets of the harvesting-machine manufacturers. The harvesting machines were classified into 7 different categories (<100, 100–119, 120–139, 140–159, 160–179, 180–199 and >199 kW), according to engine power.

2.3 Article I

In Article I, 25 harvesting entrepreneurs from Stora Enso WSF were interviewed at the end of the year 2017. The average total annual wood-harvesting volume of the enterprises was 297,840 m^3. The estimated average sizes of the thinning stands were 445 m^3 and 293 m^3 in the clear-cutting stand (in 2016 and 2017). Moreover, the entrepreneurs estimated the average distance of the machine relocation from one harvesting site to another to be 27.2 km.

2.4 Article II

In the case study in Article II, the total harvested volume was 8.9 million m^3 and 48 million stems were cut (Table 2). The study examined the relationship between the energy input and the harvesting machines' engine power by modelling the productivity of the harvest chain. In addition, the use of harvesting machines in terms of harvesting method and amount of harvesting of stems was examined. The productivity modelling was based on the functions described by Eriksson and Lindroos (2014), with the average stem size of the amount of harvesting as an independent variable (Article II). The conversion from the under-bark volume by Eriksson and Lindroos (2014) to the over-bark volume was achieved using a coefficient of 1.14 (cf. Hakkila et al. 2002). Furthermore, the effective-hour (E0) cutting productivity determined by Eriksson and Lindroos (2014) was converted to operating-hour (E15) productivity in both the thinnings and the final fellings using a coefficient of 0.88 (cf. Rajamäki et al., 1996).

Table 2. Description of total data and the average harvesting conditions at harvesting sites by harvesting method (m^3=cubic metre, m=metre).

	First thinning	Later thinning	Final felling	Total	Average
Number of harvesting sites	–*	–*	–*	18,114	
Roundwood amount of harvesting, m^3 (%)	723,900 (8.1)	3,250,000 (36.5)	4,942,100 (55.4)	8,916,000	
Amount of harvesting/harvesting site, m^3	–*	–*	–*		492
Number of stems amount of harvesting (%)	9,001,800 (18.5)	23,438,800 (48.2)	16,219,400 (33.3)	48,660,000	
Stem size of amount of harvesting, m^3	0.080	0.139	0.305		0.183
Forwarding distance, m	323	318	286		301

* The number of harvesting sites of first thinnings, later thinnings and final fellings could not be determined because more than one cutting method was used at some harvesting sites.

The modelling of the forest forwarding productivity with forwarding machines in both thinnings and final fellings was also conducted by applying the functions used by Eriksson and Lindroos (2014). The actual load size in the forest forwarding was determined using a green density of 845 kg m^{-3} of fresh timber cut (cf. Marjomaa 1992; Kainulainen and Lindblad 2005; Lindblad and Repola 2019). The effective-hour (E_0) productivity determined by Eriksson and Lindroos (2014) was converted to operating-hour (E_{15}) productivity in the thinnings and final fellings using a coefficient of 0.93 (cf. Väkevä et al. 2001).

The hour-based fuel consumption (litres per E_{15}-hour; L E_{15}^{-1}) of the cutting and forwarding was calculated by applying the functions of Brunberg (2013) with the engine power (E) of the harvesting machine as the independent variable. Furthermore, cubic-based fuel consumption (litres per m^3 harvested; L m^{-3}) for the cutting and forest forwarding was calculated by dividing hour-based fuel consumption by productivity. Total fuel consumption per harvesting site (L/harvesting site) was determined by summing up the cubic-based fuel consumption in the cutting and forest forwarding and multiplying it by the total amount of harvesting at the harvesting site.

2.5 Article III

The fuel consumption of wood-harvesting operations was examined with a long-term follow-up study that ran from March 2018 to April 2019 under different harvesting conditions. The study data were collected from the harvesting sites of Stora Enso WSF. The fuel-consumption data were collected from a total of 510 harvesting sites in cutting and 306 harvesting sites in forest forwarding. A digital Italian Piusi K24 flow meter (Piusi, 2022) was installed to refuel the fuel tank of each follow-up harvesting machine to indicate the amount of refuelling at each harvesting site. The manufacturer of the Piusi K24 flow meter guarantees a metering accuracy of ±1% (Piusi, 2022). The total refuelled fuel in the study was 306,791 L of LFO in cutting and 136,979 L in forwarding. A total of 308,113 m^3 of wood was cut from the harvesting sites and 201,174 m^3 was forwarded from the forests to roadside landings (Table 3). The production time (i.e., total time on harvesting sites, excluding longer delays due to repairs in workshops and machine relocations) using cutting machines totalled 20,148 hours and 12,202 hours when using forwarding machines.

Table 3. Data in respect of wood-harvesting operations (cutting and forwarding) by harvesting method (h=hour, L=litres, m^3=cubic metre).

Harvesting method	Number of harvesting sites	Production time (h)	Refuelled fuel (L)	Industrial roundwood amount of harvesting (m^3)
Cutting				
First thinning	29	1,470	21,187	10,000
Later thinning	170	6,646	95,164	68,397
Final felling	216	8,331	132,930	173,527
Other fellings	54	965	14,975	13,771
Several cutting methods	41	2,736	42,536	42,417
Sum	510	20,148	306,791	308,113
Forwarding				
First thinning	7	309	3,235	3,459
Later thinning	86	3,583	39,188	46,523
Final felling	120	4,636	7,000	89,554
Other fellings	30	614	52,578	9,788
Several cutting methods	63	3,060	34,975	51,850
Sum	306	12,202	136,976	201,174

Moreover, every machine participating in the study had follow-up forms in which information was recorded for each working shift. In addition to the basic machine data (manufacturer, model, year model of the machine and operating hours), basic operator data (i.e., fuel economy training background), basic data of harvest area (start and end time, batch number, wheel equipment, quantity and quality of fuel) and environment information (temperature, amount of snow) were collected from each working shift. The working time was the production time which, in addition to the efficient working time, included all interruptions at the site. For the analyses, the data were converted to stand-specific data and the corrected cubic volumes, forest transport distances, areas and stem volumes were combined with the accurate data of the ERP system of Stora Enso WSF. The hour-based fuel consumption (L/h) was calculated by dividing the total fuel refuelled by the total production hours on the harvesting site. The cubic-based fuel consumption (L m^{-3}) was defined by dividing the total fuel refuelled by the total wood amounts cut or forwarded on the harvesting site.

Cutting machines were divided into two groups based on cubic-based fuel consumption. The average stem size was 0.1–0.6 m^3. In the first group were four harvesters that consumed the most fuel (fuel-prodigal) and in the other group were four harvesters that consumed the least fuel (fuel-saver). Accordingly, forwarding machines were divided by forwarding distance of 100–500 m based on fuel consumption per cubic metre, as follows: the three forwarders which consumed the most fuel (fuel-prodigal) and the three forwarders which consumed the least fuel (fuel-saver).

The total annual fuel consumption for wood procurement of the forestry industry in Finland takes into account wood harvesting (cutting and forwarding), the relocations of harvesting machines and car travel of machine operators and harvesting managers from their homes to harvesting sites and back, as well as car travel by service and maintenance staff. The following calculation assumptions were applied: the annual wood procurement amount was 58.668 Mm^3 (Sauvula-Seppälä and Torvelainen 2021) and the distributions of different harvesting methods were as follows: first thinnings 6.952 Mm^3, later thinnings 19.899 Mm^3, final fellings 30.076 Mm^3 and other fellings 1.741 Mm^3 (cf. Peltola and Vaahtera 2021; Sauvula-Seppälä and Torvelainen 2021). Furthermore, it was assumed that one harvesting chain harvested 35,000 m^3 per year and total driving kilometres per harvesting chain were 64,500 km (cf. Statistics Finland 2022). Hence, the car travel totalled 109 Mkm (1.843 km m^{-3}). Moreover, it was assumed that the fuel consumption of the cars driven by operators, managers and service and maintenance staff averaged 8.59 L 100 km^{-1} (cf. VTT's Lipasto 2021) and that the average driving distance was 45 km. In addition, fuel consumption of harvesting-machine relocations was 0.130 L m^{-3}.

2.6 Statistical analysis

In order to determine the initial level of energy efficiency, quantitative research methods were used to determine entrepreneurs' energy-efficiency knowledge and attitudes to wood harvesting (Article I). Only the open-ended questions were examined using a content analysis method by grouping the responses into small categories and calculating the frequency (Article I). The variables relating to entrepreneurs' attitudes, harvesting machinery, machine operators and harvesting conditions, as well as fuel consumption, were analysed using percentage shares, mean values (average and mode) and standard deviations (Articles I, II and III). Statistical testing was mainly divided into correlation and variance analyses (Metsämuuronen 2002).

The Mann–Whitney U-test and the Kruskal–Wallis one-way ANOVA test (χ^2) were used for statistical analysis and applied to compare different groups in Articles II and III because normal distribution testing using the Kolmogorov–Smirnov test indicated that the study data did not correspond to a normal distribution (Nummenmaa 2004). In Article III, the Kruskal–Wallis test was used to assess whether two independent samples arose from the same population (Heikkilä 2010). The former test revealed whether the groups tested were significantly different, after which we identified specific significant differences using the Mann–Whitney U-test in paired comparisons of the group. In addition, the reliability of the results was presented using the actual p-values of the tests and significance levels (Metsämuuronen 2002).

In Article III, a regression analysis was used for harvester and forwarder fuel-consumption modelling, where harvesting machine, machine operator and harvesting site were independent variables. In addition, the suitability of the models to the data was verified based on the numerically corrected degree of explanation (adjusted R^2) and statistical significance ($p<0.05$). The stepwise method was used for the selection of variables for multivariate linear-regression analysis. In addition, fuel consumption per cubic metre was modelled using a nonlinear model (Metsämuuronen 2002). The statistical analyses were conducted using IBM SPSS Statistics 24 software.

2.7 Energy-efficiency indicator (Article II)

Indicators are calculated measures of performance consisting of a set of different metrics. Here, they are defined for forestry and the forestry industry. Energy efficiency is a strategic key performance indicator for carbon-neutral wood procurement in the forestry industry. To determine the energy efficiency of wood harvesting, Palander et al. (2020)'s model (Eq. 2), which is based on the efficiency ratio of renewable wood energy and consumed fossil energy, was used.

$$\mathrm{Eeff} = \frac{\mathrm{Eren}}{\mathrm{Efos}} \tag{2}$$

where

E_{eff} = Energy efficiency of wood harvesting
E_{ren} = Amount of renewable wood energy provided (kWh)
E_{fos} = Amount of fossil energy consumed (kWh)

It is fundamental to this model that all industrial wood material can be converted and calculated as energy. The amount of renewable wood energy supplied was calculated using the following assumptions and equations. The volume of wood harvested (m^3) was converted to kilograms using the green density of 845 kg m^{-3} of fresh wood (cf. Marjomaa 1992; Kainulainen and Lindblad 2005; Lindblad and Repola 2019). The calorific value of fresh wood was determined using Alakangas et al. (2016)'s equation. The moisture content of the wood was 55% and the calorific value of the dry wood was 19.167 MJ kg^{-1} (cf. Palander et al. 2020). When calculating the amount of fossil energy consumed, the volume of fuel was converted to kilograms using sulphur-containing light fuel oil with a diesel density of 830 kg m^{-3} (cf. Neste 2021a, 2021b). The energy content of the fuel was calculated by converting the calorific value of light fuel oils by 43 MJ kg^{-1} (Seppänen et al. 2012). The amount of energy consumed, expressed in kWh, was determined by dividing MJ by 3.6.

2.8 GHG-emission metrics (Articles II and III)

The GHG emissions were calculated in case studies (Articles II and III). The GHG emissions of harvesters, forwarders, harvesting-machine-relocation trucks and the cars driven by operators, managers and service and maintenance staff were calculated by applying the VTT's Lipasto database (2017) of the average emissions of work machinery in 2016 in Finland (Article II). In Article III, the GHG emissions of harvesters and forwarders and cars driven by operators, managers and service and maintenance staff were calculated using updated VTT Lipasto values (2021). The Lipasto model was utilised because the TYKO model has become obsolete in relation to current needs and has not been renewed during its more than 20 years of existence (Markkanen and Lauhkonen 2021). The cubic-based GHG emissions by emission category (CO_2, CO, HC, CH4, N_2O, NO_X, SO_2) and harvesting site for the study were calculated by dividing total GHG emissions in each emission category by the total amount of harvesting at the harvesting site. In addition, particulate matter (PM), which comprises different solid particles and liquid droplets in the air, was taken into account in the study (EPA 2022). The GHG emissions were also calculated for cutting and forwarding machines and harvesting-machine-relocation trucks. These GHG emissions were determined separately for the empty and loaded relocation trucks.

In Article III, CO_2-emission metrics of the harvesting-machine fleet were 2.67 kg CO_2 eq. L^{-1} for harvesters and forwarders and 325 g CO_2 eq. m^{-3} for the relocations between harvesting sites. Furthermore, the GHG emissions of cars used were calculated by applying the emission metric of 0.20 kg CO_2 eq. km^{-1} (VTT, 2021). Thus, the calculated fuel consumption of the car travel by operators, managers and service and maintenance staff was 0.158 L m^{-3} and the GHG emissions of these journeys were 372 g CO_2 eq. m^{-3} for harvested wood.

2.9 Relocation distance (Articles II and III)

In Article II, the distances between harvesting-machine relocations were calculated by assuming that machine relocation was executed using the shortest route from the coordinates of harvesting-site A to the coordinates of harvesting-site B, travelling along the common road network. A national Digiroad (2020) network database was used for calculations. The distance between harvesting sites A and B was calculated using Esri network-analysis tools, applying Dijkstra's shortest path first (SPF) algorithm (Dijkstra, 1959) for shortest-path calculations on the Digiroad network dataset.

In Article II, the final relocation-distance data consisted of 17,368 relocations. The relocation distance (with loaded relocation truck) was, on average, 26.3 km. In the study, it was assumed that each harvesting-machine relocation was a separate operation; in other words, first, a harvester of the harvesting chain was relocated, after which a relocation truck relocated another machine and, finally, a relocation truck relocated a forwarder of the harvesting chain in question. Thus, the measured relocation distance between harvesting sites A and B was the relocation distance of driving a loaded truck. According to the harvesting-machine entrepreneurs' interviews and previous reports (e.g., Kuitto et al. 1994; Väätäinen et al. 2006, 2008; Kauppinen 2010), machine-relocation distances with an empty truck are clearly longer than those with a loaded truck. Hence, it was assumed that each driving distance with an empty relocation truck would be 30 km longer than driving distances with loaded trucks. The total relocation distance of the harvesting site was the sum of the driving distances of the empty and loaded trucks.

3 RESULTS

3.1 Harvesting entrepreneurs' attitudes towards energy efficiency

3.1.1 Energy-efficiency education

About 80% of the harvesting entrepreneurs had participated in formal energy-efficiency education, which most commonly involved user training by harvesting-machine manufacturers for the productive and energy-efficient usage of harvesting-machinery equipment and the use of appropriate settings on machines. However, only 12% of the entrepreneurs had organised internal guidance related to energy efficiency for their operators during the years 2016 and 2017.

Most of the entrepreneurs (84%) underlined that there was a need for energy-efficiency guidance, practical training and theoretical education in their enterprise. For the harvesting entrepreneurs, the need was mainly for energy-efficient working methods in cutting and forwarding (28%) and for setting more optimal adjustments to machinery and its components (28%).

3.1.2 Importance of machines in energy efficiency

In the purchase of a new harvesting machine, the most important criterion for entrepreneurs was reliability. The coverage of the service network was also important for the harvesting entrepreneurs. In addition, the suitability of the machine for different cutting methods, ergonomic properties and the prices of spare parts were important. The exhaust emissions (e.g., CO, HC, NO_X, SO_2, PM) were the least significant factor for the harvesting entrepreneurs.

3.1.3 Factors affecting energy efficiency in wood harvesting

For the harvesting entrepreneurs, the factors affecting the energy efficiency of their harvesting businesses were the professional skills of the machine operators. Moreover, the attitudes and motivation of the machine operators was significantly important for the harvesting entrepreneurs. Furthermore, the stand size of the harvesting site, the sufficient size of available standing stock, hindering undergrowth in the stand, the forwarding distance from the stump to the roadside landing area, the number of timber assortments harvested, the technical condition of machinery and its components, the bearing capacity of the terrain, and machine relocations between harvesting sites were also important.

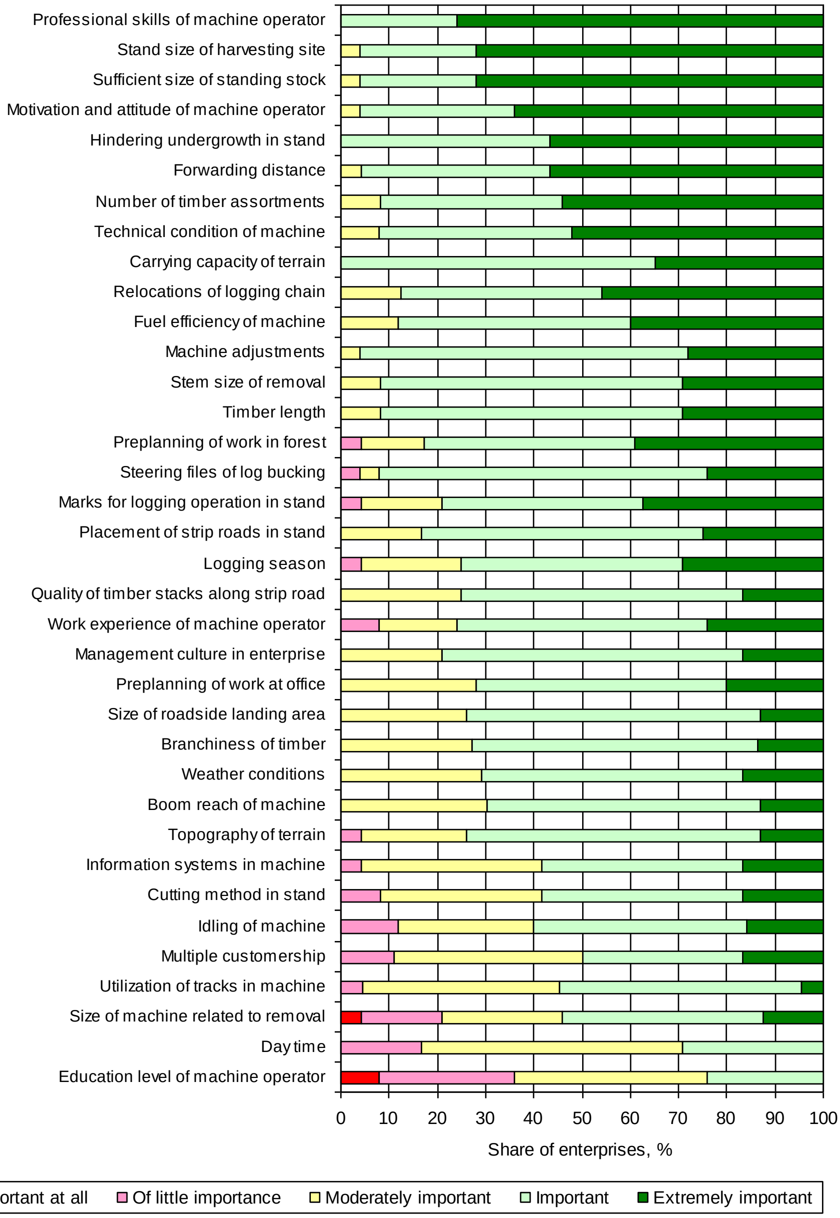

Figure 2. Factors affecting the energy efficiency of harvesting businesses during 2016 and 2017, according to the respondents.

According to the entrepreneurs, increasing cooperation, multiple customers or new clients and planning are key factors in improving energy efficiency. The entrepreneurs estimated that the importance of energy efficiency will increase in the future and increase the profitability of their business operations. In addition, almost all the entrepreneurs were willing to develop the energy efficiency of their business with their customers (Stora Enso WSF).

3.2 Energy efficiency of wood harvesting in Stora Enso

3.2.1 The utilisation of harvesting machines vs. harvesting methods

According to the results, the harvesting machines were not directed at different harvesting methods and harvesting sites based on the machine's engine power. More than a third (31.6%) of the first thinnings were cut with the largest cutting machines (engine power of >199 kW) and small and medium cutting machines (engine power >159 kW) cut almost half (49.4%) of the final fellings. Forest forwarding was most commonly conducted (48.9%) with medium forwarding machines (engine power of 140–159 kW), which accounted for the largest share of the machinery (43.8%).

3.2.2. Fuel consumption, production output and GHG emissions

The calculated total fuel consumption of the machinery was 14.2 million litres (ML) in wood harvesting and the average fuel consumption per cubic metre was 1.6 L m^{-3}. In the later thinnings, harvesting machines consumed the largest share (45.1%) of the total fuel consumption, which accounted for 36.5% of the amount of harvested wood. In total, 55.4% of the total wood amount was harvested from the final fellings, which accounted for 40.9% of the total fuel consumption of the harvesting machines. In the final fellings the productivity was the highest, with the lowest average cubic-based fuel consumption (1.2 L m^{-3}). The average fuel consumption was highest in first thinnings (2.8 L m^{-3}). Moreover, cutting machines consumed more fuel in all the harvesting methods compared to forwarding machines.

Table 4. Total and average fuel consumption of cutting and forwarding machines for comparison of the harvesting methods (L=litres, L m^{-3}=litres per cubic metre).

	First thinning	Later thinning	Final felling	Total harvesting
Total fuel consumption, L				
Cutting	1,289,462	3,838,016	2,978,679	8,106,157
Forwarding	697,690	2,573,322	2,825,113	6,096,126
Total harvesting	1,987,152	6,411,339	5,803,792	14,202,283
Average fuel consumption, L m^{-3}				
Cutting	1.78	1.18	0.60	0.91
Forwarding	0.96	0.79	0.57	0.68
Total harvesting	2.75	1.97	1.17	1.59

The calculated total fuel consumption of the relocation trucks was 1.2 ML, which was divided into the loaded driving (44.6%) and empty driving (55.4%) of the harvested wood total of 8.9 million m^3 in 2016. The relocation of one harvesting chain consumed 71.1 L/relocation/harvesting chain on average and the average fuel consumption was 43.1 L 100 km^{-1}. The average cubic-based fuel consumption was 0.13 L m^{-3}, while relocation trucks increased the harvesting fuel consumption, on average, by 4.5–10%, depending on the harvesting method.

The calculated CO_2 emissions from the harvesting totalled 37,971 t, of which 57% were from cutting machines and 43% were from forwarding machines. Furthermore, in the wood harvesting, the other GHG emissions (CO, HC, CH_4, N_2O, SO_2, PM and NO_X) ranged between 35.1% and 57.1% and the average cubic-based GHG emissions were 4.26 kg CO_2 eq. m^{-3}. The GHG emissions were proportional to the fuel consumption; the emissions from the first thinning (7.34 kg CO_2 eq. m^{-3}) were more than double those from the final felling (3.14 kg CO_2 eq. m^{-3}). Moreover, the total GHG emissions for the relocations were 2,901 t CO_2 eq. m^{-3} and the cubic-based GHG emissions averaged 0.33 kg CO_2 eq. m^{-3}.

3.2.3 Energy-efficiency indicator of wood harvesting

The energy-efficiency indicator of the wood harvesting was calculated as the ratio of the energy contents of the harvested wood to the consumed fossil fuels in the wood-harvesting operations. The value of the energy-efficiency indicator of the wood harvesting in the method of the final felling was higher than in the thinnings (Table 5). The energy content of the harvested wood was so high that the fossil-fuel consumption of the harvesting machines seemed insignificant. In the thinnings, the energy-efficiency variation was from 63 to 87 and in the final fellings, the value of the energy efficiency was 147. The harvesting-machine relocations lowered the value of the energy-efficiency indicator from the values of the wood-harvesting chain by 4.8–10.5%, depending on the harvesting method.

Table 5. Energy-efficiency indicators of harvesting methods.

Wood-harvesting operation	First thinning	Later thinning	Final felling	Total harvesting
	Energy efficiency, kWh kWh^{-1}			
Cutting (harvester)	96.8	146.0	286.1	189.6
Forwarding (forwarder)	178.9	217.8	301.6	252.2
Harvesting chain	62.8	87.4	146.8	108.2
Total wood-harvesting operation (including machine relocations by truck)	59.8	81.7	131.3	99.6

3.3 GHG-emission indicators of wood-harvesting operations

3.3.1 Fuel consumption and GHG -emission metrics

The results show that the hourly fuel consumption of the cutting machines was highest in the final fellings (15.8 L h^{-1}), followed by the later thinnings (14.38 L h^{-1}) and first thinnings (14.46 L h^{-1}). However, the percentage variation of the fuel consumption was smaller in the forwarders. For the forwarding machines, the highest hourly fuel consumption was found in the final fellings (11.78 L h^{-1}), followed by the first thinnings (11.04 L h^{-1}) and the later thinnings (10.99 L h^{-1}). The hourly fuel consumption of the cutting machines was statistically significantly different (χ^2=33.0; p<0.001) in different harvesting methods, but not for the forwarding machines (χ^2=5.3; p=0.383). The average cubic-based fuel consumptions were 2.12 L m^{-3} (over-bark) in cutting and 0.94 L m^{-3} in forwarding for all the harvesting methods. Accordingly, the average fuel consumption of the cutting machines was highest in the first thinnings (2.12 L m^{-3}), followed by the later thinnings (1.39 L m^{-3}), other fellings (1.09 L m^{-3}) and final fellings (0.77 L m^{-3}). The average fuel consumption of the forwarding machines was highest in the first thinnings (0.94 L m^{-3}), followed by the later thinnings (0.84 L m^{-3}), other fellings (0.72 L m^{-3}) and final fellings (0.59 L m^{-3}). In terms of the cubic-based fuel consumption, there were statistically significant differences between both cutting machines (χ^2=175.8; p<0.001) and forwarding machines (χ^2=43.3; p<0.001) with different harvesting methods.

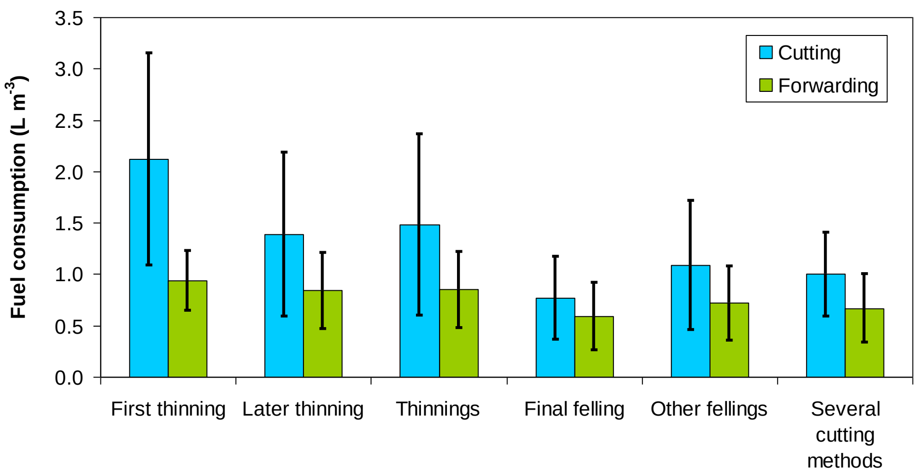

Figure 3. Fuel consumption of cutting and forwarding machines (L m^{-3}) by harvesting method. Bars illustrate average values and black lines denote standard deviation.

The average GHG emissions of the harvesting machines were also the highest in the thinnings (first thinning 8.18 kg CO_2 eq. m^{-3} and later thinnings 5.96 kg CO_2 eq. m^{-3}) and lowest in the final fellings (3.64 kg CO_2 eq. m^{-3}). The differences between the GHG emissions of the forwarding machines were small in the different harvesting methods. However, the GHG emissions of the cutting machines (5.67 kg CO2 eq. m^{-3}) in the first thinnings were more than twice as large compared to the GHG emissions of the machines (2.06 kg CO_2 eq. m^{-3}) in the final fellings.

Table 6. Average GHG emissions based on fuel consumption of machinery for cutting, forwarding and wood-harvesting chains in respect of different harvesting methods.

Wood-harvesting method	Cutting	Forwarding	Harvesting chain
	CO_2 eq. emissions (kg m^{-3})		
First thinning	5.67	2.51	8.18
Later thinning	3.72	2.25	5.96
Thinnings	3.96	2.27	6.23
Final felling	2.06	1.58	3.64
Other fellings	2.91	1.92	4.84
Several methods	2.67	1.79	4.46

3.3.2 Modelling the fuel consumption of harvesting machines

In both cutting and forwarding, the engine power of the harvesting machines significantly explained the hourly fuel consumption (L h^{-1}). Essentially, the fuel consumption lowered as the machines' operating hours increased. In addition, the forwarders' fuel consumption was explained by the use of tracks on the front bogie, which increased the fuel consumption by 1.82 L h^{-1}, as well as the soil type, since in peatlands the fuel consumption was 1.38 L h^{-1} higher than in areas with mineral soils. When modelling the hourly fuel consumption of the cutting machines, harvesting method, the air temperature on the harvesting site and the depth of snow cover also explained the fuel consumption of the cutting machines. The increase in air temperature increased the fuel consumption of the harvesters. The cubic-based fuel consumption of the cutting machines (m^3 ha $^{-1}$) was explained by the harvested stems' average size in the stand, the hectare-based wood amount (m^3 ha^{-1}) and the harvesting method. Correspondingly, in the forwarding, the hectare-based wood amount, forwarding distance and type of soil explained most of the cubic-based fuel consumption by the forwarding machines.

There were significant differences in hourly fuel consumption between the machines. The average difference between the high- and low-consumption harvesters was 0.23–0.72 L m^{-3}. Moreover, the high-consumption harvesters consumed more fuel (38–58%) than the low-consumption harvesters when the stem size of the harvested wood was 0.1–0.6 m^3. Instead, the difference between the low-consumption machines and the high-consumption machines was smaller (0.3 L m^{-3}) in the forwarding with transport distances of 100–500 m. The relative difference between the high- and low-consumption forwarding machines was 60–68%.

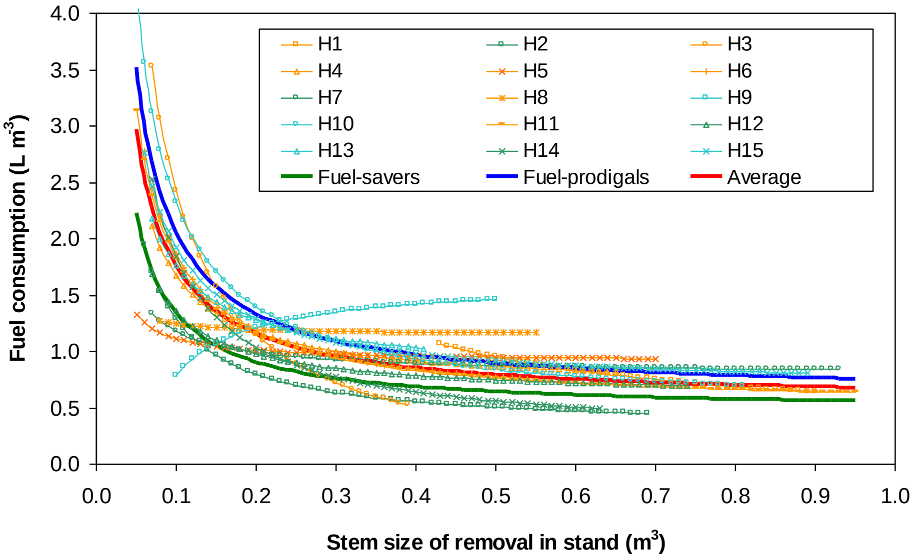

Figure 4. Cubic-based fuel consumption by cutting machines H1–H15 and by fuel-saver and fuel-prodigal cutting machines as a function of stem size of harvested wood (m^3) in stand.

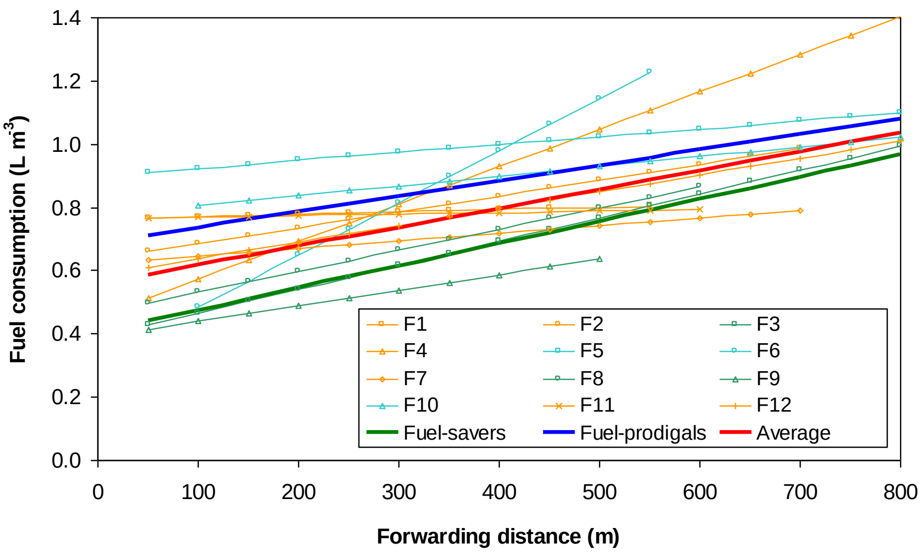

Figure 5. Cubic-based fuel consumption by the forwarding machines F1–F12 and by the fuel-saver and fuel-prodigal forwarders as a function of forwarding distance in the study.

3.3.3 Total fuel consumption and GHG emissions in Finland

In 2020, the total calculated fuel consumption of wood-harvesting operations was 126.6 ML, which means an average of 2.16 Lm^{-3}, when 58.7 Mm^3 (measured over-bark) of wood was procured by the forestry industry in Finland. The total fuel consumption of the cutting machines (67.5 ML) and forwarding machines (42.2 ML) was 109.7 ML. Furthermore, the total fuel consumption of the machines' relocations was 7.6 ML and the car travel by machine operators, harvesting managers and service and maintenance staff accounted for 9.3 ML. Overall, the total fuel consumed by the harvesting operations was divided as follows: cutting 53.3%, forwarding 33.3%, machine relocation 6.0% and car travel 7.3%.

The total GHG emissions were 334,209 t CO_2 eq., which means an average of 5.70 kg CO_2 eq. m^{-3} when 58.7 Mm^3 (harvested over the bark) of wood was procured in Finland. The largest share of GHG emissions was as follows: cutting 54.0% (180,372 t CO_2 eq.), forwarding 34.0% (112,930 t CO_2 eq.), car travel by operators, managers and service and maintenance staff 6.5% (21,840 t CO_2 eq.) and machine relocations 5.7% (19,067 t CO_2 eq.).

Table 7. Fuel consumption and GHG emissions of machinery in 2020 for wood procurement of forestry industry (58.7 Mm^3) in Finland: A = wood-harvesting operations, B = harvesting-machinery relocations and C = car travel by machine operators, logging managers and service and maintenance staff.

Wood-harvesting method	Fuel consumption (L)	GHG emissions (t CO_2 eq.)
A		
First thinning	21,273,120	56,878
Later thinning	44,374,770	118,641
Final felling	40,903,632	109,359
Other fellings	3,150,849	8,424
Sum	109,702,371	293,302
B		
First thinning	903,760	2,259
Later thinning	2,586,870	6,467
Final felling	3,909,906	9,775
Other fellings	226,304	566
Sum	7,626,840	19,067
C		
First thinning	1,100,512	2,588
Later thinning	3,150,040	7,408
Final felling	4,761,105	11,196
Other fellings	275,571	648
Sum	9,287,228	21,840
Totals		
First thinning	23,277,392	61,725
Later thinning	50,111,680	132,516
Final felling	49,574,643	130,329
Other fellings	3,652,724	9,638
Sum	126,616,439	334,209

4 DISCUSSION

The aim of this study was to examine the efficiency of wood harvesting and, more specifically, its energy efficiency. The study focused on the fuel consumption and GHG emissions of machinery in cutting, forwarding, machine relocation and car travel by machine operators, harvesting managers, and service and maintenance staff. Harvesting methods and conditions were also considered in an energy-efficiency context. However, indirect energy contributions, e.g., manual harvesting and forestry experts' travel by car, were excluded from the analysis. In addition to the direct energy-efficiency issues, the aim was to determine the factors that affect fuel consumption and the GHG emissions generated in order to make wood-harvesting operations more energy-efficient. Specifically, the first aim was to illustrate the present state of energy efficiency, as well as the awareness of and attitudes towards energy efficiency in wood-harvesting enterprises (Article I). The second aim of the study was to investigate the allocation of the harvesting machine fleet according to particular harvesting methods and calculate the fuel consumption, GHG emissions and energy efficiency of wood harvesting in Stora Enso (Article II). The third aim of the study was to calculate the total amount of fuel consumption and GHG emissions in Finland. Before the calculation, the metrics and the factors that significantly affect the fuel consumption of machinery were determined (Article III).

4.1 Justification of results and conclusions

The materials collected in the study were extensive and representative. In addition, the material in Article II featured an entire year's information from the ERP database and, in Article III, more than one year of follow-up data were examined. Furthermore, the study included a large sample of machines from different equipment manufacturers, the harvesting sites were located all over the country (Finland) and there were several harvesting operators (Articles II and III). In Article III, a large proportion of the first thinnings was cut together with other fellings (later thinnings and final fellings). In Article III, the average stem size of the harvested wood was 215 dm^3, while the average stem size in Article II was only 183 dm^3. In Article II, there were half as many first thinnings and 10% fewer final fellings than in Article III. In studies that covered data from the entire country, Jylhä et al. (2019) reported average stem sizes of 198 dm^3 and Kuitto et al. (1994) reported 290 dm^3. However, it should be noted that, in Jylhä et al. (2019)'s study, the share of final fellings was an average of 50–66% of the total amount, depending on the region. This is in line with the results obtained in this study, where the share of the final fellings was 55.4% in Article II and 56.3% in Article III. By contrast, Kuitto et al. (1994) reported that 90% of the total wood amount was from final fellings.

In Article II, Eriksson and Lindroos (2014)'s model was applied to calculate the productivity of cutting and forwarding machines. The model is based on extensive CTL harvesting data. Furthermore, Brunberg (2013)'s function was used to determine the fuel consumption of the machines from the engine power; this was based on an extensive follow-up study carried out in Sweden, with the same harvesting methods and tree structure under similar harvesting conditions in Nordic forests. Previous studies generally used values from the EPA (2016) database to calculate GHG emissions (e.g., Ackerman et al. 2017; Prinz et al. 2018; Domke et al. 2020; Hudiburg et al. 2019; Spinelli and de Arruda Moura 2019). However, in this study, the VTT Lipasto database of average emissions, which is commonly used in Finland, was used to calculate the GHG emissions. Palander (2017) and Venäläinen et al. (2019), for example, also used the VTT LIPASTO database in their research. However, the factors in both EPA and Lipasto are almost the same; thus, the results and conclusions are comparable. In Finland, the Ministry of the Environment has outlined, in their medium-term goals, that the TYKO model should be developed as part of the overall development of the LIPASTO system, in order to consider the effects of different activities (for example, different drive-power sources and methods of use of machines) on emissions (Ministry of the Environment, 2022a) more closely.

In this study, the energy efficiency of wood harvesting was calculated using a home-made system from the University of Eastern Finland (Palander et al. 2018, 2020) because the available national calculation methods (EPA, LIPASTO, TYKO) are too general for this purpose, since they cannot convert wood-material to energy values. For this purpose, Alakangas et al. (2016)'s model was used in this study to calculate the energy of the amount of harvested wood and the parameters of the model were modified for this study (Article II). The results show that in Finland, wood procurement is carbon-neutral because only renewable wood is used in industry. These results are consistent with the results presented by Palander et al. (2020). Although the technological development of forestry has contributed to improving the energy efficiency, the saving of resources, the development of efficiency and overall energy efficiency will be important even if wood energy is produced with renewable raw materials. This calculation system improved the energy-efficiency of Stora Enso's wood harvesting. Similarly, it could be applied to the forests of Finland by using the data in Article III.

According to the results, there are differences between the harvesting methods in terms of the calculated GHG emissions in Article II and Article III. The average GHG emissions with different harvesting methods calculated in Article II were slightly lower than the GHG emissions based on actual fuel consumption in Article III. The differences between the thinnings and the final felling were a few tenths; however, in the first thinnings there was a difference of almost one kg CO_2 eq. m^{-3} harvested. Compared to the results obtained by Karjalainen and Asikainen (1996) and by Berg and Karjalainen (2003), the amount of GHG emissions remained the same over two decades in Nordic countries using the CTL harvesting method. The most recent results were obtained by Lijewski et al. (2017), according to whom, using the CTL method, the average GHG emissions of the final fellings were completely consistent with the results in Article III. Klvač and Skoupy (2009)'s results were also in line with these results. In two decades, the share of GHG emissions per cubic metre decreased by 90% (including harvesting-machine transfers and cutting and forwarding machines). Comparing the results of Article II with the study by Berg and Karjalainen (2003), the relative GHG emissions were the same, but the absolute values were different. This was influenced by the improvement in productivity with the development of machines and technology, especially the development of engine technology. In addition, working techniques have been developed for cutting machines (Ovaskainen 2009).

4.2 Fuel consumption and GHG emissions of wood-harvesting operations

The development of engine power and the age of the machine had a significant effect on the hourly fuel consumption of cutting and forwarding machines (Article III). Brunberg (2007, 2013) and Holzleitner et al. (2011b) have reported that engine power significantly affects hourly fuel consumption in harvesting. According to the results in Article III, hourly fuel consumption is affected by the harvesting method, harvesting conditions such as the depth of the snow cover and air temperature in respect of harvesters, while in respect of forwarders it is affected by the utilisation of tracks in the front bogie and peatland forests. These findings are in line with those of Suvinen (2006), Brunberg (2013), Smidt and Gallagher (2013) and Pritz et al. (2018), according to which machine type, harvesting conditions and machine and components settings significantly affect machines' hourly fuel consumption, in addition to the previously described factors. The characteristics of the machine do not seem to have a significant effect on the cubic-based fuel consumption; rather, the fuel consumption is affected by the cutting conditions, such as the stem sizes of the trees in the stand, hectare-based harvested wood amount, harvesting method used, forwarding distance and forwarding on mineral soils (Article III). These results are in line with those of with previous studies, according to which the forwarding productivity and fuel consumption are mostly dependent on the haulage distance and forwarder's payload volume (Jiroušek et al. 2007; Manner et al. 2016; Berg et al. 2019).

A comparison of the results in Article II and III with those of previous studies (Rieppo and Örn 2003; Brunberg 2007, 2013) indicates that hourly fuel consumption has increased over the past two decades. The increase in hourly fuel consumption has been explained by the increased engine power of harvesting machines and use of forwarder's tracks (Brunberg 2013). Fuel consumption per cubic metre has remained at almost the same level. However, more fuel is consumed per working hour and the productivity of harvesting work has increased significantly with both harvesters and forwarders. Moreover, when comparing the results, it should be noted that Hakkila et al. (2002)'s conversion factors were used in this study to unify the amount of wood measured under the bark with the amount measured over the bark.

4.3 Improving the Energy Efficiency of Wood Harvesting in Finland

Fuel consumption is significantly affected by the harvesting method (Articles II and III). The fuel consumption per cubic metre of the harvesters was almost triple with the first thinnings compared to the final fellings. These results are in line with previous studies conducted in Nordic countries using the CTL method (Rieppo and Örn 2003; Brunberg 2013; Jylhä et al.

2019). With regard to forwarders, the fuel consumption per cubic metre was also highest with the first thinnings and the lowest with the final fellings; however, the differences were clearly smaller than with the harvesters. Similar results were previously reported by Brunberg (2013) and Rieppo and Örn (2003). Therefore, the relative consumption of fuel is significantly higher with harvesters than with forwarders between different harvesting methods. When examining the results and comparing them to those of previous studies, it should be noted that in several studies the volume of the tree (m^3) is under the bark, unlike in the studies conducted in Finland, in which the volume is measured over the bark.

According to the results obtained in Article III, the average fuel consumption per cubic metre was lowest in the final fellings (1.4 L m^{-3}). In the later thinnings it was almost twice as high (2.2 L m^{-3}) and in the first thinnings, it was almost three times as high (3.1 L m^{-3}) compared to the final felling. According to the results in Article II, it can be stated that the use of harvesting machines is not optimal. Small and medium harvesting machines harvested almost half of the final fellings and, conversely, the largest machines harvested more than a third of the first thinnings. More optimal use of machines and, thus, savings in fuel consumption may be achieved by developing planning systems. The challenge in Finland is to choose the harvesting machine with the most appropriate size for the harvest area, since entrepreneurs operate all in all possible harvest areas at one time, which means that one harvesting-machine chain needs to cut trees of different sizes with different harvesting methods. Furthermore, stands are small and relocation distances are long. To minimise the fuel consumption and GHG emissions of wood-harvesting operations, it is important to prevent unnecessary machine relocations. Therefore, thinnings are usually cut with harvesting machines that are too large. However, in previous studies, productivity was affected by the allocation of a machine of the right size, adapted to the size of the tree to be harvested (Klvač and Skoupy 2009; Jylhä et al. 2019), which should be considered in planning processes.

The results in Article II, obtained from the calculation of the energy efficiency of the wood harvesting, show that harvesting methods are carbon-neutral or -positive. In addition, wood-harvesting operations (cutting, forwarding and relocation) are also carbon-neutral or -positive. The energy-efficiency indicator shows that the final fellings are the most energy-efficient harvesting method and that harvesting operations have a significant impact on the total energy efficiency. The results presented in this study offer a strategic direction to the planning of measures and development targets to achieve the set goal of 100% carbon neutrality, which is based on the utilisation of renewable forest resources (e.g., Finnish Government, 2020). However, a possible challenge in the future is the tightening of carbon-neutral and forest-management policies, which would restrict or even prevent the current practice of balanced, sustainable and intensive forestry.

4.4 Implications of the study for practice

According to the results in Article I, the attitudes of harvesting entrepreneurs towards energy efficiency were positive and, to a large extent, the energy-efficient operation of wood procurement in the forestry industry is affected by the same factors. However, the share of fuel costs is a small part of a wood-harvesting company's total costs. At the time at which the study was conducted, the proportion of the fuel costs of wood-harvesting businesses was only 14% (Statistics Finland 2022). Therefore, the harvesting entrepreneurs presented other factors for improving energy efficiency, such as productivity. However, the price of oil has risen significantly over the past year and its effects on the profitability of companies are increasing, particularly when entrepreneurs cannot transfer the increased costs to contracting fees. This change may encourage companies to invest even more in energy efficiency and review their operating methods in order to reduce fuel consumption and improve productivity (Rohdin and Thollander 2006; Rohdin et al. 2007; Thollander and Ottosson 2008; Thollander et al. 2013; Brunke et al. 2014).

Regarding the future, all the entrepreneurs believed that the importance of energy efficiency would be emphasised and they were willing to develop their operations accordingly (Article I). According to the results, improvements in energy efficiency can increase the profitability of companies and the entire forestry sector's operations in wood harvesting. These results support Brunberg (2012) and Palander et al. (2020)'s previous findings. However, in Article III, the results outlined that when the study was conducted, only about half of the machine operators had participated in energy-efficiency education. Moreover, the challenge for entrepreneurs is to obtain sufficient knowledge and to transfer it into practice. Entrepreneurs and operators clearly need more training, guidance and instructions. In addition, according to previous studies, the lack of knowledge has been one of the most significant obstacles to the development of energy-efficient working practices (Reddy and Srestha 1998; Nagesha and Balachandra 2006). For example, only by improving and optimising machine adjustments is it possible to achieve significant energy-efficiency improvements, both in harvesting machines and in long-distance transport trucks (Prinz et al. 2018). Energy-efficiency training should also be organised for wood-harvesting entrepreneurs, which would be repeated periodically, thus ensuring the transfer of knowledge and effective operating methods.

In this study, the influence of human–machine systems of fuel consumption was examined. According to the results, there are significant differences between low-consumption human–machine systems and high-consumption human–machine systems in terms of fuel consumption per cubic metre (Articles I and III). The results of several previous studies were similar (Palander et al. 2012; Purfürst and Erler 2011; Pritz et al. 2018; Brunberg 2013; Smitdt and Gallagher 2013; Ovaskainen 2009; Tikkanen et al. 2008). According to the results of Article III, high-consumption machines consumed significantly more fuel per cubic metre than low-consumption machines and, in forwarding, these differences were even greater. Fuel consumption is affected by several factors in addition to the harvester head design, harvesting machine and harvesting method. Productivity differences between operators have been reported by Jalkanen (2010) and Purfürst and Erler (2011), according to whom, with the same stem size, the productivity differences between operators can be more than double. Previous studies confirmed that improving productivity is strongly related to the operator's professional skills and work experience (e.g., Sirén 1998; Kärhä et al. 2004; Ovaskainen et al. 2004; Dvořák et al. 2008; Ovaskainen 2009; Purfürst 2010; Purfürst and Erler 2011; Palander et al. 2012; Malinen et al. 2018). Furthermore, according to previous studies, productivity differences between harvesting operators have ranged from 20 to 55% (Glöde 1999; Kärhä et al. 2004; Väätäinen et al. 2005; Ovaskainen 2009). Väätäinen et al. (2005), Nordfjell et al. (2003), Kärhä et al. (2004), Ovaskainen et al. (2004), Klvač and Skoupy (2009) and Ghaffariyan et al. (2018) explained the differences between harvesting operators in terms of skills and education. In addition, tacit information has been found to have a large effect on the productivity of harvesters when other operator factors are equal (Väätäinen et al. 2005).

In previous studies, harvesting conditions were found to have a significant impact on wood-harvesting productivity (e.g., Kuitto et al. 1994; Sirén 1998; Ryynänen and Rönkkö 2001; Kärhä et al. 2004; Ovaskainen et al. 2004; Eriksson and Lindroos 2014). According to previous studies, the average stem size has a significant effect on machine productivity and fuel consumption (Jiroušek et al. 2007; Smidt and Gallagher 2013; Prinz et al. 2018; Ovaskainen et al. 2004; Nurminen et al. 2006). As the average size of the stem increases, the hourly fuel consumption increases; however, the increase in productivity per cubic metre is greater and fuel consumption per cubic metre decreases (Rieppo and Örn 2003). Nevertheless, Kärhä et al. (2004, 2018), Ryynänen and Rönkkö (2001) and Visser and Spinelli (2012) reported that, when the stem size of the trees in the stand becomes sufficiently large, the productivity of harvesting machines begins to decrease. However, interestingly, this observation was not supported by the material in this study.

According to the results in Article I, the average machine-relocation distance between stands is one of the most significant factors affecting energy efficiency. Relocation trucks accounted for less than a tenth of the total fuel consumption (Articles II and III). In addition, the transfer of machines between locations is carried out by trucks if the closest location is not directly next to the original location, in which case the machines can be driven to the destination and the use of relocation trucks is not necessary. The length of the relocation distance is affected by many conditions: geographical location, the business area of the entrepreneur and planning. With good planning of the chaining of harvesting stands, it is possible to shorten the length of the relocation distance. As fuel prices rise, the number and length of relocation transport distances become even more prominent.

In order to fight against climate change, the forestry sector must find ways to restrain GHG emissions and improve energy efficiency. The results of this study show the factors that have an impact on the fuel consumption of machines, GHG emissions and energy efficiency in terms of wood harvesting. The amount of domestic wood harvesting has increased in recent years to the current level of 76 million m^3 (Natural Resource Center 2022). Moreover, the forestry industry is expected to grow by 175 billion EUR by 2035 (AFRY 2021). The growth of the market is driven by many simultaneous factors, such as the replacement of plastic packaging, the increased use of packaging for online retail, digitalisation, population growth, urbanisation, increasing consumer awareness of environmental impacts and targets for carbon neutrality, including GHG-emission reductions (AFRY 2021). Regarding the future, it is difficult to predict the development of the amount of harvested wood, because there is significant political pressure within the EU region regarding the processing of forests and the amount of felling. In 2020, 9.3 million cubic metres of wood were imported to Finland from Russia, which corresponds to approximately 10% of the raw-wood material requirements (Natural Resources Institute Finland 2022b). As a response to the war in Ukraine, the EU imposed an import ban on Russian roundwood and lumber from the beginning of April. This affects the forestry industry's wood imports and operations, especially in Eastern Finland. Finland is committed to the EU's biodiversity strategy, which requires the increase in protected regions to 30% of the total land and sea area (Ministry of the Environment 2022b; EU commission 2022c). However, in the future, it can be assumed that regulations and laws will become stricter and that the need to reduce fuel consumption and emissions will only increase (Ministry of the Environment 2022b). This may increase the pressure to improve the energy efficiency of wood harvesting and to develop technology for wood-harvesting operations (Markkanen and Lauhkonen 2021).

The machines used in forestry are currently powered by combustion engines. However, with the help of automation, they can be electrified, especially for predictable and repetitive work tasks (Lajunen et al. 2018). Nevertheless, it has been estimated that the machine techniques used in forestry will take a significant time to become electrified, and that the first fully electric machines will be commercially available in 2035 at the earliest (Lajunen et al. 2018). However, the harvesting-machine manufacturer Ponsse recently presented the concept of a 15-tonne forest tractor with a fully electric transmission, an Epec power-distribution unit and a hybrid control unit. The power transmission was implemented entirely with batteries, although the batteries still need to be charged with fossil fuels (Ponsse 2022). According to the current TYKO model, hybrid machines cannot be taken into account (Markkanen and Lauhkonen 2021). In addition to the electrification of harvesting machines, the fuels used in the future may arise from renewable energy sources. Therefore, improving energy efficiency and reducing fossil-fuel consumption will also be important in the future (Nylund et al. 2016). Moreover, improving energy efficiency and reducing emissions is also important from the point of view of life-cycle assessment, as 80% of the energy use and emissions of a machine's life cycle are derived from its use (Athanassiadis 2000).

5 CONCLUSIONS AND FUTURE-RESEARCH NOTES

In this study, the aim was to determine the energy efficiency of CTL wood harvesting and the factors which have the greatest impact on it in Finnish forest conditions. This was the first investigation of the fuel consumption and GHG emissions of all the equipments of CTL-harvesting operations. This study has shown that energy efficiency in wood harvesting is still largely unexplored and that its potential is untapped. Moreover, the utilisation of harvesting machines is not optimal and there are significant differences between human–machine systems in terms of fuel consumption and total productivity in both harvesters and forwarders. Although the general attitude of harvesting entrepreneurs towards energy efficiency is positive, they still need information and training on how to operate energy-efficiently regarding machine and components adjustments, technology and working methods. This study also included the calculated fuel consumption and GHG emissions review of machine relocations and the car travel by machine operators, logging managers and service and maintenance staff to and from harvesting sites. The results show that although the share of these factors is small, they account for around 10% of the total fuel consumption and emissions.

In the future, the examination of fuel consumption and GHG emissions should be extended to the entire wood-harvesting chain, including long-distance transportation and the timber trade. In addition, harvesting conditions influence fuel consumption and GHG emissions. Therefore, when the conditions can be influenced, such as in silviculture and preclearance, these indicators should be considered in order to reduce GHG emissions and obtain higher fuel and energy efficiency from harvesting methods. In addition, operational planning should be developed; for example, it is possible to reduce the use of relocation trucks and the average transport distance by chaining the harvesting sites as closely as possible and trying to harvest all the harvesting sites at one time. The technological development of harvesting machines contributes to improvements in energy efficiency; however, saving resources, developing efficiency and overall energy efficiency are important even if the energy is produced with renewable raw materials.

In terms of fuel consumption, emissions and energy efficiency, the effect of different factors should be investigated in more detail in the future. Although the influence of operators is significant, in the future, it could be possible to determine more precise working methods for operators, which significantly affect cutting and forwarding efficiency. In addition, this review should be extended to the transportation of wood and forest energy sources. In this study, the determination of the GHG emissions was based on calculations and models; however, these emissions could be determined with the help of a follow-up study, in which case, more detailed information would be obtained about the actual emissions, their amounts and their influencing factors.

In addition, in the future, technological developments can significantly increase the energy efficiency of wood harvesting through the development of harvesting machines, such as engines with lower emissions and fuel consumption, as well as the utilisation of renewable fuels. Further, energy-efficiency measures should be developed so that entrepreneurs and operators can obtain real-time information and feedback about the level of energy efficiency of their own operations. Moreover, various automated systems and robotics can help to reduce the operator's impact on energy efficiency. With the help of open data, digitisation and new digital platforms, it is possible to improve the planning of the entire wood-harvesting process and to optimise the energy efficiency of routes and the placement of machines.

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