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Decarbonizing forest machinery of wood harvesting in Finland

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Academic dissertation

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ABSTRACT

Reducing greenhouse gas (GHG) emissions from wood harvesting remains a significant challenge. This dissertation evaluates the impact of alternative powertrains and idling times on reducing emissions and thus, decarbonization of the machinery of Finnish wood harvesting.

The first study examined the potential of alternative powertrains in non-road mobile machinery (NRMM). The results highlighted that hybrid and full-electric technologies have the greatest potential to replace conventional diesel engines in the future. The main challenges identified were battery reliability and high technology costs. Regarding biofuel, biogas, and hydrogen, the benefits were mainly lower emissions while the challenges were high costs and low production rates currently. The highest Technology Readiness Levels (TRLs) were identified for hybrid and full-electric solutions. The TRL assessment for full-electric, biogas, and hydrogen solutions in forest machinery was precluded due to the absence of adequate research information.

The second study used survey data to depict the visions of Finnish logging (*Loggers*) and timber-hauling (*Timber-haulers*) entrepreneurs regarding the idle times of their forest machinery and timber trucks. The study revealed that only a quarter of the loggers and half of the timber-haulers were aware of the idle times of their fleets. The results also indicated that the entrepreneurs preferred lower idling times compared to current levels. Several working phases and their potential to reduce idling were reported. Furthermore, improving entrepreneurs' awareness concerning idling was seen as an essential measure to reduce idling.

The third study aimed to estimate the idle times and fuel consumption during idling using automatically collected machine big data. A scenario approach was used to describe the influence of idle times on the volume and price of carbon dioxide (CO_2) emissions. The results highlighted that the idling time and fuel consumption during idling of harvesters were greater than those of forwarders. Moreover, reducing idling could produce major cost and emissions savings and generate notable additional revenues when transferring the reduced idle engine hours into productive working hours.

Findings of this dissertation provide novel research information and contribute to more efficient and environmentally friendly NRMM operations. While several challenges remain in Finland, the results of this thesis strengthened the foundation when moving towards low-emission wood harvesting operations in Finland and globally.

Keywords: alternative powertrains, climate change, fuel consumption, greenhouse gas (GHG) emissions, idling, non-road mobile machinery (NRMM)

Pesonen, J. (2026) Metsäkoneiden kasvihuonekaasupäästöjen vähentäminen puunkorjuussa Suomessa. Dissertationes Forestales 388. 54 p. https://doi.org/10.14214/df.388

TIIVISTELMÄ

Puunkorjuusta aiheutuvien kasvihuonekaasupäästöjen vähentäminen sekä energiatehokkuuden parantaminen ovat edelleen merkittäviä haasteita. Tässä väitöskirjassa arvioidaan vaihtoehtoisten käyttövoimien sekä metsäkoneiden tyhjäkäynnin vaikutuksia kasvihuonekaasupäästöjen vähentämiseen ja siten ilmastokestävämmän puunkorjuun kehittämiseksi Suomessa.

Ensimmäisessä osajulkaisussa selvitettiin vaihtoehtoisten käyttövoimien potentiaalia raskaissa työkoneissa. Tulokset osoittivat, että hybridi- ja täyssähköisillä teknologioilla on suurin potentiaali korvata perinteiset dieselmoottorit tulevaisuudessa. Havaitut haasteet olivat pääasiassa akustojen luotettavuus sekä korkeat kustannukset. Biopolttoaineiden, biokaasun ja vedyn osalta haasteina todettiin korkeat teknologiakustannukset sekä vähäiset valmistusmäärät. Korkein teknologinen valmiustaso (TRL) todettiin hybridi- ja täyssähköisillä ratkaisuilla. Täyssähköisten sekä biokaasu- ja vetykäyttöisten metsäkoneiden TRL-arviointia ei voitu tehdä riittävän tutkimustiedon puutteen vuoksi.

Toisessa osajulkaisussa selvitettiin suomalaisten puunkorjuu- ja autokuljetusyrittäjien näkemyksiä metsäkoneiden ja puutavara-autojen tyhjäkäyntiajoista kyselytutkimusten avulla. Tulokset osoittivat, että yrittäjät kokivat tyhjäkäyntiaikojen olevan vähennettävissä nykytasosta. Tutkimuksessa raportoitiin myös useita puunkorjuun ja puutavaran autokuljetuksen työvaiheita sekä niiden tyhjäkäynnin vähennyspotentiaalia. Merkittävänä toimenpiteenä vähentää tyhjäkäyntiä korostettiin yrittäjien tietoisuuden parantaminen tyhjäkäynnin vaikutuksista.

Kolmannessa osajulkaisussa tutkittiin metsäkoneiden tyhjäkäyntiaikoja automaattisesti kerätyn laajan konedatan avulla. Tutkimuksessa hyödynnettiin myös skenaariotarkastelua kuvaamaan tyhjäkäynnin vaikutuksia hiilidioksidipäästöihin ja kustannuksiin. Tulokset osoittivat, että hakkuukoneiden tyhjäkäynnin osuus kokonaiskäyttöajasta sekä tyhjäkäynninaikainen polttoaineenkulutus olivat suurempia kuin kuormatraktoreiden. Lisäksi tutkimuksessa todettiin, että tyhjäkäynnin vähentäminen voisi tuottaa merkittäviä kustannus- ja päästövähennyksiä sekä vuotuisia lisätuloja, mikäli vähentynyt tyhjäkäyntiaika voitaisiin siirtää koneiden tuottavien työtuntien määrään.

Tämän väitöskirjan tulokset tarjoavat uutta tutkimustietoa sekä edistävät siirtymistä tehokkaampiin ja vähäpäästöisempiin työkoneoperaatioihin. Vaikka haasteita ilmenee edelleen Suomessa, tämän väitöskirjan tulokset vahvistavat pohjaa siirryttäessä kohti vähäpäästöistä puunkorjuuta Suomessa ja globaalisti.

Asiasanat: vaihtoehtoiset käyttövoimat, ilmastonmuutos, polttoaineenkulutus, hiilidioksidipäästöt, tyhjäkäynti, raskaat työkoneet

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Joensuu, 25th March 2026

Jarkko Pesonen

LIST OF ORIGINAL ARTICLES

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

I Pesonen J, Prinz R, Ovaskainen H, Kauranen P, Poikela A, Kärhä K (2025) Alternative Powertrains and Fuels in Heavy Non-Road Mobile Machinery and Their Future Expectations - A Review. *Current Forestry Reports* 11: 10. https://doi.org/10.1007/s40725-024-00244-2.

II Pesonen J, Jeskanen J, Kangas M, Prinz R, Ovaskainen H, Kauranen P, Kärhä K (2025) Idle times of forest machine and truck fleets in Finnish logging and timber-hauling enterprises. *European Journal of Forest Research* 144: 1537–1550. https://doi.org/10.1007/s10342-025-01824-y.

III Pesonen J, Rantala T, Prinz R, Ovaskainen H, Poikela A, Kauranen P, Kärhä K (2026) Reducing the idle times of forest machines: A scenario analysis with machine big data in Finland. Manuscript submitted.

Jarkko Pesonen is fully responsible for the summary of this doctoral thesis. The contribution of Jarkko Pesonen to the studies included in this thesis was as follows:

I Jarkko Pesonen (JP) was the main author. JP and Kalle Kärhä (KK) conceptualized the study. JP collected and analyzed the data. KK was responsible for funding acquisition. KK, Robert Prinz (RP), Heikki Ovaskainen (HO), Pertti Kauranen (PK), and Asko Poikela (AP) supervised the study.

II JP was the main author. JP and KK conceptualized the study. Jeremias Jeskanen (JJ), Matias Kangas (MK), and KK collected the survey data. JP performed statistical analyses and wrote the article. KK was responsible for funding acquisition. KK, RP, HO, and PK supervised the study.

III JP was the main author. JP, KK, and Topi Rantala (TR) conceptualized the study. JP, KK, and TR collected and analyzed the data. KK was responsible for funding acquisition. KK, RP, HO, AP, and PK supervised the study.

TABLE OF CONTENT

LIST OF ABBREVIATIONS

ATV	All-terrain vehicle
CO_2	Carbon dioxide
CTL	Cut-to-length
ESS	Effort Sharing Sector
ETS	Emissions Trading System
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FMS	Fleet management system
GHG	Greenhouse gas
Gt	Gigatonne
G_{15}	Gross effective time, including delays shorter than 15 minutes
HC	Hydrocarbon
HVO	Hydrotreated vegetable oil
IEA	International Energy Agency
kW	Kilowatt
LCA	Life cycle analysis
LBG	Liquefied biogas
m^3	Cubic meter (solid over bark)
NOx	Nitrogen oxide
NRMM	Non-road mobile machinery
PM	Particulate matter
Rpm	Rounds per minute
SME	Small and medium-sized enterprise
SO_2	Sulfur dioxide
Std	Standard deviation
TRL	Technology Readiness Level

INTRODUCTION

GHG emissions and fuel consumption in the forest sector

During the last decade, global warming has progressed rapidly in comparison to the early 2000s (European Commission 2024) driven by global greenhouse gas (GHG) emissions, setting a record of 37.8 Gt in 2024 (International Energy Agency (IEA) 2025). The European Union (EU) aims to reduce GHG emissions by 55% by 2030 (European Commission 2020) and 100% by 2050 (European Commission 2023a). The vision is to decarbonize the economy by achieving net-zero GHG emissions through new technological solutions and comprehensive collaboration between the government, research community, and citizens (European Union 2019a). According to Meyer-Ohlendorf et al. (2025), current actions are insufficient for achieving carbon neutrality by 2050. Therefore, more actions, especially in areas where emissions have reduced slowly, are required (Meyer-Ohlendorf et al. 2025).

Decarbonizing forest sector requires measures that focus on, among other things, preventing deforestation and implementing new practices for sustainable forest management to increase carbon sequestration (Food and Agriculture Organization of the United Nations (FAO) 2020). Moreover, replacing fossil fuels with renewable fuels would further support emissions reductions (International Energy Agency (IEA) 2023). Additionally, decarbonizing non-road mobile machinery (NRMM), especially forest machinery, with new technological solutions and efficiency improvements could help cut the GHG emissions (Denton et al. 2022).

In recent decades, due to the lag in emission standards, concern about the emissions produced by NRMM has increased (Hagan et al. 2022). The Effort Sharing Sector (ESS) (i.e., sector outside the Emissions Trading System (ETS), excluding the Land Use Sector) in Finland, which covers 65% of total GHG emissions, faces new requirements with regard to reducing emissions from industry, agriculture, transportation, and NRMM (Ministry of the Environment 2025). In Finland, the ESS emissions reduction target by 2030 is 50% compared to 2005 level (Ministry of the Environment 2022). Together, NRMM accounts for 9% of the GHG emissions caused by the ESS, and 6% of the total GHG emissions in Finland (Ministry of the Environment 2025). Of those NRMM emissions, 46% occur from construction and industrial machinery, and 35% from forestry and agricultural machinery (Ministry of the Environment 2025). Moreover, approximately 30% of the total emissions caused by transportation occur from heavy-duty vehicles (Ministry of the Environment 2022).

Previously, NRMM emissions have been studied extensively regarding fuel consumption of diesel-powered forest machinery, for example, Athanassiadis (2000), Lijewski et al. (2017), Numazawa et al. (2017), Prinz et al. (2018), Pandur et al. (2019), Spinelli and De Arruda Moura (2019), Bacescu et al. (2022), Haavikko et al. (2022), Kopseak et al. (2022), Kärhä et al. (2023; 2024), and Conrad et al. (2025). Fuel consumption and emissions of other NRMM, such as construction and agricultural machinery, have also been examined previously (e.g., Kim et al. 2011; Vukovic et al. 2017; Kolator 2021; Lee et al. 2022).

Although agricultural and construction machinery are the two largest machinery segments in terms of GHG emissions at the EU-level (Söderena et al. 2024), forest machines play a major role in Finland. Approximately 14% of the total NRMM emissions originate from wood harvesting machinery (Ministry of the Environment 2025). In 2024, totally around 4,500 harvesters and forwarders were operating in Finnish forests (Saarijärvi 2024). Furthermore, approximately 1,600 timber truck combinations were used for the road transportation of industrial roundwood in 2024 in Finland (Palojärvi 2024). Therefore, the interest is prominent in optimizing forest sector (i.e., logging and timber-hauling operations), and the setups of used machines or trucks for reduced fuel consumption and carbon dioxide (CO_2) emissions (Prinz et al. 2018).

According to Kärhä et al. (2024), the global CO_2 emissions caused by fully mechanized cut-to-length (CTL) can be assessed around four million tons. Of those, harvesters are responsible for approximately 57% and forwarders 43%, respectively (Kärhä et al. 2024). As with timber transportation, a precise estimate for global CO_2 emissions is unavailable.

In 2022, the total harvesting volume of industrial roundwood in Finland was around 68 million cubic meters (m^3) (Natural Resources Institute Finland 2025), causing CO_2 emissions of approximately 506,000 tons (wood harvesting: 300,000 tons; road transportation: 206,000 tons) (Poikela and Strandström 2023). This corresponded to a total of 218 million liters (L) of fuel used (wood harvesting: 121 million L; road transportation: 97 million L) (Poikela and Strandström 2023). The total costs of the logging operations and road transportation of industrial roundwood were around €640 million and €596 million in Finland in 2024, respectively (Strandström 2025). The fuel costs, on the other hand, are responsible for approximately 10% of the total logging costs and 28% of the total timber-hauling costs (Statistics Finland 2023).

Measures to reduce emissions

In Finland, achieving the ESS target of reducing emissions by 50% by 2030 requires further actions (Ministry of Economic Affairs and Employment of Finland 2021; Ministry of the Environment 2022). Consequently, many directives, regulations, and laws, such as The European Climate Law, the European Green Deal, and the Emissions Trading System Directive have been established (European Commission 2018; 2023b; European Union 2019). The Ministry of the Environment in Finland has also proposed several actions for achieving the EU's emissions reduction target (Ministry of the Environment 2022). Few of these actions are increasing the taxes and price of fossil fuels, developing new accounting models for GHG emissions, expanding the registration obligation of machinery, and including CO_2 emissions to Stage Regulation (2016/1628) (European Union 2016; Ministry of the Environment 2022).

One goal is also to increase the share of renewable fuels in NRMM operations from the 2021 level of 18% to 28.5% by 2028 (Pihlatie et al. 2022). The target for increasing the distribution obligation of light biofuel oil by 2028 is 10% from the 3% level in 2021 (Ministry of the Environment 2022). This combined with procurement support for electric and biogas-powered NRMM would accelerate boosting low-emission NRMM operations (Ministry of the Environment 2022).

Improving utilization and resource efficiency would result in cost and emission savings (Auvinen et al. 2025) reducing the need for new machines, since the utilization rate of a single machine would increase. Hence, operator training on energy-saving working techniques is also important to make operations more low-emission and efficient, in conjunction with minimum engine running time and maintenance, as well as low fuel consumption and GHG emissions (Rutty et al. 2013; Hassani 2020; Vilkuna 2020; Hartsch 2023). For instance, time studies conducted by Ovaskainen et al. (2021) and Pohjala et al. (2024) indicated that the effect of the operator's skills on productivity is notable. One option to improve the skills of the operators is simulator training, which has been determined as a safe and cost-efficient way to improve their knowledge (Burk et al. 2023; 2024). However, skills acquired through simulator training tend to ignore the characteristics of the actual working environments (Burk et al. 2024). Therefore, training should be continuously aimed towards maintaining more efficient operating techniques under real-world operating conditions (Ghaffariyan et al. 2018; Sigurjonsdottir et al. 2022; Kärhä et al. 2023).

The data obtained from machines is extremely valuable for strengthening the knowledge base required to achieve the national and global emissions reduction goals (Ministry of the Environment 2025). Nowadays, undergoing development of the fleet management systems (FMSs) and telematics systems provide continuous and accurate data concerning, for instance, engine running time and fuel consumption of the machines (Ovaskainen and Kivilinna-Korhola 2016; Sharpe and Schaller 2019). In addition, the CAN-Bus data of forest machines allow detailed monitoring of, for instance, engine load, operator behavior, and idling times, which can be used to identify, among other things, the emissions reduction possibilities (Spencer and Torres 2022; Guerra et al. 2024). The setting parameters of forest machines can also be optimized (Prinz et al. 2018), or forest machines can be allocated based on the operational environment, such as soil conditions, for higher efficiency (Grigorev et al. 2020; Haavikko et al. 2022).

Alternative powertrains as a promoter of low-emission forest sector

In heavy-duty NRMM, the technological maturity, which is usually reflected with Technology Readiness Levels (TRL) (European Commission 2015), differ substantially due to differing operational environments and performance requirements. The development trajectories of alternative powertrains are also different, and some solutions advance towards commercial use more rapidly than others (Olander et al. 2025). The most distinguishable alternative powertrains of NRMM are currently hybrid, full-electric, and biofuel solutions, as the utilization potential of such powertrains is greater compared to, for instance, biogas or hydrogen powertrains (Auvinen et al. 2025). Currently, several machine manufacturers, such as Caterpillar, Liebherr, LiuGong, Logset, and Volvo, have developed hybrid and full-electric NRMM that are commercially available on the market (Caterpillar 2026; LiuGong 2026); Logset 2026; Strabag 2025; Volvo Construction Equipment 2026).

Correspondingly, full-electric and biogas solutions are currently two of the most common alternative powertrains in heavy-duty (gross vehicle weight of more than 60 t) trucks in Finland with commercially available full-electric and biogas-powered truck models on the market (Mercedes-Benz 2026; Scania 2026; Volvo Trucks 2026a; 2026b). Full-electric and biogas-powered trucks cover approximately 7% of the total number of heavy-duty truck vehicles in Finland (Ministry of the Environment 2025).

Considering NRMM, hybrid technology has been found to improve the efficiency of excavators (e.g., Do et al. 2023; Khan and Huang 2023; Nguyen et al. 2023), while full-electric solution reportedly reduces costs and energy consumption (e.g., Ge et al. 2017; Engström and Lagnelöv 2018; Guo et al. 2020; Fu et al. 2020a; 2020b). Electrification could also improve efficiency due to improved power adjustment (Antila et al. 2025). For instance, Tölli (2024) reported that the overall energy efficiency of an electric powertrain is approximately 70%, whereas the corresponding efficiency of diesel engines with hydrostatic transmission is 30% at most. Few studies also including wheel loaders (e.g., Nokka 2018; Shafikhani and Åslund 2021; Fei et al. 2023; Lin et al. 2024; Ming et al. 2025) and forklifts (e.g., Conte et al. 2014; You et al. 2018; Paul et al. 2019; Haghi et al. 2020), have highlighted promising results regarding hybrid and full-electric powertrains. However, electrifying forest machines is currently a challenge, especially in Finland, as charging remains a significant issue (Auvinen et al. 2025).

Currently, road transportation from the forests to mill yards is greatly dependent on heavy-duty diesel-powered trucks (Iyer et al. 2025a; Venäläinen et al. 2025). Despite that Liimatainen et al. (2019) reported that electric trucks are a viable solution in road transportation, forest sector differs from other sectors. For instance, Iyer et al. (2025a) reported that in the forest sector, long transportation distances and differences in transportation conditions, such as seasonal variation and varying forest road profiles, require robust and reliable solutions for electric timber trucks. Moreover, Ajolinja (2021) and Iyer et al. (2025b) highlighted that hybrid electric timber trucks could be suitable for long-distance timber transportation, especially on hilly routes.

Drawer et al. (2024) reported that it is possible to convert diesel-powered vehicles to fuel-cell-powered vehicles. Fuel-cell-powered heavy-duty trucks have been found to allow the same payload capacity as diesel-powered trucks, whereas the payload capacity of battery-electric heavy-duty trucks are reportedly lower due to the extra weight caused by batteries (Wilson 2023). Additionally, several hydrogen-powered construction machines have been recently tested in the operational environment (e.g., Komatsu 2023; Kobelco Construction Machinery 2023; Hyundai Construction Equipment 2025; Strabag 2025). The results have indicated, for instance, better ergonomics due to less vibration and noise (Hyundai Construction Equipment 2025). However, Haghi et al. (2020) reported that battery-electric solutions are more cost-effective than hydrogen solutions in forklifts, which, however, is affected by the availability of low-cost electricity and the need for storing energy throughout the year. According to Miranda (2017), refueling time and battery replacements should also be considered when comparing the cost-efficiencies of battery-electric and fuel-cell solutions. Nevertheless, generalizing hydrogen as an alternative fuel requires more hydrogen production and lower manufacturing costs (International Energy Agency (IEA) 2019).

According to Puricelli et al. (2021), biofuels accounted for 4.5% of the total energy consumption in road transportation and NRMM in Europe in 2017. Currently, biofuels are primarily used in road transportation (Pihlatie et al. 2022), although contemporary NRMM development also includes the design of engines that are compatible with conventional diesel and biofuels (AGCO Power 2025). For instance, rapeseed (*Brassica napus*) oil and hydrotreated vegetable oil (HVO) have been studied in recent years in NRMM, particularly in agricultural machinery (e.g., Pexa et al. 2013; Pirjola et al. 2017). Moreover, Hosseinzadeh-Bandbafha et al. (2021) found that mixing biodiesel and bioethanol with diesel improved efficiency and reduced emissions. Moreover, similar fuel efficiency than conventional diesel engines have been found with rapeseed oil in wood harvesting operations (Athanassiadis 2000; Emberger et al. 2021).

Biogas have been studied less exhaustively in NRMM. Pihlatie et al. (2022) reported that the biogas infrastructure is currently rather weak in Finland, thereby affecting the attractiveness of biogas-powered NRMM. Nevertheless, agricultural tractors powered with biogas are stated to have the same performance with lower costs than conventional diesel engine (Härkönen 2010; Konepörssi 2022). However, Lacour et al. (2011) showed that utilizing biogas in NRMM causes similar problems as conventional diesel engines. A recent study conducted by Huuskonen et al. (2025), on the other hand, showed that liquefied biogas (LBG)-powered timber trucks are a feasible option for replacing diesel-powered timber trucks, while producing substantial emission reductions.

Minimizing idling as a measure to improve efficiency

Idling time refers to engine running time while stationary at low rotation speeds between 600–1200 rpm (Lutsey et al. 2004). In most cases, idling occurs during delays, which can be described as needless engine running time or unproductive working time, such as time excluded from the actual cutting, extraction or secondary transportation time (Menzies 2005; Nurminen et al. 2006; Nurminen and Heinonen 2007; Mousavi et al. 2011; Mousavi and Naghdi 2013; Haavikko et al. 2019). According to Spinelli and Visser (2008), delays occur rather erratically during operations and so are a challenge to quantify precisely. In other words, delays can be, for example, waiting times during logging operation (Dowling 2010; Johansson et al. 2024). Although all delays cannot be avoided, with appropriate planning they can be reduced (Vitorelo et al. 2011).

Eventually, idling wears out the engine by increasing the engine running hours (Brodrick et al. 2002; Mollenhauer and Tschöke 2010; Molari et al. 2019). Moreover, the increased operating hours due to unnecessary idling lowers the exchange value of the machine significantly (Viitamäki et al. 2015). Higher number of operating hours also cause the need for maintenance to occur more frequently (Shancita et al. 2014), as longer idling periods affect, for instance, the operation of the diesel particulate filter by obstructing cleaner combustion (Komatsu Forest 2017). Consequently, the forest machine manufacturer Ponsse (2025a) has recommended that their forest machines be regularly maintained at intervals of 900 machine hours.

Under extreme conditions, a certain degree of idling may be desirable, especially in very cold or warm weather, where idling can be used to heat or cool the cabin as well as the engine of the machine and vehicle (Allman et al. 2021). For example, Stodolsky et al. (2000) reported that the acceptable idling time for heavy-duty diesel-powered motor vehicles in temperatures of under -6 °C is 20 consecutive minutes due to the required heating activities. On the other hand, at temperatures below -10 °C, Ponsse (2025b) suggests preheating the engine for up to an hour, then running the engine for an equivalent period before the operation to ensure proper battery charging and to warm up the hydraulic oils.

In most cases, however, idling is considered redundant, as shown by Molari et al. (2019) who reported that 67% of all idling time of agricultural tractors was unnecessary, and resulted in wastage of 1.6% of the fuel used. This corresponds to Mörk (2012) who found that it was possible to achieve fuel savings of 1.5% in forest machines with lower idling times. Rutty et al. (2013), on the other hand, reported that lower idling times resulted in average daily fuel savings of 27% in gasoline-powered and hybrid-powered passenger vehicles. In addition, Menzies (2005) and Zietsman et al. (2018) showed that various technologies, such as auxiliary power units, could help reduce fuel consumption of trucks during idling periods. In the absence of unnecessary idling, maintenance requirements occur less frequently, which result in cost savings and a longer life cycle for the machine or truck (Mörk 2012; Shancita et al. 2014). Knowledge of life-cycle costs, warranties, and maintenance requirements of the fleet can also guide forest enterprises to conduct more efficient operations (Menzies 2005).

To date, research information concerning the idling of forest machinery has mainly focused on relatively small machine-generated datasets. For instance, in the example calculation by Viklund (2012), the proportion of idle time of one harvester in Sweden was 22%, whereas Polowy and Molińska-Glura (2023) reported slightly lower average idle times of approximately 15% in two harvesters operating in Poland. With larger datasets that are based on automatically collected machine data, such as CAN-Bus or FMS data, the effects of idling on, for instance, fuel consumption and CO_2 emissions could be examined more precisely and comprehensively (Ovaskainen and Kivilinna-Korhola 2016; Spencer and Torres 2022; Guerra et al. 2024). As Finnish small and medium-sized enterprises (SMEs) recognize idling as an operational phase that affect energy efficiency (Haavikko et al. 2019), perception-based studies focusing on SMEs could provide additional insights of the possibilities to reduce idling during operations.

Objectives

The aim of the thesis was to map alternative powertrains and solutions introduced and demonstrated in heavy non-road mobile machine fleet globally and report the most promising decarbonizing options for forest sector. Moreover, this thesis investigated the possibilities to minimize idling time to accelerate the decarbonization of forest sector based on the visions of logging and timber-hauling enterprises as well as with machine big data from forest machines. Beneath are the specific aims for studies **I-III**:

(1) To provide a comprehensive overview of the potential of alternative powertrains in NRMM by assessing TRLs for different machinery types (Study **I**).

(2) To clarify the level of idling times in the forest sector based on the views of logging and timber-hauling enterprises (Study **II**) and machine big data (Study **III**).

(3) To estimate the impact of idling times on CO_2 emissions and operating costs of logging operations (Study **III**).

By addressing these objectives, this thesis aims to accelerate decarbonization in the forestry sector by presenting different technical solutions and by highlighting the ways to enhance the current forest operations to be more efficient. The findings will contribute to achieving the emission reduction goals, improving the profitability of forest operations, and increasing the awareness of low-emission NRMM operations.

MATERIALS AND METHODS

Overview of data and methods

Decarbonization can be understood as a multidimensional and systemic process that spans technological, economic, social, and institutional domains (Köhler et al. 2019). As such, its analysis requires a broad conceptual perspective and the integration of versatile data sources. Prior research has shown that different types of data and multiple different methods are needed to understand the drivers that affect low-carbon transition (Geels 2011; Sovacool 2014; Köhler et al. 2019).

In this thesis, three complementary data types are used: 1) global scientific literature, 2) surveys, and 3) automatically collected machine big data from forest machinery in Finland. This data combination enables a broad examination of decarbonizing forest sector with alternative powertrains, where global literature frames the technological possibilities and development steps. The data also supports more condensed view, emphasizing the visions of Finnish entrepreneurs operating in forest sector and utilization of operational data collected from the machines to improve efficiency. The analytical approach is primarily quantitative, relying on numerical analyses of large datasets. This integrated approach supports a comprehensive and realistic understanding of the emission reduction potential of NRMM and of the roles that both alternative powertrains and changes in operating practices play in advancing the sustainability transition in the forest sector.

Study I

In study **I**, global research information was collected and analyzed for a comprehensive overview regarding the potential of alternative powertrains in heavy-duty NRMM. The final dataset focused on 91 peer-reviewed articles and 24 non-reviewed publications published between 2010–2024, which were classified based on country, publication year, machinery type, and powertrain for further analysis. Studies were screened and selected based on their suitability for further evaluation. Literature searches were conducted by using several keywords (see Table 1 in Study **I**). Only articles in English and Finnish were collected due to language barrier with other languages.

A total of 17 forestry, industrial, construction, and agricultural machinery types were identified and used to classify collected studies. Few machine types, such as feller-bunchers, cultivators, and lightweight machines, such as snowmobiles, all-terrain vehicles (ATVs), and mowers were excluded from the data due to the lack of studies. A total of 20 studies included 2–5 powertrains or machine types. These studies were classified in multiple groups, which increased the total number of observations from 115 to 143 (Table 1).

Table 1. Total number of studies and observations used in study **I**.

	Number of powertrains/machines					
	1	**2**	**3**	**4**	**5**	**Total**
Number of studies	95	15	3	1	1	**115**
Number of observations	95	30	9	4	5	**143**

A total of 83 studies were used to assess TRLs of different powertrains and machinery segments in study **I**. Of those, 73 studies included only one machine or powertrain and 10 studies between 2–4 machines or powertrains, increasing the total number of observations to 97. The assessment of TRL was conducted based on the classification by European Commission (2015). Furthermore, studies were sorted into groups based on machinery type, such as forestry machinery, industrial machinery, construction machinery, agricultural machinery, and other NRMM. This was followed by identifying the investigated powertrain from each study and determining the prevalence of those in each machine group.

As the first step of the analyses in study **I**, the studies of alternative powertrains were investigated in general to emphasize whether the respective study included the testing of machine or powertrains in an actual working environment or laboratory. In a second step, the studies were examined more specifically regarding the outcomes, which expressed the successes and challenges besides being used to determine TRLs. In a final step, the average TRL of solutions presented in each study were defined. As a result, TRLs were presented from the perspective of each alternative powertrain or machine category (Figure 1).

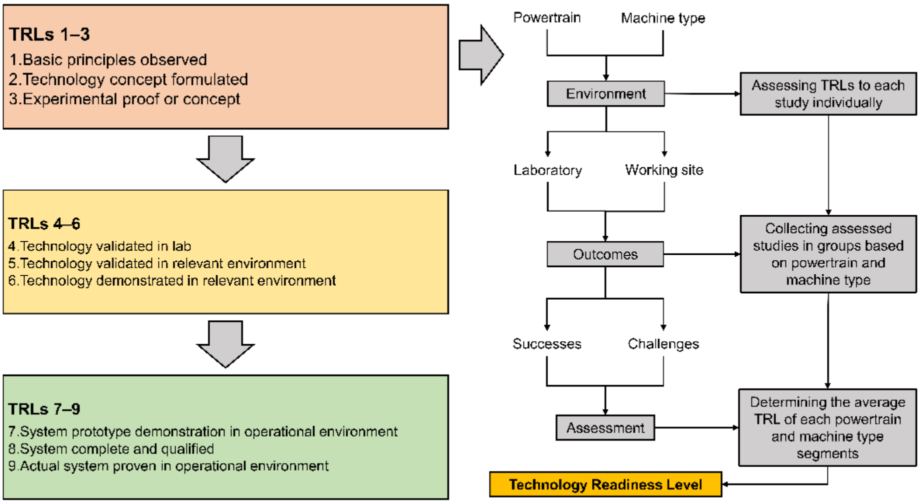

Figure 1. Data analyzing and TRL determination process for each alternative powertrain and machinery type in study **I** based on the TRL classification by European Commission (2015).

Study II

In study **II**, visions of Finnish logging and timber-hauling enterprises on the effects of idling times were investigated. The data were collected in two separate surveys during 2023, which were sent to logging (*loggers*) and timber-hauling (*timber-haulers*) SMEs operating in Finland. The first survey questionnaire was sent to 339 timber-haulers, of which 87 responded (Table 2). The second survey was sent to 817 loggers operating in Finland and 146 responded. Both surveys had a similar structure and were created using the electronic survey system Webropol (Webropol 2025). The surveys were divided into four sections, in which different information was collected from the respondents with open and fixed answer questions (see Table 1 in Study **II**).

A non-response follow-up was conducted via phone to improve the credibility of the data of study **II**. Every sixteenth logger respondent ($N_{\text{Non-response}}$=54) was systematically selected from the total population (N=817) by the Trade Association of Finnish Forestry and Earth Moving Contractors. Moreover, every tenth timber-hauler respondent ($N_{\text{Non-response}}$=34) was selected from the total population (N=339) by the Association of Finnish Timber Trucking Entrepreneurs. Respectively, a total of 51 new responses from 31 loggers and 20 timber-haulers were gathered during the non-response follow-up (see Appendix 1 in Study **II**).

Depending on the level of awareness (i.e., knowledge of the amount and effects of idling time) expressed by the respondents, the following groups were formed in study **II**: *Aware loggers*, *Unaware loggers*, *Aware timber-haulers*, and *Unaware timber-haulers*. Furthermore, proportions, average values (means, medians, and modes), and standard deviations were calculated for the defined groups. Current and desirable idle times were determined by calculating the distributions of the responses within the following idle time categories: < 2%, 2–5%, 6–9%, 10–14%, 15–19%, and > 19%.

With regard to the potential to reduce idling during operations, the exact values were determined by calculating the mean values of the responses given on the scale of 1–5 (1 = No potential, …, 5 = Very high potential). The effects of operator/driver training and incentives were described by calculating the mode of the current idle times for those respondents who had trained their operators and drivers or used incentives, and correspondingly for those respondents who had not trained their operators and drivers or used incentives.

Table 2. The total number of loggers and timber-haulers operating in Finland, the responses received with surveys, and the response rates of study II.

	Total population (N)	Responses (n)	Response rate (%)
Loggers	817	146	17.9
Timber-haulers	339	87	25.7

Study III

In study **III**, idling times of forest machinery were examined based on automatically collected machine big data. Monthly data were collected from 10 logging enterprises between May 2021 and April 2024. The data included a total of 28 harvesters and 23 forwarders from the same manufacturer. Data collection involved the machine data from harvesters for a combined 668 months, and from forwarders for a combined 632 months, respectively. Table 1 in study **III** shows the number of machines and data collection months of different enterprises.

Factors related to their machines and operations were collected from the logging enterprises. These included machine model, manufacture date, serial number, operating hours at the beginning and at the end of the data collection period, and the volume of fuel consumed. Furthermore, enterprise code, data collection month, total timber volumes (m^3), and removals (number of stems) were also acquired from the enterprises. The data lacked the volume of timber hauled by forwarders; thus, the amount was assumed to be the same as the harvesting volume.

Monthly, enterprise and machine type-specific proportion of idling times were calculated by first summing the idle times of all machines in each enterprise and then dividing the sum by the total operating hours of all machines in each enterprise during the period of interest (i.e., values weighted by the total operating hours). Moreover, cubic meter-based fuel consumption was calculated by dividing fuel consumption (L) by the total harvested volume (m^3). The relationship between fuel consumption during idling and engine power (kW) was modeled for both harvesters and forwarders. Detailed descriptions of the models are presented in Table 3 in study **III**.

In study **III**, the impacts of idling on CO_2 emissions and operating costs were examined by comparing current CO_2 emissions and operating costs (i.e., business as usual) (Scenario 1: BAU) to four alternative scenarios (Table 3). The machine-specific values resulted from the calculations were further multiplied by 1,900 for both machinery types, which represented the total number of harvesters and forwarders operating in Finland (Koneyrittäjät 2025). In Scenario 2, idle times were reduced by 25% (Scenario 2: -25) and in Scenario 3 by 50% (Scenario 3: -50), while the productive hours were assumed to remain the same in both scenarios. In Scenarios 4 and 5, it was assumed that all reduced idle times would transfer into productive operating hours, thus increasing the productive hourly rates.

In addition to CO_2 emissions and operating costs, possible revenues (i.e., income from the increased productive hours compared to the costs of the remaining share of idling) were also calculated by multiplying the increment of harvesting volume by cubic meter-based operating cost. The main costing parameters and detailed description of the method used in the machine cost calculations are presented in study **III**.

Table 3. Proportional changes (%) of idling times within each alternative scenario compared to the business as usual (BAU) scenario. In Scenarios 2 and 3, the productive operating hours were assumed to be the same as in BAU. In Scenarios 4 and 5, the reduced idle times were assumed to transfer into productive operating hours.

	Idle time reduction (%)	**Increment of productive operating hours**
Scenario 1 (BAU)	0	No
Scenario 2 (-25)	-25	No
Scenario 3 (-50)	-50	No
Scenario 4 (-25_PH)	-25	By reduced idle times
Scenario 5 (-50_PH)	-50	By reduced idle times

Statistical analysis

The data of studies **II** and **III** were initially tested for the assumption of normal distribution with the Kolmogorov-Smirnov (K-S) test, which indicated that the data was not normally distributed. Therefore, non-parametrical tests, such as Kruskal-Wallis (K-W) one-way ANOVA and Mann-Whitney (M-W) U tests were used for statistical analyses. These tests allowed the comparison of, for example, machinery type (harvesters and forwarders) (M-W), enterprises (A–J) (K-W), and operating months (January–December) (K-W). In study **II**, statistical tests were employed to examine differences in entrepreneurs' awareness and estimations considering idling times, their previous actions to address idling (e.g., operator training and incentives), and to assess the validity of the collected data. Correspondingly, in study **III**, the effects of machinery type, enterprises, operating months, and engine power (kW) on the level of idling times were emphasized with statistical tests.

The significance of statistical values was evaluated at a 95% confidence level ($p<0.05$). In study **III**, the relation between hourly fuel consumption during idling and engine power (kW) was modeled with a linear regression model for both harvesters and forwarders, and further examined by calculating the Pearson correlation coefficient.

RESULTS

This section presents the findings of the three articles included in the thesis. Study **I** presents the outcomes of the global literature review of the potential of alternative powertrains in heavy-duty NRMM. Study **II** highlights the visions of Finnish logging and timber-hauling entrepreneurs on reducing idling times of forest machines and timber trucks. Study **III** illustrates the impact of idling times on CO_2 emissions and operating costs based on automatically collected machine big data. Detailed information on the methodology and outcomes can be found in the original articles.

The potential of alternative powertrains in heavy NRMM

In study **I**, the advantages, disadvantages, and limitations of different alternative powertrains in various NRMM segments were identified (Table 4). Hybrid and full-electric solutions were found to improve fuel efficiency and reduce emissions, although the implementation and reliability of the batteries especially in forestry machinery can cause major challenges. With biofuel and biogas solutions, the benefits were mainly lower emissions, whereas the challenges and limitations were mainly the availability of the fuel as well as the profitability of the biofuel or biogas production. As for hydrogen powertrains, the possible efficiency improvements and emission reductions were underlined as benefits, although the costs of hydrogen solutions and lack of hydrogen production were found to limit the widespread use of hydrogen-powered machinery.

Table 4. Advantages, disadvantages, and limitations of alternative powertrains in forestry, industrial, construction, agricultural machinery, and general NRMM development based on the analysis of selected studies in study **I**.

Hybrid	**Advantages**	**Disadvantages**	**Limitations**
Forestry machinery	Lower fuel consumption Lower CO_2 emissions, More stabilized operations	Reliability, Higher costs, Increased weight due to batteries	Lack of recharge possibilities, Implementation of batteries is difficult, Profitability requires higher productivity compared to diesel
Industrial machinery	More extensive charging connection, Lower fuel consumption, Short-term high-power operations, Less noise, Improved efficiency	Reliability, Higher costs	Limited adequacy of electricity
Construction machinery	Lower fuel consumption Lower CO_2 emissions, More stabilized operations	Reliability issues, Higher costs, Weight of the batteries No infrastructure for cable connection	Lack of recharge possibilities, High costs of electric components, Short operating area with cable connection
Agricultural machinery	Lower fuel consumption Lower CO_2 emissions, Adaptability to varying conditions	Reliability issues, Higher costs, Weight of the batteries, No infrastructure for cable connection	Lack of recharge possibilities, Challenging implementation of batteries
General NRMM development	Lower fuel consumption when boosting diesel engines with hybrid	Size and weight cause challenges when implementing large batteries	Manufacturing processes of large batteries may cause emissions as much as the emission savings produced are
Full-electric	**Advantages**	**Disadvantages**	**Limitations**
Forestry machinery	Environmentally friendly, Smooth and continuous power control, Better ergonomics	Increased weight due to batteries, No possibilities to cable powering	Lack of charging connection, Reliability issues due to cold working conditions
Industrial machinery	More extensive charging connection, Improved efficiency, Lower costs, Zero emissions during operations	Reliability of batteries in extreme conditions, Disposal process of batteries, Limited operation area due to cable powering	Battery technology requires more development, Cable powering requires stationary operations
Construction machinery	Lower energy consumption during operations compared to diesel	Reliability of batteries in extreme conditions, Limited operation area due to cable powering	Lack of charging connection, Cold working conditions can cause reliability issues
Agricultural machinery	Compact engine design, Maintains performance, More stabilized operations	Increased weight due to batteries, No possibilities to cable powering	Lack of charging connection, Cold working conditions cause reliability issues
General NRMM	Lower CO_2 emissions during life cycle,	Costs of the batteries and maintenance,	Availability of electric components,

development	No fuel consumption	Lower reliability in extreme conditions	High costs
Biofuels	**Advantages**	**Disadvantages**	**Limitations**
Forestry machinery	Lower emissions (CO_2, NOx, PM)	Productivity and fuel consumption can be at the same level as conventional diesel engine	More research is required regarding biofuel properties under extreme conditions and cooling down the system
Industrial machinery	Lower emissions (CO_2, NOx, PM)	Availability of renewable fuels causes additional costs and time due to increased transportation	Low availability of biofuels Lack of knowledge regarding biofuel properties
Construction machinery	Lower emissions (CO_2, NOx, PM)	Availability of renewable fuels causes additional costs and time due to increased transportation	Low availability of biofuels, Lack of knowledge regarding biofuel properties
Agricultural machinery	Cleaner combustion, Lower CO_2, SO_2, and PM emissions	Higher fuel consumption, Similar performance than with diesel	The profitability issues with local biofuel production
General NRMM development	Lower emissions (CO_2, NOx, PM)	Higher fuel consumption, Issues with sustainability criteria	Large scale generalization requires significant amount of bio-based resources
Biogas	**Advantages**	**Disadvantages**	**Limitations**
Forestry machinery	Lower CO_2 emissions	New engines require specialized design due to retrofitting costs	Lack of sufficient solutions and methodologies
Industrial machinery	Lower CO_2 emissions	New engines require specialized design due to retrofitting costs	Lack of sufficient solutions and methodologies
Construction machinery	Lower emissions and increased torque	The availability of biogas causes additional costs and time due to increased transportation	Lack of sufficient solutions and methodologies
Agricultural machinery	Lower emissions, Lower maintenance and repair costs	New engines require specialized design due to retrofitting costs	Low availability of biogas
General NRMM development	Lower CO_2 emissions, Compatibility with different fuel blends	New engines require specialized design due to retrofitting costs	Current infrastructure requires compatibility and adaptability for profitable biogas production
Hydrogen	**Advantages**	**Disadvantages**	**Limitations**
Forestry machinery	-	-	-
Industrial machinery	Lower emissions, Cost-efficient during operations, More stabilized power control	High costs of fuel-cells, High costs of re-fueling infrastructure, The size of required hydrogen storage	Further development could reduce costs significantly
Construction machinery	Higher performance, Lower emissions	High costs of hydrogen technology, Increased weight due to large hydrogen storage	Lack of hydrogen production
Agricultural machinery	Lower CO_2 emissions while maintaining performance	Performance is at the same level as diesel, Requires a large storage	Lack of hydrogen production
General NRMM development	Lower emissions (CO_2, HC, NOx)	Higher energy consumption	Lack of hydrogen production

The emission reduction potential assessed in study **I** showed that full-electric and hydrogen powertrains produce zero local emissions during operations (Figure 2). However, we were unable to verify the origin of the electricity, which affects the emission-free definition. During the life cycle of the machine, including the technology production and maintenance, the emission reduction potential with full-electric and hydrogen powertrains averaged at 59% (std 0.05–0.13). Although hybrid has been considered the most potential alternative powertrain, its emission reduction potential averaged 36% (std 0.16–0.21) during the operations and life cycle. With regard to biofuels, the average emission reduction potential during the operations and life cycle was 38% (std 0.18–0.23), whereas biogas embraced the greatest emission reduction potential, varying from 66% (std 0.22) to 81%. The detailed description of the references used in the emission reduction potential assessment can be found in study **I**.

The average TRL of hybrid-powered forestry machinery averaged 6.8, followed by biofuel technology (4.0) (Figure 3). The detailed TRLs for different machines can be found in Table 5 in study **I**. In industrial machinery, the highest average TRLs of 7.4 and 6.9 were achieved with full-electric and hybrid solutions, respectively. We were unable to determine the TRL of biofuel and biogas technologies with industrial machinery. The level of development of biofuel solutions averaged 6.0 in construction and agricultural machinery. Biogas solutions had the lowest average TRLs (2.5–4.0) mainly due to the lack of research information. Hydrogen, on the other hand, has been studied more frequently especially in wheel loaders and forklifts, thus averaging 5.2 on the TRL scale.

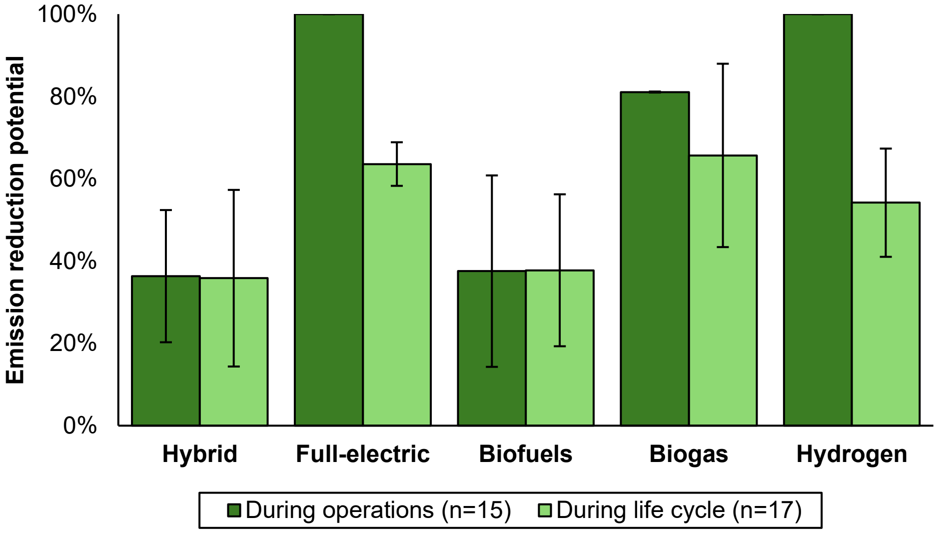

Figure 2. Average emission reduction potential during operations and life cycle of each alternative powertrain based on previously reported results. The grey lines describe the standard deviation in each powertrain group. The observations are based on the analysis of the selected studies in study **I**, where emissions of alternative powertrains were compared to diesel/gasoline (n=32).

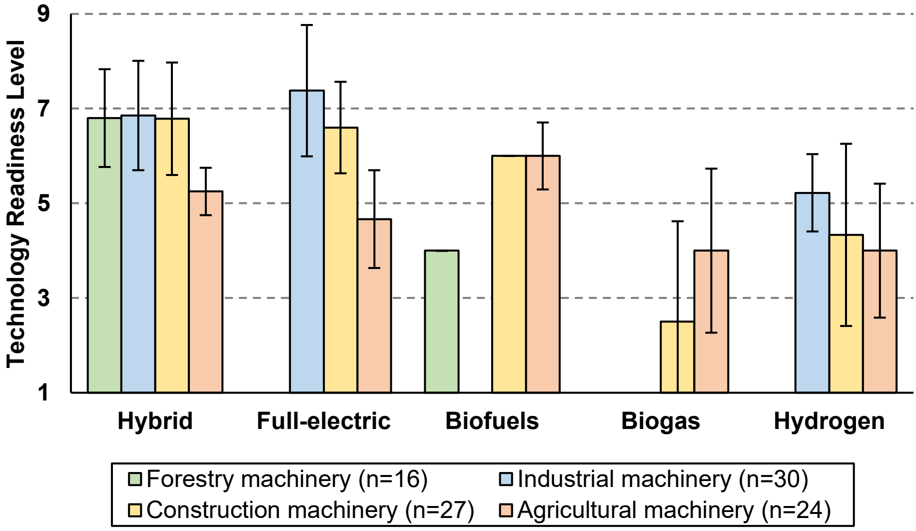

Figure 3. Average TRLs of forestry, industrial, construction, and agricultural machinery types (n=97). The grey lines describe the standard deviation of the TRLs of each powertrain inside the machinery segments presented in study **I**.

Visions of Finnish logging and timber-hauling entrepreneurs regarding idling

The results of study **II** showed that 27% of loggers and 51% of timber-haulers had previous awareness of idling time in their enterprises. Moreover, a total of 53% of the loggers and 77% of the timber-haulers had trained their operators/drivers with regard to engine idling time, although there were no statistically significant differences in relation to the effects of training on current idling time (loggers: M-W, p=0.971; timber-haulers: M-W, p=0.761). The results also showed that only seven loggers and six timber-haulers had used incentives, such as a bonus payment, to reduce idling in their enterprises. No statistically significant differences were found in idle times in relation to the use of incentives (loggers: M-W, p=0.710; timber-haulers: M-W, p=0.750).

The median proportion of idle time was lower with aware loggers (2–5%) than with unaware loggers (6–9%) (Figure 4). There was no statistically significant difference between loggers who were aware and unaware of idling (M-W, p=0.060). Most of the timber-haulers that were aware of idling revealed that the idling proportion ranged between 6–9% (median values) in their operations. Conversely, half of the timber-haulers who were unaware of idling estimated their idle times to be around 2–5% (median) (Fig. 4). A statistically significant difference occurred between timber-haulers aware and unaware of idling (M-W, $p<0.05$).

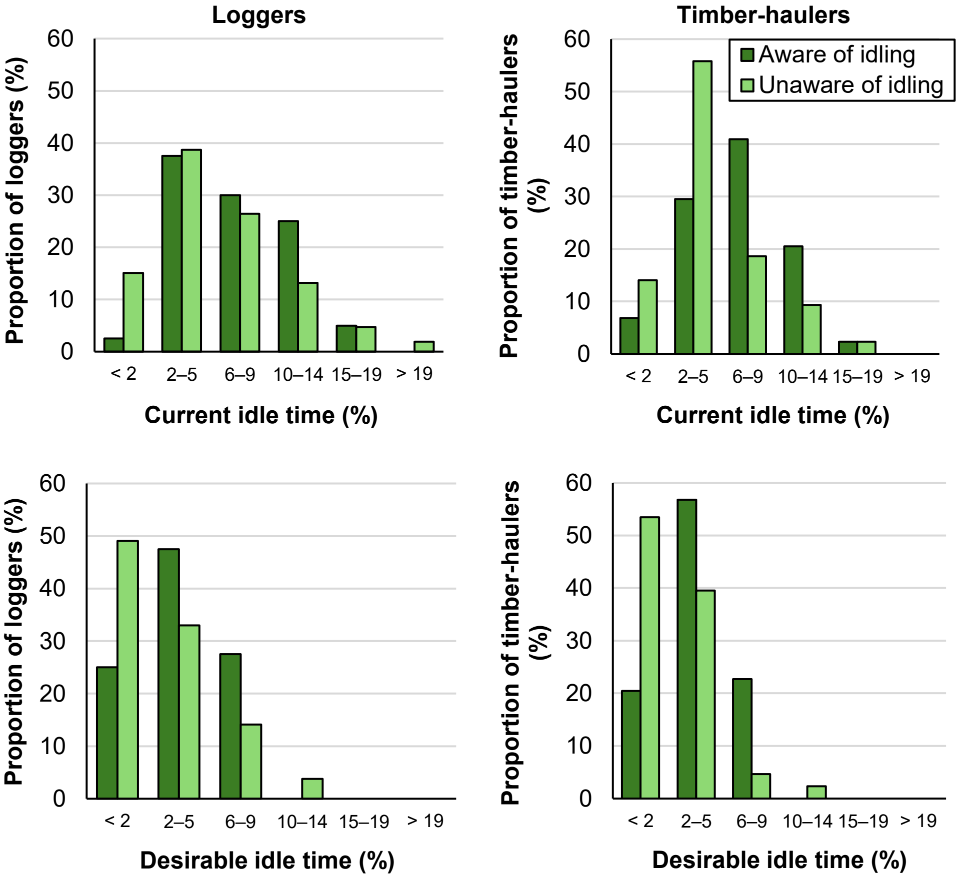

Figure 4. Distribution of estimations on current and desirable idle times as expressed by loggers (n=146) and timber-haulers (n=87) in study **II**, who were aware and unaware of idling time.

With regard to desirable idle times of forest machines, the median value of preferable idle time was 2–5% for both aware and unaware loggers in study **II**. Furthermore, the median value of preferable idle time was 2–5% with aware timber-haulers and < 2% with unaware timber-haulers (Figure 4). Statistically significant differences were observed between the loggers that were aware and unaware of idling (M-W, $p<0.05$) and timber-haulers that were aware and unaware of idling (M-W, $p<0.001$).

The work phases with the greatest potential to reduce idling times during logging in study **II** were found to be during planning on the harvesting site (3.95, std 1.02), operator breaks (3.78, std 1.03), and the initial work tasks on the harvesting site, such as uploading logging and bucking instructions to a harvester (3.75, std 1.03) (Fig. 3). The work phases with the least potential were maintenance tasks and during possible visits on harvesting site, for example, by forest landowners or logging supervisors and officers (3.05–3.08, std 1.25–1.47). A statistical difference between the aware and unaware loggers occurred almost in every work phase (p<0.05), with the exception of sending the performance data (M-W, p=0.307) and visits on site (M-W, p=0.115) (Figure 5).

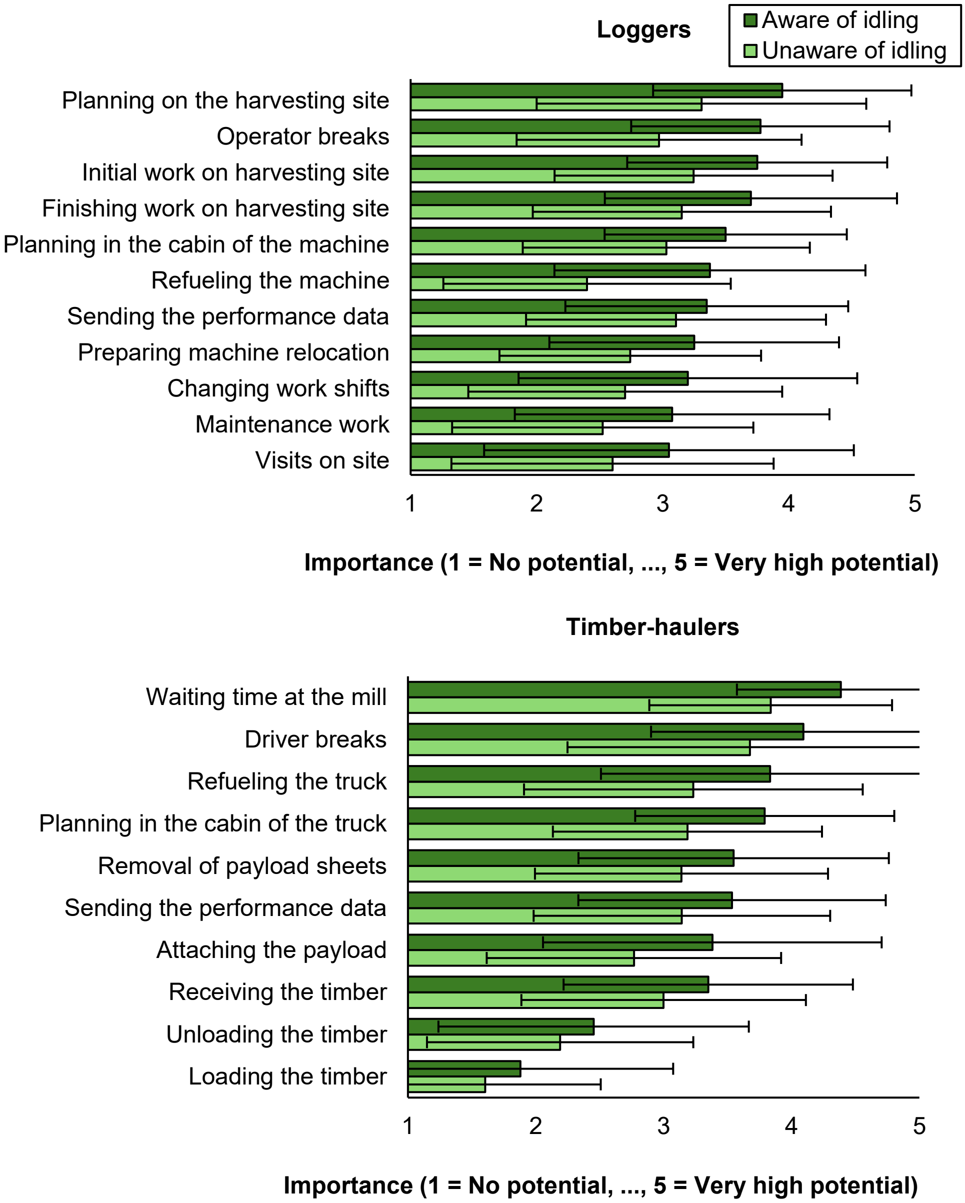

Figure 5. Estimated potential to reduce idling in logging operations as indicated by loggers (n=146), and in timber-hauling as indicated by timber-haulers (n=87) based on the results of study **II**. Black error lines represent the standard deviation.

During timber hauling, the work phases with the greatest potential to reduce idling were assessed in study **II** as: waiting at the reception of timber mill, driver breaks, and refueling the truck, which overall, averaged from 3.83 (std 1.32) to 4.39 (std 0.81).The work phases with the least potential to reduce idling were loading and unloading of the timber (1.88–2.45, std 1.19–1.21). A statistical difference was observed for waiting time at the mill (M-W, p<0.01), planning in the cabin of the truck (M-W, p<0.01), attaching the payload (M-W, p<0.05), and refueling the truck (M-W, p<0.05) (Figure 5).

Idle times of forest machinery based on machine big data

In study **III**, the average annual idle time of a single harvester was 253 hours, which represented 14.0% of the total engine running hours. The average annual idle time of each forwarder was 223 hours, which accounted for 11.1% of the total engine running hours. The standard deviation (std) was higher with harvesters (std: 5.5%) than with forwarders (std: 3.2%). A statistically significant difference was observed between harvesters and forwarders with regard to idle times (M-W, p<0.001).

Study **III** showed the greatest proportion of harvester idle times was observed with enterprise A (18.8%) (std: 2.8%) and the lowest with enterprise B (5.5%) (std: 1.1%) (Figure 6). For forwarders, the greatest proportion of idle times occurred with enterprise J (13.3%) (std: 2.5%) and the lowest with enterprise B (7.6%) (std: 1.2%). Statistically significant differences were observed between enterprises in the idle times of harvesters and forwarders (K-W, p<0.001). For the six enterprises that had previously focused on idling, average idle times of harvesters and forwarders were 13.1% and 9.9%, respectively. In contrast, average idling times of harvesters and forwarders were 13.5% and 12.1% for the remaining four enterprises, who had not focused on idling. A statistically significant difference occurred between the enterprises that had focused on idling and those that had not (harvesters: M-W, p<0.05, forwarders: M-W, p<0.001).

The monthly idling times of harvesters and forwarders varied approximately by 3–4%-units during the year in study **III**. The greatest proportions of idling times were observed during the winter months (November–February) for both harvesters and forwarders (std: 3.1–5.8%-units) (Figure 7). Statistically significant differences between operational months were found between the idle times of both harvesters and forwarders (K-W, p<0.001).

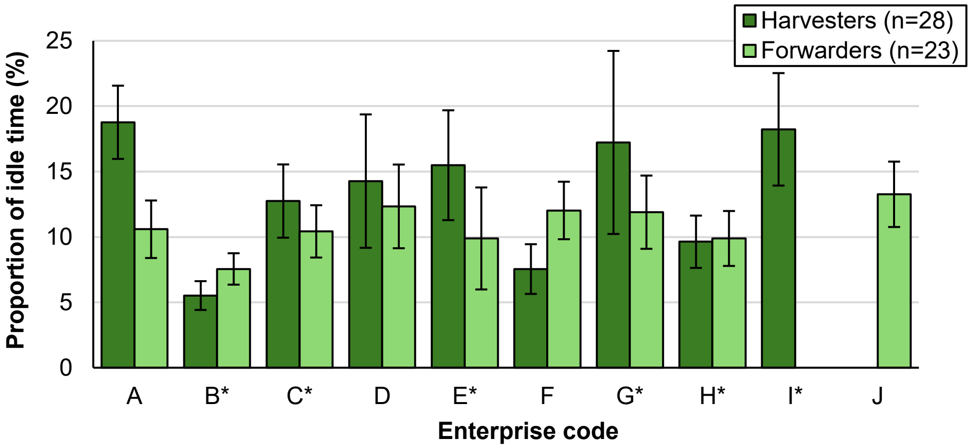

Figure 6. Enterprise-specific idle times of harvesters and forwarders based on machine big data of study **III**. Error bars represent the standard deviation. The values are weighted by total operating hours of the month under review. Enterprises marked with an asterisk had previously focused on idling.

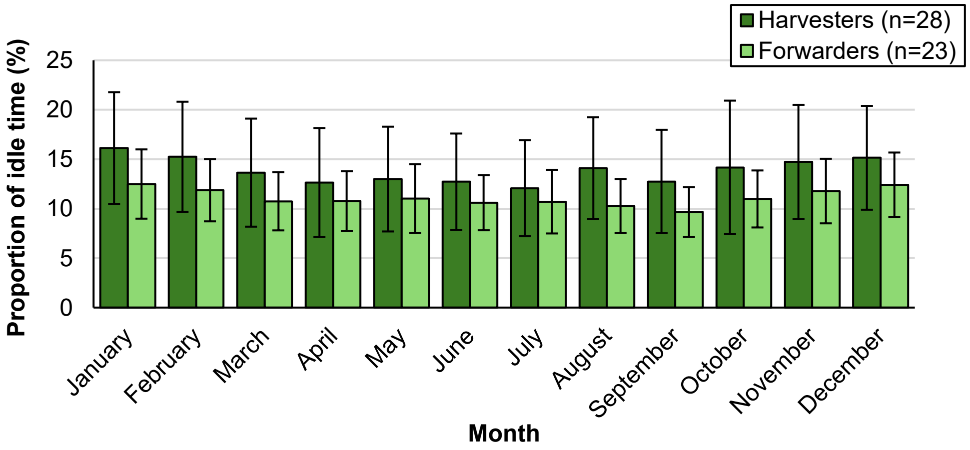

Figure 7. Monthly average idling times of harvesters and forwarders based on machine big data of study **III**. The values are weighted by total operating hours of the month under review.

On average, the annual amount of fuel consumed during idling was 1,093 L per harvester and 734 L per forwarder in the data of the study. The proportion of fuel consumed during idling (of the total amount of fuel consumed) was 3.6% by harvesters and 2.9% by forwarders. The average hourly fuel consumption of harvesters during idling was 4.28 L h^{-1} (std: 0.92) and 3.38 L h^{-1} (std: 0.61) for forwarders. The monthly idle fuel consumption is shown in Figure 4 in study **III**.

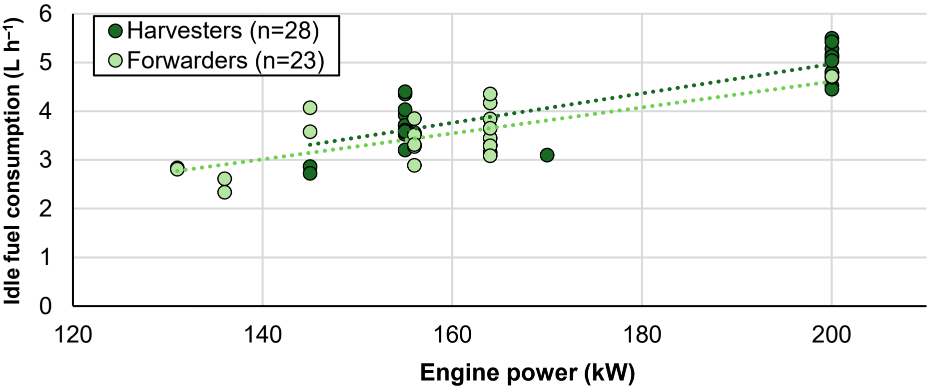

Figure 8. Average hourly idling fuel consumption as a function of engine power of the machines. Individual points represent the machines and the lines modeled functions The model used is presented in Table 3 of study **III**.

Hourly fuel consumption during idling and the engine power of the machine were found to be significantly correlated in study **III**: the correlation with harvesters was 0.813 ($p<0.001$) and 0.782 with forwarders ($p<0.001$) (Figure 8). Average hourly idling fuel consumption of harvesters and forwarders with engine power of more than 180 kW was 4.90 L h^{-1}, whereas average hourly idling fuel consumption of harvesters and forwarders with engine power of less than 150 kW was 3.41 L h^{-1}. A statistically significant difference was found between hourly idling fuel consumption and engine power with both harvesters and forwarders (K-W, $p<0.001$).

CO_2 emissions, costs, and revenues caused by idling

Based on the assumption that the annual total harvesting volume in Finland is 66.8 million m^3 (Natural Resources Institute Finland 2025), the total annual CO_2 emissions caused by idling were estimated at 10,672 t (Scenario 1: BAU) in study **III**. If idling were reduced by 25% for both harvesters and forwarders (Scenario 2: -25), emission savings would be 2,659 t CO_2. Reduction of idling by 50% (Scenario 3: -50) would reduce CO_2 emissions by 5,318 t CO_2 compared to BAU (Scenario 3: -50). If the reduced idle time was transferred into productive operating time (Scenario 4: -25_PH; Scenario 5: -50_PH), CO_2 emissions from harvesters and forwarders would increase by 7,552 and 15,240 t CO_2, respectively.

In study **III**, the total annual costs caused by idling in the BAU scenario were €48.4 million (Figure 9), of which repair and maintenance costs accounted for 28% (€13.8 million), decrement of the exchange value 62% (€30.2 million), and fuel costs 10% (€4.5 million). An idle time reduction of 25% (Scenario 2: -25) was found to reduce costs by €12.1 million, and a reduction of 50% (Scenario 3: -50) would produce approximately €24.1 million in cost savings compared to BAU. Within Scenarios 4 (-25_PH) and 5 (-50_PH), idle time transformation into productive operating hours would generate substantial revenues; reduction in idling by 25–50% would result in annual revenues of approximately €28–55 million.

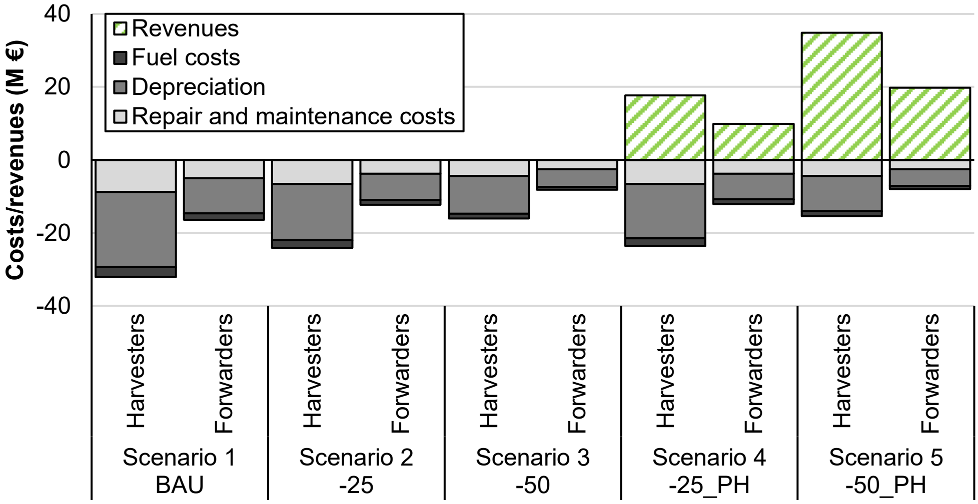

Figure 9. Costs and revenues caused by idling in million euros based on the scenario analysis in study **III**. Within scenarios 4 (-25_PH) and 5 (-50_PH), the reduced idling is assumed to transfer into productive operating hours.

DISCUSSION

Strengths and limitations of the thesis

This thesis highlighted the possibilities for decarbonizing heavy-duty NRMM in forest sector based on global research information, visions of the entrepreneurs within forest sector, and automatically collected machine big data. The data used was considered unique and novel, and this thesis successfully used different methods to analyze the data. This enabled diverse results, all of which contribute to a reduction in emissions in the forest sector.

There is rather little research information concerning forest machines with alternative powertrains. Therefore, in study **I**, global research information also including other NRMM was gathered from more than 30 countries over the past 15 years, offering the most up-to-date results, which were used to evaluate recent technological development and current challenges. However, some of the studies tended to focus on the different aspects of technology evaluation with different methodological approaches, thereby presenting various results. For example, Radica et al. (2021) and Yu et al. (2021) focused on the energy efficiency of excavators and forklifts with laboratory tests and simulations. In addition, Ge et al. (2017), Troncon and Alberti (2020), and Poikela and Ovaskainen (2022) performed field tests with excavators, agricultural tractors, and harvesters regarding energy and fuel efficiencies as well as performance requirements. Lajunen et al. (2016; 2018) clarified the technology implementation aspects of electrification by mapping the present and future trends. Beligoj et al. (2022) and Khan and Huang (2023), on the other hand, examined the emissions and costs of NRMM through life cycle analysis (LCA).

It must be noted that the emission calculations can be derived from, for example, fuel consumption by using different coefficients or standards in calculations or by measuring the actual emissions from the machine. Consequently, methodological inconsistencies of different studies caused variation in the results. For instance, several review studies (e.g., Pandur et al. 2021; Baker et al. 2022; Leitner et al. 2023) and field test studies (e.g., Emberger et al. 2016; Einola and Kivi 2024), were used to assess the emission reduction potential in study **I**. Hence, the emission reduction potential only illustrated the possible influence of each alternative powertrain on emissions reduction (see Figure 2). A more precise determination of the emissions caused by each alternative powertrain would require a more detailed analysis of the characteristics of the powertrains throughout their life cycle.

Despite that study **I** presented few examples of the utilization of biofuels and hybrid solutions in forest machines (e.g., Emberger et al. 2021; Poikela and Ovaskainen 2022; Einola and Kivi 2024), the representativeness of alternative powertrains in forest machines was quite low compared to other machinery segments. However, in general, the total number of forest machines is significantly lower than, for example, the number of construction machines (Pihlatie et al. 2022; Auvinen et al. 2025). Thus, there is also less research information available regarding alternative powertrains in forest machinery. Still, it was possible to highlight and compare the benefits, challenges, and limitations in different NRMM. Especially with hybrid solutions, technological development of forest machines is comparable to other NRMM, indicating positive view for future development.

The survey data in study **II** corresponded to an average response rate of approximately 20% (Table 2). Nevertheless, a total of 233 Finnish wood harvesting and timber-hauling entrepreneurs participated in study **II**, some of whom operated with fleets comprising more than ten forest machines or timber trucks (see Appendix 1 in Study **II**). Since the reliability of the entrepreneur's estimations remained unverified, the results may have contained biases. Therefore, a non-response follow-up was conducted to verify the accuracy of the respondent's estimations. A comparison between the original survey data and non-response follow-up data showed only minor differences in the estimations of current and desirable idle times among loggers, and in the number of timber-haulers who had given training to their operators (see Appendix 1 in study **II**). Thus, we were able to illustrate the views of logging and timber-hauling entrepreneurs considering idle times. Successful validation of the responses with non-response follow-up indicated the survey data of study **II** was sufficiently comprehensive to capture the views and expectations of the logging and timber-hauling enterprises regarding idle times.

The data for study **III** included machine data from three years, covering a total of 28 harvesters and 23 forwarders from the same forest machine manufacturer. The data used was considerably larger compared to previous studies focusing on idling of forest machines (e.g., Nordfjell et al. 2003; Ringdahl et al. 2012; Viklund 2012; Polowy and Molińska-Glura 2023) (Table 5). However, the data included only ten enterprises, which was rather low number compared to the number of 1,900 representing the total number of logging enterprises operating in Finland (Koneyrittäjät 2025). Nevertheless, the data collection period was approximately three years, thus enabling data collection from varying operating conditions.

Table 5. Comparison of different studies that have investigated idling of forest machines regarding the number of machines, average proportion of idling time reported, and average idling fuel consumption reported. Values marked with an asterisk represent the mode of the level of idling estimated by Finnish logging entrepreneurs.

Study (Publication year)	Machine type	Number of machines	Reported idling time (%)	Reported idling fuel consumption (L h^{-1})
Nordfjell et al.	Harvester	-	-	-
(2003)	Forwarder	2	-	2.0
Viklund	Harvester	1	22.0	2.8
(2012)	Forwarder	-	-	-
Ringdahl et al.	Harvester	-	-	-
(2012)	Forwarder	1	21.0	2.0
Polowy and Molińska-Glura	Harvester	2	14.7	-
(2023)	Forwarder	-	-	-
Study **II**	Harvester	-	2–5*	-
(2025)	Forwarder	-	2–5*	-
Study **III**	Harvester	28	14.0	4.3
(2026)	Forwarder	23	11.1	3.4

* Median of the estimations from Finnish logging entrepreneurs.

Although the self-reported estimates in study **II** lacked verification, they revealed attitudes and organizational perspectives that are important when reducing idling. Study **III**, on the other hand, provided objective and high-resolution values regarding idling times based on several forest machines, thereby overcoming the accuracy limitations inherent in perception-based estimations. However, automatically collected machine data tends to ignore the enterprise-specific factors, such as motivation for reducing idling. Therefore, a combination of objective values (Study **III**) and organizational perspectives (Study **II**) provided holistic view of the prevailing levels of idling times in forest machines as well as the opportunities to reduce idling.

A scenario approach was also used in study **III** to depict the impact of idling on CO_2 emissions and operating costs. The cost calculations were based on predefined, assumed cost parameters and input values (see Appendix 1 in Study **III**), which may lead to differences when compared to, for instance, a specific machine cost calculation for a single machine or entrepreneur. However, similar method for cost calculations has been used in recent studies: for example, Ahtikoski et al. (2024) calculated machine-specific costs of CTL harvesting and Kemppainen et al. (2025) calculated the cost-efficiency of mechanized excavator-based forest tree planting. The scenarios of study **III** (cf. Table 3) were based on the idling reduction opportunities identified in study **II**. Furthermore, the CO_2 emission and cost savings depicted in study **III** highlighted that the benefits of lower idling times from the point of view of decarbonization are undeniable.

Challenges and opportunities with alternative powertrains

A decade ago, electrified NRMM were estimated to become more common (Karner et al. 2014). Recently published research by Kalociński (2022) forecasted that NRMM hybridization is expected to be rapid, and the share of hybrid-powered machines may increase significantly. In industrial and construction environments, more interest is aimed at full-electric machinery, since the machines operate in smaller areas and thereby enable fluent recharging. For instance, several battery-electric wheel loaders and excavators are currently available on the market and ready for operations (Caterpillar 2026; LiuGong 2026; Volvo Construction Equipment 2026). Cable powering could also be a suitable solution for industrial machinery that operate stationary or in smaller areas (Carlson and Arellano Divina 2024), such as cranes (Alasali et al. 2017; 2019a; 2019b). Due to the limited grid connection, cable powering cannot be used on machines that operate in disperse areas, such as forestry or agricultural machinery. Therefore, battery technology is currently the most common full-electric solution for NRMM in general (Antila et al. 2025).

Longer life cycle expectation of an electrified powertrain under a suitable environment indicates requirements for further development with battery technology (Honkanen 2023; Fairuz et al. 2026). Hence, the evaluation of feasibility and potential of batteries should focus on reliability, costs, and life cycle of batteries (Buning 2010; Lajunen et al. 2018; Jun et al. 2018; Fu et al. 2020b; Khan and Huang 2023; Malozyomov et al. 2025) as well as compact implementation without an increase of the total weight (Lin et al. 2020). Especially in environments with varying trafficability, such as forestry and agricultural environments, the weight caused by batteries can be a major challenge. Thus, electrifying forestry and agricultural machinery can be seen as more challenging compared to, for instance, road transportation (Scolaro et al. 2021).

Since there are still challenges and barriers in electrifying NRMM, renewable fuels offer a low-emission solution, most of which can be used in the existing engines instead of conventional diesel (Remmele et al. 2014; Neste 2023a). For instance, AGCO Power (2025) has developed a new series of diesel engines that are currently compatible with HVO fuels and may in the future be adaptable to other alternative fuels, such as biogas. However, biofuels may increase the fuel or energy consumption compared to diesel (Athanassiadis 2000; Emberger et al. 2021; Matijošius et al. 2022). Still, biofuels could serve as a practical solution towards cleaner NRMM operations. Given that Finland, for instance, plans to expand its biofuel distribution obligation (Pihlatie et al. 2022), biofuels could gain even more relevance. Consequently, the proportion of renewable fuels would increase in road transportation and NRMM operations. However, the production rate of biofuels is currently low, increasing transportation costs considering, for instance, agricultural operations (García et al. 2019; Honkanen 2023). Therefore, investing in biofuel production could strengthen domestic expertise and provide a low-emission alternative for the existing diesel-powered NRMM fleet (European Commission 2025).

Biogas could also be a potential alternative for diesel in terms of emissions reduction. According to Börjesson et al. (2014), the advantages of biogas are mainly based on the utilization of waste streams for which there are otherwise fewer alternative uses. In Finland, LBG is currently more frequently used powertrain in road transportation, as its positive effects on environmental friendliness have found to be undeniable (cf. Huuskonen et al. 2025). One important feature that supports the usage of biogas in heavy-duty trucks is refueling infrastructure, which is under continuous improvement (St1 2025). Currently, there are already several LBG-powered heavy-duty truck options available (e.g., Scania 2026; Volvo Trucks 2026a).

NRMM operations are usually located outside refueling infrastructure, which is one reason for the lack of biogas-powered heavy-duty NRMM. The development of biogas solutions in NRMM has progressed more in agricultural machinery (i.e., tractors), than in other NRMM (e.g., Härkönen 2010; Konepörssi 2022), since the availability of the feedstocks for local small-scale biogas production is better in the countryside. Moreover, Finnish farms have shown interest in improving self-sufficiency through biomethane production (Pihlatie et al. 2022). Still, small-scale biogas production tends to be less viable than large-scale production due to higher production costs and thus less affordable fuel (Baker et al. 2022). Thus, regardless of the clear environmental benefits, the applicability of biogas in NRMM remains limited.

With hydrogen, it is possible to maintain the same performance compared to diesel engines during NRMM life cycle (Martini et al. 2022). One of the main challenges with hydrogen is the great energy consumption of hydrogen production, which requires a significant amount of electricity and lowers the overall efficiency (Neste 2023b). Due to these issues with production efficiency and costs, machine testing with hydrogen powertrain has focused on smaller NRMM (i.e., forklifts) (Miranda 2017; Haghi et al. 2020), although hydrogen-powered heavy-duty NRMM have already been under testing (Strabag 2025). The reason is that powering heavy-duty NRMM by hydrogen is expensive, and the lack of knowledge considering such technology maintains prudence regarding investments. Overall, hydrogen could be effective solution when decarbonizing NRMM, but widespread adoption depends on further development in clean production, infrastructure, and cost reduction.

Augmenting the focus of idling activities

Logging entrepreneurs may tend to underestimate the idle times of their fleet. Study **II** showed that most of the logging entrepreneurs estimated the idle times of their fleet to be less than 10% of the total operating time. In study **III**, on the other hand, idle times of less than 10% for both harvesters and forwarders were only in two of the ten enterprises (see Figure 6). According to Haavikko et al. (2019), machine operator skills are the most important factor that influence energy-efficient working methods. For instance, Rutty et al. (2013) found that operator training reduced daily average idling times by 4–10%. Consequently, machine operators should be encouraged to reduce idling, for example, by offering financial incentives for successfully reduced idling or fuel consumption (Lutsey et al. 2004). However, in Finland, the use of incentives to favor the reduction of idling time has been rather poor.

Despite the current idling times of forest machines being found to be too high, it is extremely difficult to remove all idling phases from forest operations. This is because operating conditions, such as air temperature or size of the harvesting site, vary between countries, and thus affect the potential to reduce idling in different parts of the world (Stodolsky et al. 2000). Total absence of idling could even be detrimental to operations, as some idling is needed to ensure the performance of the machines and the comfort of the operator (Rahman et al. 2013). For instance, forest machine manufacturers may recommend running the machine at idle for some time after operations to allow the engine to cool down sufficiently. Consequently, lack of awareness with regard to idling may distort entrepreneurs’ views on the situations where idling could be reduced and by how much.

Comprehensive planning of forest operations is crucial (Haavikko et al. 2022; Picchi et al. 2022). Within the wood harvesting chain, delays occur and miscellaneous working times are an inherent feature (Nurminen et al. 2006; Kärhä et al. 2018; Hildt et al. 2020; Papandrea et al. 2024). Nowadays, automated data collection can offer a practical way to identify unnecessary engine running time in forest operations. Relevant operational data can be used to improve the awareness of idling and consequently, improve the skills of the machine operators. As FMSs of forest machines provide accurate operational data (Ovaskainen and Kivilinna-Korhola 2016), it could be used to recognize the operation phases where idling could be reduced, such as preparing work for machine relocation (Kärhä et al. 2007; Väätäinen et al. 2021). However, unproductive working hours may occur due to challenging operating conditions or in harvesting sites with abundant undergrowth. Thus, reducing idling should start from high-quality forest management, which is one of the key factors that drive sustainable and efficient operations (Schweier et al. 2019; Kärhä et al. 2023).

In Finland, the emissions reduction goal of NRMM in the next decade would mean a reduction of around 70,000 tons annually for forestry machinery (Ministry of the Environment 2025). In this thesis, it was found that reducing idling by, for instance, 25% would cover around 4% of the required emissions reduction (cf. Figure 9). However, better performance and lower emissions are usually two desired outcomes of lower idling times (Spinelli and De Arruda Moura 2019), which means that at least some of the operating hours saved through reduced idling time must be transferred into productive working hours. Since fuel consumption during productive working time is approximately quadruple compared to idling fuel consumption, transferring idling time into productive working time would increase CO_2 emissions. However, while the amount of wood harvested would also increase, CO_2 emissions per cubic meter would remain at the same level. From the larger perspective, the greater amount of harvested wood resulted from the conversion of idle engine hours into productive engine hours could contribute positively to climate change mitigation, as the potential to replace, for instance, fossil fuels and plastic with wood-based products would increase.

In addition to CO_2 emissions, idling has a major impact on operating costs, especially depreciation and fuel costs. These are strongly associated with operating hours; as unnecessary engine running time is decreased, the need for maintenance occurs less frequently, and thus extends the life cycle of the machine. Furthermore, idling time could increase the number of productive working hours, which would raise revenue and profitability of the operation. In the long-term, minimizing idling systematically contributes to lower operation costs, more efficient wood harvesting operations, and sustainable use of forest machinery.

Future prospects

Regarding alternative powertrains, forthcoming research should, in addition to improving charging infrastructure, cover new solutions to manufacture compact and energy-efficient batteries, as well as ensuring the functionality during operations. Future machine designs should also incorporate battery architectures that allow the integration of higher-capacity batteries into the same machines instead of lower-capacity batteries. This is because extending the charging network in forestry or the agricultural environment is challenging, making battery technology necessary under those operational environments in terms of electrification. Although reliability issues with batteries under extreme conditions still arise (Lin et al. 2020; Khan and Huang 2023), making the batteries more feasible in various conditions would improve the applicability of the electric NRMM fleet.

Current challenges with biofuel and biogas solutions include a low production and the availability of the fuel (Owczuk et al. 2019; García et al. 2019), affecting especially forestry and agricultural machinery due to the more dispersed operation area compared to industrial machinery. Thus, further research should concentrate on biofuel and biogas production, which is followed by technology implementation and infrastructure improvements. Furthermore, lowering the price of biofuels would help maintain profitability of, for instance, wood harvesting operations, since fuel costs of forest machines account for a noticeable share of the total operating costs (see Figure 9). For hydrogen, upcoming research should focus on improving the profitability of the manufacturing and distribution processes as well as reducing technology costs (Venäläinen et al. 2021). After this, the willingness to implement hydrogen technology into NRMM would be greater and thus, the technology development would take a further step.

In addition to alternative powertrains, several studies have highlighted ways to improve the efficiency of logging operations (e.g., Prinz et al. 2018; Haavikko et al. 2022; Kärhä et al. 2023). Nevertheless, there are still research gaps and a need for research information. One possible step to reduce the impact of idling periods may be stop-and-go systems, which already exist in passenger cars and trucks (Volvo Trucks 2017). This could be a possible innovation in the future with forest machines (Kangas et al. 2023). However, especially in Nordic countries, frequent cold starts caused by harsh operating conditions and safety issues due to automatic shutdowns can prevent the application of stop-and-go systems in forest machines. These challenges could be mitigated through, for instance, electrifying auxiliary systems, more robust batteries and starter systems, as well as with hybrid powertrains, which would improve reliability and safety of the operations. Thus, further investigation of the potential to reduce idling in other NRMM, as well as in road transportation fleets is needed in the future.

Since the machine operator has a significant effect on efficient operations (Haavikko et al. 2022; Kärhä et al. 2024), it is recommended that future operator training is expanded to also cover comprehensively the effects of idling. For instance, simulator training is one option to improve the learning process of the operator (Polowy and Rutkowski 2024). However, the skills acquired by simulator training most likely differ from the actual working environment (Burk et al. 2023; 2024). According to Pagnussat et al. (2021), the results of operator training become visible after approximately nine months of comprehensive training. Consequently, persistent training should be from the entrepreneurs' point of view and applied to each operator (Kavanagh and Ashkanasy 2006).

CONCLUSIONS

This dissertation explored the possibilities for decarbonizing NRMM especially in the forestry sector, providing novel information for accelerating low-emission wood harvesting operations. The findings of the three scientific articles comprised in this dissertation contribute to a broader and more comprehensive understanding of the measures and solutions to reduce the emissions in forestry operations. Study **I** mapped the potential of alternative powertrains in heavy-duty NRMM globally and reported the most promising solutions for decarbonizing forest machinery. Studies **II** and **III** highlighted the possibilities to decarbonize wood harvesting operations through minimizing idling times of forest machinery and timber trucks.

Developing alternative powertrains to achieve the globally set emission reduction objectives can eventually replace diesel engines, if the profitability of manufacturing, implementation, and reliability are improved. Especially NRMM electrification has faced major interest in the industrial environment, aiming to derive the positive effects of low-emission and energy-efficient operations in forestry and agricultural machinery. Utilizing renewable fuels can also lead to more sustainable NRMM operations due to their ability to reduce emissions. Hence, future research should focus on the improvement of the implementation of alternative technologies as well as the improvement of the manufacturing infrastructure in NRMM operations.

In addition, lower idle times could eventually lead to lower operating costs, as well as more environmentally friendly operations. To gain benefits from lower idle times, the ability of the operators to incorporate more efficient working methods must be improved through operator training. To promote these positive effects, awareness of idling must be improved among loggers and timber-haulers, as well as among their machine operators and truck drivers. However, the achievement of lower idle times requires continuous and long-term leadership, where the data provided by the FMSs, combined with communication including data-based constructive feedback and motivated incentives between the forest SMEs and their operators and drivers, can result in noticeable benefits. Once increased attention is paid to idling, logging and timber-hauling can be conducted more efficiently, thereby leading to lower fuel consumption and GHG emissions. If the actions towards lower idle times were extended to the entire NRMM fleet globally, the results would be even more promising.

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