Toward Sustainable Forestry Logistics: Assessing Energy Infrastructure Accessibility in Northern Sweden

Mathilda Nilsson

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Swedish University of Agricultural Sciences, SLU
Department of Forest Biomaterials and Technology
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Mot hållbar skogslogistik: En studie av energi-infrastrukturens tillgänglighet i norra Sverige

Mathilda Nilsson

Supervisor:	**Justin Herdegen, Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology**
Examiner:	Dimitris Athanassiadis, Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology

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Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Department of Forest Biomaterials and Technology

Abstract

Climate change is a global challenge, and the European Union has set a target of achieving net-zero greenhouse gas emissions by 2050. The forestry sector contributes to these emissions using fossil-fuel-powered machinery. Electrified forestry machines are currently under development as a potential solution, but a major challenge is the lack of suitable energy supply infrastructure in remote forest environments. This study aims to investigate how existing energy infrastructure could be used to spatially support electrified forestry operations in remote areas of northern Sweden. In addition, the study evaluates the applicability of satellite-detected harvesting data from the Swedish Forest Agency for spatial analyses of forestry activities.

The analysis focuses on a study area in northern Sweden located between Örnsköldsvik and Lycksele. Data on harvesting from the forestry company Holmen was combined with satellite-detected harvesting polygons from the Swedish Forest Agency. Distances from harvesting sites to existing public charging stations and sawmills were calculated using the OpenRouteService routing engine to assess the accessibility of potential energy supply locations.

The results show that in the study area between Örnsköldsvik and Lycksele, 46% of harvested sites from 2022–2025 are within 20 km of a public charging station, while 14% are more than 40 km away. When analyzing proximity to sawmills, 81% of the sites are located more than 40 km away, while only 4% are within 20 km. These findings indicate that public charging stations are generally more geographically accessible than industry, although sawmills could potentially be better adapted to meet the specific energy demands of the forestry industry. The study assumes that mobile charging stations could be charged within the existing infrastructure network and then transported to harvesting sites. In this context, sawmills could function as more specialized energy hubs, while public charging stations may play a broader role in covering geographic demand.

Overall, the results highlight both the opportunities and limitations of the current infrastructure network and provide a methodological framework for analyzing energy supply accessibility for electrified forestry operations. The proposed approach can be applied to larger geographical areas and support future planning of energy infrastructure for electrified forestry machinery.

Keywords: Electrified forestry, Spatial analysis, Remote forest operations, Energy infrastructure accessibility

Sammanfattning

Klimatförändringar utgör en av vår tids stora globala utmaningar, och Europeiska unionen har som mål att uppnå nettonollutsläpp av växthusgaser till år 2050. Skogssektorn bidrar till dessa utsläpp genom användningen av maskiner som drivs med fossila bränslen. För att minska dessa utsläpp lyfts elektrifiering fram som en möjlig lösning. I dagsläget finns det i mindre skala både hybridvarianter av elektrifierade skogsmaskiner och ett antal prototyper under utveckling. En central utmaning är dock bristen på lämplig energiförsörjningsinfrastruktur. Syftet med denna studie är att undersöka hur befintlig energiinfrastruktur rumsligt skulle kunna stödja elektrifierade skogsbruksåtgärder i ett område i norra Sverige. Studien utvärderar även användbarheten av satellitskannade avverkningsdata från Skogsstyrelsen för rumsliga och temporära analyser.

Analysen fokuserar på ett studieområde beläget i norra Sverige mellan Örnsköldsvik och Lycksele. Avverkningsdata från skogsföretaget Holmen kombinerades med satellitskannade avverkningar från Skogsstyrelsen. Avstånd från avverkningsplatser till befintliga allmänna laddstationer och sågverk beräknades med hjälp av rutverktyget OpenRouteService för att bedöma tillgängligheten till potentiella platser för energiförsörjning.

Resultaten visar att inom studieområdet mellan Örnsköldsvik och Lycksele ligger 46 % av avverkningsplatserna från åren 2022–2025 inom 20 km från en publik laddstation, medan 14 % ligger mer än 40 km bort. När avståndet till sågverk analyseras visar resultaten att 81 % av avverkningsplatserna ligger mer än 40 km bort, medan endast 4 % ligger inom 20 km. Detta visar att publika laddstationer generellt är mer geografiskt tillgängliga än industrin. Samtidigt kan sågverk ha bättre förutsättningar att anpassas efter skogsbrukets specifika energibehov. I studien antas att mobila laddlösningar kan användas, där energi laddas vid befintlig infrastruktur och sedan transporteras till avverkningsplatserna. I ett sådant system skulle sågverk kunna fungera som mer specialiserade energinoder, medan publika laddstationer kan bidra till att täcka det geografiska behovet av energi.

Sammantaget belyser resultaten både möjligheterna och begränsningarna i det nuvarande laddinfrastrukturnätet och bidrar med ett metodologiskt ramverk för att analysera tillgängligheten av energiinfrastruktur för elektrifierade skogsmaskiner. Den föreslagna metoden kan tillämpas på större geografiska områden och bidra till framtida planering av energiinfrastruktur för elektrifierade skogsmaskiner.

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Abbreviations

API	Application Programming Interface
CRS	Coordinate Reference System
GIS	Geographic Information System
HPR	Harvester Production Reports
NOBIL	Norwegian EV charging database
ORS	OpenRouteService
SKS	Swedish Forest Agency (Skogsstyrelsen)
SLU	Sveriges lantbruksuniversitet (The Swedish University of Agricultural Sciences)
SWEREF 99 TM	Swedish Reference Frame 1999 (EPSG:3006)
VO	Worksite identifier (timber order number)
WGS84	World Geodetic System 1984 (EPSG:4326)

1. Introduction

Climate change poses a global challenge, and the European Union is proactively developing legislation and strategies to address this issue. The European Climate Law (EU Regulation 2021/1119) establishes a legally binding target for the European Union to achieve climate neutrality by 2050, implying a phase-out of fossil fuel-related emissions (European Union 2021). Several sectors contribute to greenhouse gas emissions, thereby negatively impacting the climate. One of these is the forestry sector, which primarily uses machines powered by fossil fuels. (Antila et al. 2025).

Wood products constitute a global commodity with diverse applications and are also classified as a renewable resource, capable of substituting other fossil-based products. For nations possessing extensive forest areas, forestry can play a significant role in economic development. Sweden is among these countries, with approximately 68% of its land covered by forests (SCB 2020), which have been managed since the 17th century (Holmberg 2005). As a result, forest-derived raw materials have been an essential resource for the country, contributing to its economy and public welfare (Skogsindustrierna 2025). In 2023, the total volume of harvested timber in Sweden reached 88.9 million cubic meters (Skogsstyrelsen n.d.)

According to data and statistics from the Swedish Environmental Protection Agency (Naturvårdsverket), CO_2 emissions from non-road working machines have decreased by approximately 2% between 1990 and 2024. However, the forestry sector accounted for around 14% of the CO_2 emissions from non-road working machines, and is therefore one of the most significant sectors in that category (Naturvårdsverket 2025). To reduce fossil fuel use, there is a need to transition to renewable fuels. The sole currently available commercial alternative is HVO (hydrogenated vegetable oil), which can be used in drop-in fuel. However, this is not regarded as a sustainable long-term solution, given that production at the required scale cannot be achieved sustainably and it remains relatively costly (Naturvårdsverket 2022).

The reduction of fossil fuel use in private vehicles is being achieved on a larger scale through electrification. For the working machines, electrification has not been widespread for long due to challenges with large, heavy batteries and a non-existent charging infrastructure. There is ongoing work to address the battery issue for the machines, and then the supply system needs to be addressed and prepared for (Naturvårdsverket 2022). To implement a transition to an electrified forestry industry, access to electricity is crucial. Since work takes place in various locations

at varying distances from communities with well-developed road and power grid infrastructure, access to power is a challenge. (Antila et al. 2025).
As highlighted by the Swedish Environmental Protection Agency and Antila et al., a major obstacle to the transition towards renewable and low-emission fuel options is the need for a decentralized energy supply system capable of supporting electrified working machines in forestry.

The aim of this study is to investigate potential configurations for future energy supply systems that could facilitate the transition to electrified forestry machinery and thereby reduce reliance on fossil fuels. In addition, the study seeks to improve the understanding of the spatial and temporal distribution of logging sites in northern Sweden by analyzing their geographic distribution in relation to the road network and the accessibility of existing charging infrastructure.

The study further aims to assess the validity and reliability of open-access forestry data by comparing it with company-provided datasets. By analyzing the spatial overlap and differences between these datasets, the study seeks to evaluate the extent to which publicly available forestry data can accurately represent actual harvesting activities. In addition, the study explores the spatial distribution of logging sites relative to existing infrastructure to support future analyses of energy-supply accessibility for electrified forestry operations. Based on these objectives, the research questions addressed in this thesis are:

- To what extent do open-access forestry data accurately represent harvesting activities?
- To what extent could existing charging infrastructure spatially support electrified forestry worksites in remote areas of northern Sweden?

The outline of this paper is as follows: Section 2 presents a review of relevant literature on the Swedish forestry transportation system, the logistics of forest machinery, and previous research on the transition toward electrified forestry operations, highlighting the research gap. This section describes current forestry practices and existing research in the field and concludes with analytical methods for the spatial analysis of energy infrastructure. Section 3 presents the datasets used in the study and describes the methodology applied to investigate the conditions required to support electrified forestry machinery through accessible energy supply infrastructure. In Section 4, the results are presented and discussed, focusing on the key conditions identified and the potential of existing charging infrastructure to support electrified forestry worksites. Finally, Section 5 summarizes the study's main conclusions and suggests directions for future research.

2. Background

The purpose of this literature review is to provide an overview of the current logistics of forestry operations and to examine the present state of electrification within the forestry sector. In addition, the review summarizes existing research related to electrified forestry machinery and energy supply systems, with the aim of identifying key findings as well as existing knowledge gaps in the field. By reviewing previous studies, the section aims to establish the current state of knowledge and provide a foundation for the subsequent analyses presented in this thesis.

The literature review is structured into five subsections, each addressing key aspects relevant to the research topic. The first subsection provides an overview of the current logistics of forest raw materials. Building on this, the second subsection describes the operational logistics of forestry machinery and the main types of forestry operations carried out in forest management. The third subsection then presents an overview of the potential energy demand required to supply forestry machinery in a future electrified system. The fourth subsection subsequently reviews existing research related to the electrification of forestry operations and highlights current developments within the field. In addition, this section aims to identify existing knowledge gaps and areas where further research is needed. Finally, the fifth subsection introduces analytical approaches that can be used for the spatial analysis and mapping of energy infrastructure for forestry operations.

2.1 Transportation of forest biomass in Sweden

The transportation system for roundwood and forest biomass is highly complex, encompassing numerous factors, including transportation infrastructure, weather variability, technological considerations, raw material characteristics, and handling and storage procedures. To analyze and optimize this system, various analytical methods have been applied, including linear programming, heuristic approaches, and simulation techniques. The Swedish transport system is characterized by long transport distances and a strong reliance on truck-based road transport for short- and medium-distance haulage, while rail transport is primarily used for the longest distances (Väätäinen et al. 2021).

According to Davidsson et al. (2024), the average transport distance from forest to industry in Sweden is approximately 91 km. Transport distances are generally longer in northern Sweden, where the average distance is about 130 km for sawlogs. In Norrland, around 25.5 million tons of forest raw material are transported annually. Most forest biomass is collected at the harvesting site and transported directly to industry, while a smaller share is delivered to railway terminals or intermediate storage facilities before onward transport. The same report, based on data from 2013–2022, further shows that the entire Swedish road network is utilized for forest transport. National and regional roads are the most frequently used, followed by motorways and European roads. The results also indicate that approximately 94% of forest transport operations took place on the public road network during the ten-year period (Davidsson et al. 2024)

Both Väätäinen et al. (2021) and Davidsson et al. (2024) note that policies allowing heavier trucks has been implemented, enabling increased load capacities and a reduction in total transport distances. This development offers considerable environmental benefits. At the same time, the use of heavier vehicles places higher demands on transport infrastructure, particularly with respect to bridge capacity. They further note that forest biomass accounted for approximately 12% of the total transport work performed by Swedish-registered trucks, underscoring the importance of a well-functioning and robust road network.

Overall, the literature highlights that the Swedish forestry transportation system is characterized by long transport distances and a strong reliance on road-based logistics. Forest biomass is typically collected directly at harvesting sites and transported to industrial facilities through an extensive road network that includes both public and private roads. These logistical characteristics illustrate that forestry operations are already adapted to operating across large spatial scales. Consequently, when considering a transition towards electrified forestry machinery, the spatial distribution of worksites and the associated transport distances become important factors for the planning of charging infrastructure. Energy supply solutions will therefore need to be integrated with the existing machine and transport logistics to ensure that energy can be provided close to or directly at the harvesting sites.

2.2 Machine logistics and operating in forestry

In Sweden, forestry operations are predominantly mechanized and commonly based on a two-machine system consisting of a harvester and a forwarder. In this system, the harvester fells and processes trees into optimized assortments based on predefined price lists, after which the forwarder loads and transports the timber to roadside landings (Skogsskötselserien 20: Final felling, 2014).

It is common that harvesting operations are carried out in teams consisting of the harvester and forwarder, operated by separate drivers. In many cases, these machines are owned and operated by independent contractors who perform harvesting services on behalf of forest companies, although some companies also own and operate machinery themselves (Bredström et al. 2010; Eriksson & Lindroos 2014)

The forest machinery typically operates in remote areas, far from populated communities, and frequently relocates between worksites due to the temporary nature of harvesting operations, where project durations can vary greatly. When worksites are not located in close proximity, machines are commonly transported between sites using trailers (Bredström et al., 2010, *Skogsskötselserien 20: Slutavverkning* 2014).

Machine teams are assigned to harvesting sites based on factors such as geographical location, assortment composition, and accessibility. This allocation is commonly facilitated by a tract bank, which comprises a pool of inventoried stands available for final felling or thinning. The tract bank supports medium-term operational planning, where harvesting activities are typically scheduled approximately one to two months in advance (Nilsson et al. 2013; Nilsson et al. 2017)

In conventional forestry operations, fuel supply to forest machines is handled on-site as part of daily operations and is typically managed by the machine contractors. Timber is subsequently transported by truck from roadside landings to industrial facilities, railway terminals, or other intermediate storage locations as part of the downstream forest supply chain (D'Amours et al. 2008)

2.3 Factors that affect the fuel consumption

Fuel consumption in fully mechanized cut-to-length (CTL) harvesting operations is influenced by several operational and machine-related factors. A study by Eliasson (2024), based on machine data collected from Swedish logging operations, analyzed fuel consumption in harvesters and forwarders under different harvesting conditions. The results show that the type of harvesting operation is an important factor influencing fuel consumption. In general, fuel consumption is higher in thinning than in final fellings due to lower productivity and smaller average stem volume. According to the study, the average fuel consumption in Swedish logging operations was approximately 1.7 L of diesel per m^3fub in 2022, with 2.73 L/m^3fub in thinning and 1.4 L/m^3fub in final felling. Eliasson further notes that, in addition to harvesting type, several machine- and site-related factors influence fuel consumption. For forwarders, important factors include forwarding distance, payload size, and removal intensity. For harvesters, fuel consumption is mainly affected by the harvester class, the number of trees per cubic meter, and the harvested volume per hectare. Further analysis of fuel consumption in Swedish logging operations was conducted by Eliasson, Kärhä, and Arlinger (2023), who examined machine performance and fuel use across different harvester and forwarder size classes. Their results show that fuel consumption varies significantly with machine size. Smaller harvesters consume around 1.5–1.6 L/m^{3}fub, whereas larger harvesters consume approximately 0.7 L/m^{3}fub, although their hourly fuel consumption is higher (about 19 L/h compared with 13 L/h for smaller machines). A similar pattern is observed for forwarders: smaller machines (<10 m^3 load capacity) may consume up to 1.2 L/m^{3}fub, while larger machines consume around 0.7 L/m^{3}fub, but with higher hourly fuel consumption (14–15 L/h compared with 9–10 L/h). Overall, fuel consumption in CTL harvesting operations in Sweden typically ranges between 1.4 and 3.4 L per m^{3}fub, depending on harvesting conditions, machine size, and forwarding distance. Operator technique may also influence fuel consumption, although these effects are more difficult to quantify.

A complementary perspective is provided by Skogforsk (2024), which analyzed the energy demand of harvesters and forwarders through a detailed energy mapping of typical forestry operations. The results show that forwarders consume most of their energy during machine driving, as they transport timber loads across uneven terrain, whereas harvesters primarily use energy in hydraulic systems operating the crane and harvesting head. This reflects the different operational roles of the two machines within CTL harvesting. These findings indicate that the energy demand of forestry machinery is strongly influenced by both operational conditions and machine characteristics, which has important implications for the design of energy supply systems for electrified forestry operations.

2.4 Electrification of forestry machinery

In their study, Antila et al (2025), examine electricity as a renewable energy resource with the potential to replace fossil fuels currently used in forestry machinery. Electricity may be supplied either directly from the existing power grid or indirectly through stored energy in battery-based storage systems. It is assumed that electricity can be generated from existing renewable sources, such as wind power or solar energy, to charge batteries that are subsequently stored at fixed battery facilities. The authors argue that the technology required to manufacture electrically powered forestry machines is largely mature, and that the primary barrier to large-scale implementation lies in supporting energy infrastructure. They further evaluate several potential energy supply scenarios, including off-grid solutions based on wind power, solar panels, and battery storage. Given that forestry operations are characterized by frequently relocating worksites, the authors emphasize the importance of mobile energy solutions, such as mobile charging stations or battery container systems. Battery exchange concepts are also discussed; however, these solutions are recognized as potentially costly and operationally complex.

In a preliminary study, Skogforsk (2024), investigated different design concepts for harvesters and forwarders with regard to energy consumption, climate impact, resource depletion, and cost. Four conceptual machine configurations were analyzed: hybrid-electric and fully battery-electric concepts for both harvesters and forwarders. The hybrid concepts combined a combustion engine with electric components, while the battery-electric concepts relied on significantly larger battery systems to power the machines. The concepts were designed to maintain performance comparable to machines used in final felling operations.
For the battery-electric concepts, the estimated battery capacities were approximately 500 kWh for forwarders and 750 kWh for harvesters, which were considered sufficient to support around 8 hours of operation under typical Swedish harvesting conditions. These estimates are broadly consistent with the findings of Norouzi et al. (2025), who estimated a daily energy demand of approximately 486 kWh for a 9.2-hour work shift. This similarity suggests that the energy demand of forestry machines during a full working shift may be in the range of several hundred kilowatt-hours.

Further insights into the energy requirements of electrified forestry machinery are provided by Norouzi et al. (2025), who simulated electrification scenarios using operational data from a Ponsse forwarder operating under off-grid conditions. The authors analyzed different charging concepts, including mobile charging stations and battery swapping systems, to estimate energy demand, charging time, and associated economic impacts. Based on operational data from a 9.2-hour work shift, the results indicated that the studied forwarder would require approximately 486 kWh of energy per working day, corresponding to an average power demand of around 53 kW during operation. Two potential battery technologies for electrified forestry machines were evaluated: Lithium Iron Phosphate (LFP) batteries and Lithium-ion Solid-State Batteries (SSBs). Based on the available battery volume in the machine, the estimated battery capacities were 189 kWh for the LFP system and 441 kWh for the SSB system. Given the daily energy demand of approximately 486 kWh, the LFP battery would require around three charging events per working day, whereas the SSB battery would require approximately one recharge per day. These results highlight that, due to the high daily energy demand of forestry machinery, battery capacity strongly influences the operational feasibility of fully electrified machines.

The study also suggests that in operational scenarios where machines work consecutive shifts, and where downtime costs are critical, solutions involving high-capacity battery systems combined with high-power charging infrastructure may be preferable.

These findings mentioned above are also reflected in ongoing industrial developments. Several forestry machine manufacturers have begun developing hybrid-electric prototypes as an intermediate step toward full electrification of forestry machinery. For example, both Ponsse and Komatsu Forest have introduced prototype machines that combine electric drivetrains with conventional diesel engines. In these concepts, the electric drivetrain improves energy efficiency and enables partial electrification of machine functions while maintaining the operational reliability of a combustion engine (Ponsse Plc 2019; Komatsu Forest 2025)

The continued use of a diesel engine in these hybrid prototypes is largely related to the challenge of supplying sufficient electrical energy at remote harvesting sites. Forestry operations are often conducted in areas without access to the electricity grid, making it difficult to rely solely on battery-electric systems. Hybrid configurations therefore allow machines to benefit from electric powertrain technologies while still ensuring a stable on-site energy supply (Antila et al. 2025).

To supply energy in remote forest environments, Norouzi et al. (2025.) further propose mobile energy supply concepts. In the case of mobile charging stations, a delivery vehicle transports movable battery storage units with sufficient capacity to supply the machine’s full daily energy demand to the harvesting site. For battery swapping solutions, fully charged battery packs are transported to the site and exchanged based on the required number of battery swaps during the work shift. The study also discusses the cost of electricity supplied from the grid and potential strategies to reduce these costs.

As highlighted by Antila et al. (2025), several strategies have been proposed to support the electrification of forestry machinery. These include the use of stationary battery storage systems that can be charged slowly from the grid and subsequently deliver high power during machine charging. Additional strategies involve demand-response approaches, where charging occurs during periods of lower electricity prices, as well as local electricity generation through solar photovoltaic (PV) systems. The results indicate that although technological solutions for electrified forestry machinery are emerging, reliable energy supply infrastructure is still required to support operations in remote harvesting areas.

The study of Skogforsk (2024) further indicates that hybrid concepts could reduce operational CO_2 emissions by approximately 20–30% compared with conventional diesel-powered machines, while fully battery-electric machines could potentially eliminate most emissions during the use phase. In addition, rapid developments in battery technology and expected cost reductions may make battery-electric forestry machines economically competitive with conventional machines by around 2030, particularly in combination with increasing fuel prices. Finally, the authors highlight that a major challenge for electrified forestry operations is how to supply sufficient energy to remote harvesting sites, where access to the electricity grid is often limited.

Taken together, these findings highlight the substantial energy demand associated with electrified forestry operations and underline the importance of reliable energy supply infrastructure in remote harvesting areas.

2.5 Spatial accessibility analysis for charging infrastructure

Several studies have applied spatial optimization and network-based analysis to support the planning of electric vehicle charging infrastructure. For example, Frade et al (2011) analyzed the optimal placement of electric vehicle charging stations in a neighbourhood in Lisbon using a spatial optimization approach. Charging demand was estimated at the census-block level based on population, employment, and car ownership data, as well as the difference between residential (nighttime) and workplace (daytime) charging demand. A maximal covering location model was then applied to identify station locations that maximize demand coverage within an acceptable walking distance of approximately 400–600 m, while also considering capacity constraints of 2–10 charging points per station.

While Frade et al. focused on accessibility within a relatively small urban area, other studies have incorporated more detailed representations of transport networks and driver behavior. He et al. (2015) developed a spatial optimization model for charging station deployment within a road network using a tour-based network equilibrium approach, in which electric vehicle drivers are assumed to complete multiple sequential trips and may adapt their routes depending on the availability of charging infrastructure. The charging station planning problem was formulated as a bi-level optimization model, where the upper level determines the location and type of charging stations under a budget constraint, while the lower level simulates traffic flows and charging decisions in the transport network. The results show that optimized station placement can significantly reduce total travel and charging time, and that higher-power charging stations tend to attract more users due to shorter charging times.

Similarly, Dong et al. (2013) developed an activity-based modeling framework to analyze the deployment of public charging infrastructure using GPS-based travel data from 445 vehicles in the Seattle metropolitan area. In this study, real-world travel patterns, including trip distances, destinations, and parking durations, were used to simulate drivers' charging behavior. Potential charging locations were identified based on frequently visited destinations, and a genetic algorithm was used to determine the optimal placement and types of charging stations under budget constraints. The results show that the spatial distribution of charging infrastructure strongly influences the feasibility of electric vehicle travel, and that strategically located charging stations can significantly reduce range-related travel constraints.

Taken together, these studies demonstrate the importance of spatial accessibility, travel behavior, and infrastructure optimization when planning charging networks for electric vehicles. However, existing research has primarily focused on urban passenger transport systems, where travel patterns are relatively well defined and charging infrastructure can be connected to existing electricity grids. In contrast, the application of similar spatial accessibility analyses to forestry logistics and remote harvesting operations remains limited. Forestry operations are characterized by mobile worksites, large spatial variation in harvesting locations, and limited access to existing energy infrastructure, which creates different challenges for planning energy supply systems. Consequently, there is a need for spatial analyses that evaluate the accessibility of potential energy infrastructure in relation to the geographic distribution of forestry worksites, which is the focus of the present study.

3. Method

3.1 Study Area

The geographical scope of this study is confined to a selected region in northern Sweden. This delimitation is primarily based on the availability of comprehensive forestry data from a company, which enables a more reliable and spatially nuanced analysis than is possible with open-access data alone. The regions under study are representative of northern Sweden, where forestry activities occur in inaccessible areas, leading to longer transportation distances and inadequate infrastructure.

The study area used in the analysis is shown in Figure 1 below. The area extends from the coastal city of Örnsköldsvik to the city of Lycksele in northern Sweden. Major transport routes within the study area include the European route E4, a north–south highway along the Swedish east coast, the European route E12, an important east–west corridor and the Swedish national road 92, which links the coastal areas around Umeå with inland municipalities in Västerbotten.

Figure 1. Map of the study area in northern Sweden, extending from the coastal area around Örnsköldsvik to the inland region of Lycksele.

3.2 Data sources

The data used in this study include harvester production reports (HPR) from the forestry company Holmen, open-access forestry data from the Swedish Forest Agency, geospatial data on the road network from Lantmäteriet, and open data from NOBIL, the Norwegian Energy Agency's database of electric vehicle charging stations. An overview of the data sources, including their origin and spatial coverage, is presented in Table 1.

Table 1. shows a summary of the used datasets in the study, including their sources, data formats, spatial coverage and purposes.

Dataset	Source	Type	Coverage	Purpose
Swedish Forest Agency detected harvesting (2022 to 2025)	(Skogsstyrelsen 2025a)	GPKG	Sweden	Comparison analysis
Company harvester production reports, HPR (2022 to 2025)	(Holmen skog 2026)	HPR	Björna, Lycksele, Bjurholm	Reference data
Public charging stations	(NOBIL 2025)	JSON	Sweden	Distance to charging capacity
Sawmills in the Baltic region	(Dimitris Athanassiadis 2024)	SHP	Sweden	Distance to charging capacity
Road network	(Lantmäteriet 2019)	SHP	Sweden	Distance calculations

The Swedish forestry agency's open data

The Swedish Forest Agency (Skogsstyrelsen) is responsible for implementing national forest policy and providing information on Sweden's forest resources. As part of this work, the agency produces and publishes open datasets containing forest-related information that are regularly updated and publicly accessible (Skogsstyrelsen 2025b)

One of these datasets consists of detected final fellings derived from change analyses of satellite imagery. Since 2003, satellite-based change detection has been used to identify areas where forest harvesting has occurred. From 2022 onwards, this process has been automated, whereas earlier analyses were conducted manually (Skogsstyrelsen, 2025). In this analysis, detected harvest areas from the years 2022 to 2025 within the study area were used, as shown in Figure 2.

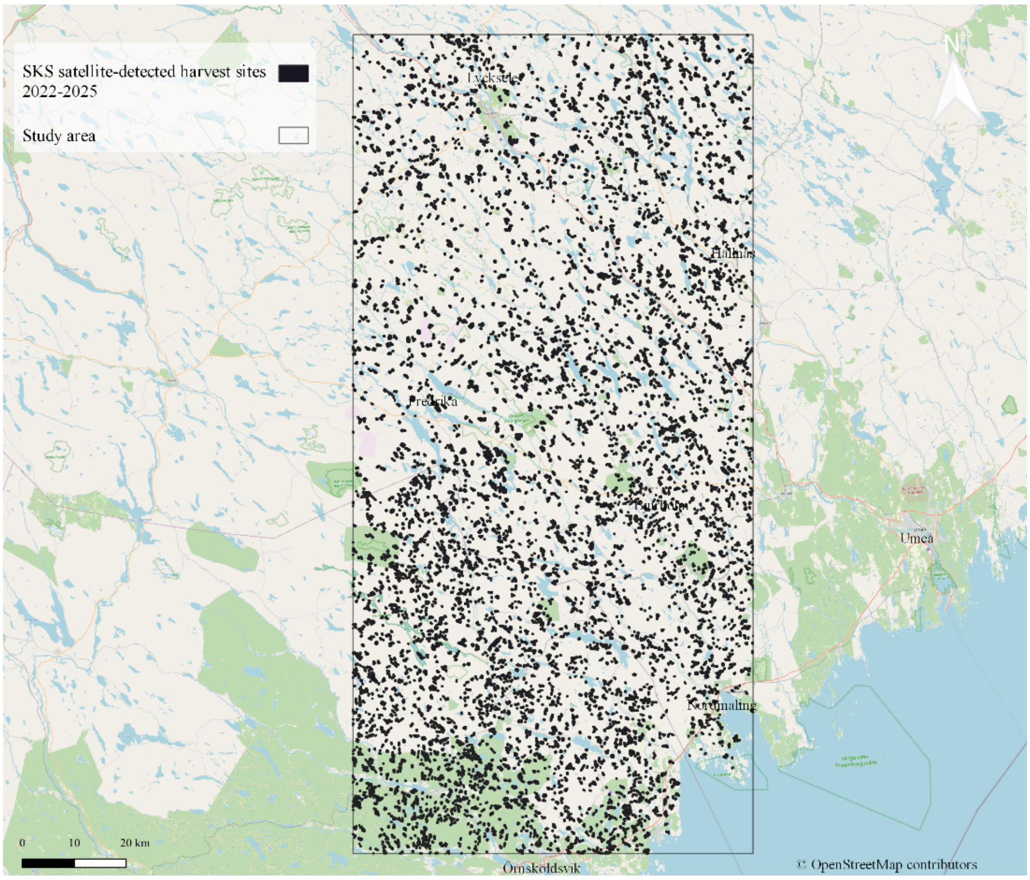

Figure 2. Map of the study area showing the distribution of satellite-detected harvesting sites from the Swedish Forest Agency. The detected harvest areas are distributed across the entire study area.

Company harvester production reports (HPR)

In the harvester computer, detailed information is recorded during harvesting operations for each individual tree that is cut. This information includes, among other variables, stem length, diameter, volume, stem identifier, harvesting timestamp, and geographic coordinates. The files are structured using an XML format (Möller et al., 2013).

To analyze these files, the software hprAnalys, an open tool developed by the Forestry Research Institute of Sweden (Skogforsk), was used. The tool enables processing, analysis, and aggregation of harvester production files (HPR) (Skogforsk n.d.). The harvesting sites used in this study are primarily located in the areas of Björna close to Örnsköldsvik, Bjurholm, and Lycksele. The spatial distribution of the sites within the study area is illustrated below in Figure 3.

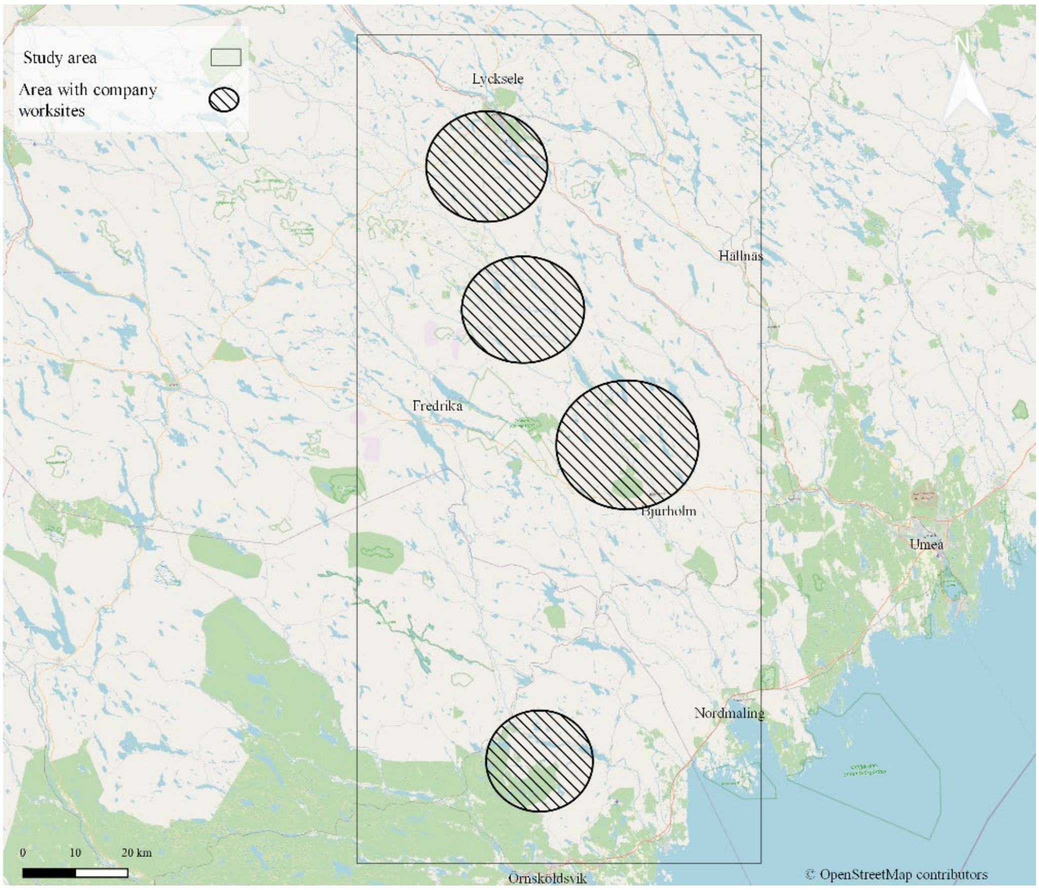

Figure 3. Map of the study area showing the locations of company worksites. The worksites are distributed within the area of Björna outside Örnsköldsvik and in the region between Lycksele and Bjurholm in northern Sweden.

The Norwegian Energy Agency's database of electric vehicle charging stations.

NOBIL is a publicly available database containing information on electric vehicle charging stations in Norway and Sweden. The database is owned by the Norwegian governmental agency Enova and maintained in Sweden by the Swedish Energy Agency (Energimyndigheten). It provides standardized data on charging station locations and characteristics and is widely used for analyses of charging infrastructure (NOBIL, 2025). Data on public charging stations in Sweden were retrieved from the NOBIL database through its API and downloaded as JSON format.

Lantmäteriet - Property map transport network

The road network data used in this study were obtained from the GSD-Fastighetskartan vector dataset provided by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet). The dataset is based on Lantmäteriets fundamental geographic databases and includes information on property boundaries, administrative features, topography, buildings, land cover, hydrology, and transport infrastructure (Lantmäteriet 2019). In this study, only the road network layers were used. These include public roads, private roads, and other road types such as minor roads and paths. The data are provided in the Swedish national coordinate reference system SWEREF 99 TM (EPSG:3006) and were used as input for road-network snapping and routing analyses.

Sawmill location data

The locations of sawmills were obtained from a dataset developed within the CEForestry project under the Interreg Baltic Sea Region programme. The dataset provides an inventory of sawmills across the Baltic Sea Region and was compiled using information from literature reviews, industry associations, and direct communication with sawmills (Dimitris Athanassiadis 2024)

In this study, only the spatial locations of sawmills in Sweden were used as input data for distance calculations.

3.3 Data processing

3.3.1 Data preprocessing

To ensure consistency across datasets, all spatial data were transformed to the same coordinate reference system, SWEREF 99 TM/EPSG:3006, to ensure reliability in the spatial analysis and distance calculations. The harvester production files (HPR) were converted to text format through the software hprAnalys, and then to Excel format, to allow further data processing. The Excel files were then standardised by normalising column names, converting coordinate and volume fields to numeric formats, and parsing harvesting timestamps to dates. From the converted HPR files, unique stem identifiers, along with their corresponding coordinates, worksite ID, and volume attributes, were read from each file to generate a GeoDataFrame with point geometries representing individual stems, which was then saved as a GeoPackage.

A compiled statistics table was then also generated from the HPR-converted Excel files to summarise company harvesting activity. All statistical data were linked to the worksites' unique timber order number (VO), which is used consistently throughout the analysis to connect attribute data to the specific worksites (harvest operation). For each VO, stem volumes (m^3sk) were aggregated to obtain the total harvested volume, and harvesting dates were summarised as the earliest and latest recorded harvest dates. The resulting statistical table was exported to an Excel file and additionally saved as a CSV file for subsequent analyses.

The Swedish Forest Agency GeoPackage of detected harvesting sites was clipped to the study area to reduce dataset size and include only the data required for the analysis. The same was done to the Lantmäteriet road network datasets.

3.3.2 Matching of company worksites and SKS polygons

To verify the reliability of the dataset of scanned final felling sites from the Swedish Forest Agency, a matching analysis was conducted in which the company's worksites were used as a reference and compared with the Swedish Forest Agency's data. This comparison was performed to assess whether the Swedish Forest Agency's dataset can be used for larger-scale analyses.

For this step, the stem point layer from the HPR files was subsequently used to generate a polygon layer for each worksite identifier, including associated attributes and area information representing the harvested area. To create continuous geometries from the point data, each stem point was buffered by 10 m. This buffering step helps close gaps that may occur between stems with larger spacing and ensures that neighbouring points form connected geometries.

The resulting buffered geometries were then processed with an explode operation to separate multipart geometries into individual polygons, allowing areas to be calculated correctly for each spatially distinct section. As worksites may consist of multiple disconnected areas, the polygons were subsequently grouped using a dissolve operation based on the worksite identifier to treat them as a single unit where necessary.

Since area attributes were not included in the original HPR files, area values were calculated for each polygon part and for the overall worksite area. The total worksite area was derived by summing the areas of all polygon parts belonging to the same worksite identifier. The polygons with attributes were stored as a GeoPackage.

The company worksite polygons were matched to the SKS clear-cut polygons using a spatial intersection approach. The company polygons, as mentioned earlier, were dissolved into a single geometry per worksite. Candidate matches were generated by overlaying geometries with SKS polygons and calculating the intersection area. For each candidate pair, overlap was quantified as the share of the company harvesting sites area covered by the intersection, and geometric similarity was scored using Intersection over Union.

Since the SKS polygons consisted of multiple geometries that in practice corresponded to a single company worksite, these fragments needed to be treated as a single unit when several candidates matched a company polygon. To address this, the SKS geometries were filtered using a minimum overlap threshold of 10% and an area ratio constraint requiring the SKS polygon area to be no more than 1.5 times the company worksite area. This ensured that geometries with only minor or incidental overlap, such as those slightly intersecting a road along the edge of a worksite, were not selected as matching candidates. The area ratio constraint also prevented unrealistically large polygons, which clearly did not represent the same worksite but could otherwise match due to spatial overlap, from being included in the matching process. Conflicts were resolved by assigning each SKS polygon to at most one company worksite, selecting the candidate with the highest Intersection over Union score, while allowing each company worksite to match multiple SKS polygons. Then, matched pairs were stored, and a layer was created by dissolving matched SKS geometries per company worksite.

3.3.3 Comparison between the SKS dataset and company worksites

Temporal comparison of felling dates
To evaluate the reliability of SKS harvesting dates, company HPR records were used as reference data, and temporal correspondence was assessed for worksites with a geometric match to SKS polygons. For SKS, the harvesting date was extracted for all matched polygons and aggregated to a company worksite-level date span defined by the minimum and maximum dates. Company dates were obtained from the earlier created statistics table in the same format as the SKS dates. If the end date was missing, it was set equal to the start date. To quantify temporal deviation, the company start date was compared against the SKS date span: the deviation was set to 0 days when the company start date fell within the SKS span; otherwise, it was calculated as the number of days to the nearest boundary of the span. To describe the seasonal distribution of harvesting, monthly activity distributions were derived for both the company and SKS datasets, using the geometrically matched worksites. A worksite was considered active in all calendar months covered by this interval, and the number of unique active worksites was counted for each month and visualised as monthly activity grouped by year.

Area comparison
To evaluate differences in estimated worksite size between datasets, the area of company worksite polygons was compared with the corresponding matched SKS polygons. The relative area difference was calculated as the percentage difference between the SKS polygon area and the company polygon area, using the company area as the reference (function 1). Positive values, therefore, indicate that the SKS polygon is larger, whereas negative values indicate that the company polygon is larger. Summary statistics were calculated to describe the distribution of area differences, including the mean and standard deviation of the percentage difference. In addition, the share of worksites with area differences within ±10% and ±20% was calculated to assess the level of agreement between datasets. The ±10% threshold was used to indicate close agreement between the two datasets, indicating that the mapped areas are highly comparable. The broader threshold of ±20% was included to capture matches that may still be considered reasonable given differences in delineation methods, spatial resolution, and the fact that the datasets were produced using different mapping approaches. Together, these thresholds

indicate both strict and more tolerant levels of spatial agreement between the company worksites and the SKS polygons.

Finally, the proportion of VOs where the SKS polygon area was larger or smaller than the company polygon area was reported.

Area difference:

$$D = \frac{As - Ac}{Ac}\ x\ 100 \tag{1}$$

D= difference (%)
As = area SKS-polygons (m^2)
Ac=area company-polygons (m^2)

Spatial overlap analysis

Spatial overlap between company worksites and SKS-detected polygons was quantified. Company polygons were dissolved to one geometry per worksite identifier, and the same was applied for the matched SKS polygon. For each matched worksite, the geometric intersection between the company polygon and the corresponding SKS polygon was computed, and the intersection geometry was dissolved per worksite to avoid double-counting of overlapping parts. Overlap area was calculated and expressed as the share of the company area covered by SKS polygons (Function 2), For completeness, the overlap was also expressed relative to the SKS polygon area (Function 3). To summarise overlap agreement, worksites were classified into three overlap categories based on overlap share: low (0–40%), medium (40–70%), and high (70–100%). The number and share of worksites in each category were reported. In addition, overall match coverage was summarised as the number and share of company worksites with at least one SKS polygon match.

Share of overlap – company

$$Oc = 100\ x\ Ia/Ac \tag{2}$$

Oc= Share of overlap (%)
Ia = inter area (m^2)
Ac = area company-polygons (m^2)

Share of overlap – SKS

$$Os = 100\ x\ Ia/As \tag{3}$$

Os= Share of overlap (%)
Ia = inter area (m^2)
As = area SKS-polygons (m^2)

3.4 Distance calculations

Company worksites distance calculations

To analyze the spatial conditions for energy supply within the study area, distances from harvesting worksites to the nearest public charging station and sawmill were calculated. Distance calculations were performed using the OpenRouteService routing API. Representative points derived from the worksite polygons were used as origin locations for the routing calculations. Since harvesting worksites are typically located within forest stands and not directly on the road network, each representative point was snapped to the nearest road segment prior to routing. The road network data were obtained from the Lantmäteriet transport network datasets.

Public charging stations were obtained from the NOBIL database and converted from JSON format to a spatial point dataset. To identify the nearest charging station for each worksite, a two-step approach was used. First, a nearest-neighbor spatial join based on Euclidean distance was performed to identify the closest candidate charging station using straight-line distance. This step was used to reduce the number of routing requests to the OpenRouteService API and is also described in the literature as a common strategy for identifying candidate locations for further, more precise analyses (Esri 2026).

After identifying the nearest charging station, the network distance and the distance from the worksite to the station were calculated using the OpenRouteService routing service with the profile driving-car. Because OpenRouteService requires geographic coordinates, both the representative worksite points and the charging station locations were transformed to WGS84 (EPSG:4326) prior to routing. The routing calculations produced estimates of road distance (m) from each worksite to the nearest charging station.

The same methodology was used to calculate distances to sawmills. The sawmill dataset was imported as a point layer. Some data cleaning was performed to avoid coordinate reference system (CRS) inconsistencies. Raw coordinate columns were removed, and a bounding box for Sweden was applied to filter out spatial outliers. The calculations resulted in the driving distance in meters to the nearest sawmill.

To analyze spatial accessibility, the resulting distances were summarized using distance distributions and cumulative distance distributions. In addition, area-weighted cumulative distributions were calculated to account for differences in harvested area between worksites. Worksites were first sorted by increasing routing distance to the nearest destination. The cumulative share of harvested area was then calculated according to Equation 4. This approach ensures that larger harvesting sites contribute proportionally more to the analysis than smaller ones.

Cumulative share of harvested area to distance

$$C_i^{(A)} = \frac{\sum_j^i = 1\, A_j}{\sum_j^n = 1\, A_j} \tag{4}$$

C_i = Cumulative share of harvested area up to distance d_i (%)
Aj = Harvested area of worksite j (m^2)
n = Total number of worksites

Distance calculations for the whole study area SKS-geometry

Distance calculations were also performed for the entire study area using the SKS dataset. The overall methodology followed the same principles as described for the company worksite polygons, but several adjustments were required due to the larger size and structure of the SKS dataset. Each SKS geometry contains a unique identifier, and representative points were generated for these geometries in the same way as previously described for the company polygons. These representative points were then snapped to the nearest road segment. Because the SKS dataset contains a large number of geometries located close to one another, the snapped representative points were aggregated to reduce the number of routing calculations. Points located within a grid of 2500 m cell size were initially grouped together, allowing routing calculations to be performed for a single representative origin per group rather than for each individual geometry. To ensure that points grouped within the same grid cell also were connected through the same road network, a topological graph of the road network was constructed. In this graph, nodes represent the endpoints of road segments, while edges represent the road segments connecting these endpoints. Connected components of the graph were then identified, assigning a component identifier to each road segment. Each snapped representative point was linked to its nearest road segment and inherited the corresponding component identifier.

Using this information, a final origin group identifier was defined based on the combination of grid cell location and road network component. This ensured that representative points grouped together were both spatially close and located within the same connected road network. The resulting group identifier was stored in a mapping table linking each SKS polygon to its corresponding origin group. To balance the number of OpenRouteService (ORS) routing requests with the spatial precision of the distance estimates, the grid sizes 1000, 1500, 2500 and 3000 were tested before selecting the final configuration of 2500 m which had an acceptable level of ORS request while maintaining a catchment area of an appropriate size. Routing calculations were then performed from each representative origin group to the nearest charging station and to the nearest sawmill. First, the nearest station and sawmill were identified using Euclidean distance. Subsequently, the driving distance and travel time were calculated using the ORS routing service with the driving-car profile.

Due to API limitations, the routing requests were executed in batches of 100 origins with a pause of two seconds between requests. Results were continuously saved to a CSV file to prevent data loss in case of interrupted runs. After all routing calculations were completed, the results were joined back to the individual SKS geometries using the mapping table. This produced a final dataset containing estimated driving distance (meters) and travel time (minutes) from each SKS geometry to its nearest charging station and nearest sawmill.

To analyze spatial accessibility for the SKS dataset, cumulative distance distributions weighted by harvested area were calculated using the same procedure as described for the company worksites. The worksites were ordered by increasing routing distance $d_i$to the nearest destination, and the cumulative share of harvested area was calculated according to Equation 4.

3.5 Data processing and analysis tools

All data processing and analyses were conducted using Python. The workflow was performed in Visual Studio Code, which was used as the integrated development environment for script development, data processing, and for the analytical pipeline. Several open-source Python libraries were used for data processing, spatial analysis, and visualisation. Tabular data handling, data cleaning, and aggregation of attribute data were performed using the pandas library. Spatial data processing, including the management of vector geometries, spatial joins, and overlay operations, was conducted using GeoPandas (*GeoPandas* n.d.). Numerical computations and array-based operations used for data transformations and statistical summaries were carried out with NumPy. For graphical outputs and the generation of figures used in the analysis, the Matplotlib library was applied. Additional geometric operations, such as intersection calculations, buffering, and other geometry manipulations, were handled through the Shapely library (*Shapely* n.d.), which provides the geometric engine underlying GeoPandas. Coordinate reference system transformations and projection management were performed using PyProj. Routing calculations for estimating travel distances and travel times along the road network were performed using the OpenRouteService API, accessed through the OpenRouteService Python client. All scripts used for data processing, spatial analysis, and distance calculations were organised in a reproducible workflow and executed as Python notebooks and scripts. This ensured transparency and reproducibility of the analytical pipeline from raw data processing to the generation of final datasets and figures. Further details on the Python libraries and tools used are provided in Appendix 1.

4. Results and Discussion

4.1 Validation of the Swedish Forest Agency's satellite-detected harvesting data

Overview of dataset and match rate with SKS satellite-detected harvesting data

The geometric matching between the company harvesting sites and the SKS-detected harvest sites yielded 123 matches out of 226 company worksites, corresponding to a matching rate of 54%. Consequently, 103 worksites in the company dataset remained unmatched, accounting for 46% of observations. The distribution of matched and unmatched worksites is illustrated in Figure 4.

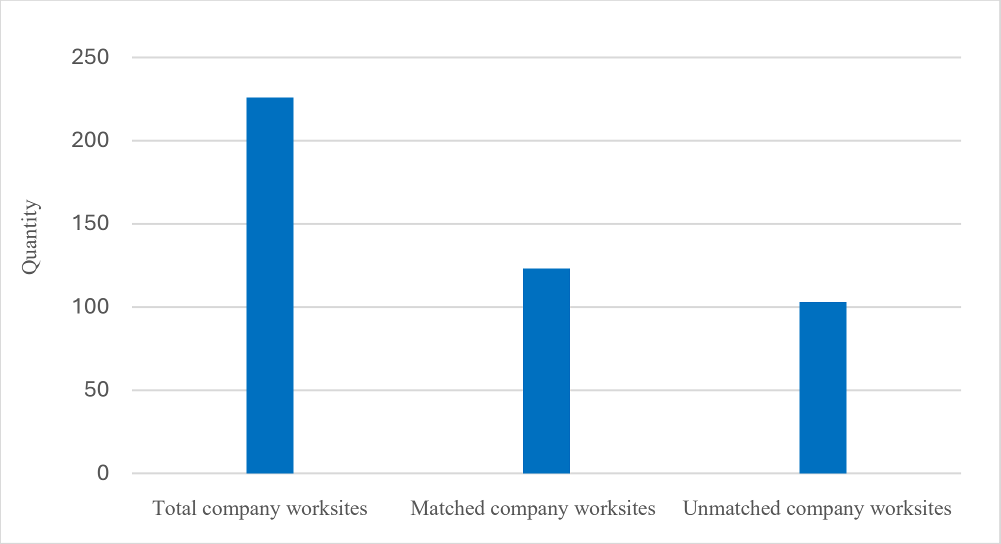

Figure 4. Overview of the matched datasets of company harvesting sites and the Swedish Forest Agency detected harvesting sites for the years 2022-2025.

As shown in Figure 4 above, the matching rate between the datasets is relatively low. This can largely be explained by differences in the content and scope of the datasets. The company dataset contains a mixture of thinning operations and final fellings, whereas the SKS dataset records only completed final fellings detected via remote sensing. Consequently, only the final felling sites in the company dataset could potentially be matched with corresponding SKS geometries. A small number of additional mismatches may also be explained by recently harvested sites from 2025 that have not yet been registered in the SKS dataset. Furthermore, it should be considered that the dataset does not include unreported fellings or harvest areas smaller than 0.5 ha, which apply to a small portion of the company data.

Comparison of polygon area between company worksites and SKS remote sensing data

A comparison of polygon areas between the company records and the SKS remote sensing dataset was conducted to verify the correspondence between the geometrically matched polygons. For this purpose, the spatial overlap between the matched geometries was calculated as a percentage. The results are presented in Figure 5, which shows that most matched polygons have a spatial overlap between 60% and 90%.

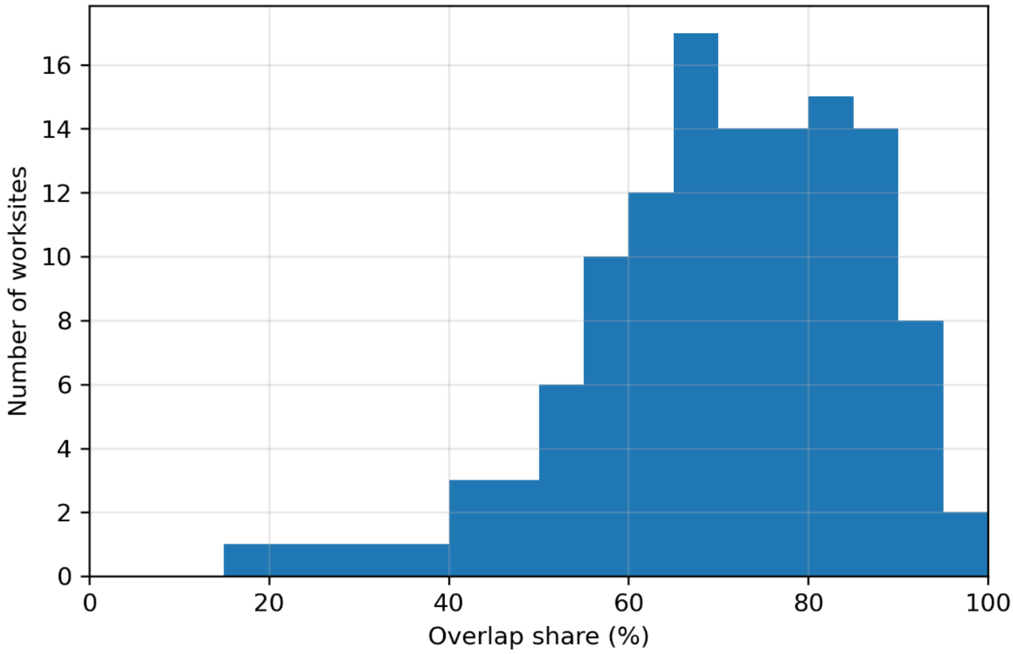

Figure 5. Percentage distribution of spatial overlap between matched company worksite polygons and corresponding SKS-detected clear-cut polygons.

The results in Figure 5 indicate that, despite differences in polygon delineation, the spatial location and general extent of the harvesting sites correspond well between the datasets. Consequently, the level of spatial overlap can be considered sufficient for the purposes of regional-scale analyses, where the overall spatial distribution of harvesting sites is of greater importance than an exact correspondence of polygon boundaries. Some divergence in area can be explained by differences in how the polygons were generated. The company polygons were created by applying a buffer around representative points derived from the company dataset. In addition, the company dataset includes road segments cleared for machine access, which are not captured in the SKS dataset derived from satellite imagery.

An area comparison was also conducted for the matched polygons, and the resulting summary statistics are presented in Table 2. The mean percentage difference of -16% indicates that the SKS polygons were generally smaller than their corresponding company polygons. This pattern is reasonable, as mentioned earlier the company polygons are known to be slightly systematically overestimated. One contributing factor is the use of a 10 m buffer applied around representative points when generating the company polygons. The buffer size was selected to ensure that individual harvesting sites were represented as continuous polygons. Tests with smaller buffer distances (e.g. 5 m and 3 m) resulted in fragmentation, where single harvesting sites were split into multiple smaller polygons due to the distance between stem positions exceeding the buffer radius. This led to an unrealistic representation of the spatial extent of the harvesting operations. The choice of buffer size therefore represents a trade-off between geometric precision and the ability to capture harvesting sites as coherent spatial units. While smaller buffers would reduce the systematic overestimation of area, they would also decrease spatial coherence. The selected buffer distance of 10 m was therefore considered a reasonable compromise for representing the overall extent of harvesting sites.

The standard deviation of 27% further supports this observation, indicating substantial variation in the area differences between the corresponding polygons. Only 18% of the matched polygons differed by less than ±10%, while 44% fell within a ±20% difference. This suggests that although a considerable proportion of the polygons show a moderate level of similarity, exact correspondence in area between the datasets is relatively uncommon. A clear asymmetry is observed in the direction of the differences: in 80% of the cases the SKS polygons were smaller than the corresponding company polygons, while only 19% of the SKS polygons were larger.

Table 2. Area-difference comparison SKS vs. Company

Parameter	Value	Description
n	123 st	Number of matched worksites
Mean diff (%)	-16 %	Average value for the area difference comparison
SD (%)	27 %	Standard deviation of the area difference between SKS and company worksites
Share within ± 10 %	18 %	Proportion of polygons whose area differs by less than 10%
Share within ± 20 %	44 %	Proportion of polygons whose area differs by less than 20%
SKS > Company worksites	19 %	Proportion of SKS-polygons that were larger than company worksites
SKS < Company worksites	80 %	Proportion of SKS-polygons that were smaller than company worksites

Despite these differences shown in Table 2, the overall match between the datasets can be considered adequate for regional-level analyses. The results suggest that the SKS dataset accurately depicts the location of harvesting sites with reasonable agreement, despite remaining differences in the mapped area.

Comparison of felling dates between company worksites and SKS scan records

To estimate the capacity required for a future energy supply system, the temporal dimension of forestry operations is an important factor. Therefore, a comparison of the dates associated with harvesting operations was conducted between the datasets, as illustrated in Figures 6 and 7. The company dataset shows a relatively even distribution of activities across most months, with the exception of the summer months of June, July, and August, most likely due to holiday periods during these months. In contrast, the SKS detections are strongly concentrated between May and July, as shown in Figure 7.

To further evaluate the temporal correspondence between the datasets, the number of days between the harvesting dates recorded in the company dataset and those reported in the SKS dataset was calculated. The distribution of these differences is presented in Figure 8. The results show substantial discrepancies between the two datasets, with differences ranging from 2 to approximately 300 days. This clearly indicates that the harvesting dates reported in the SKS dataset do not consistently correspond to the actual harvesting dates recorded by the company.

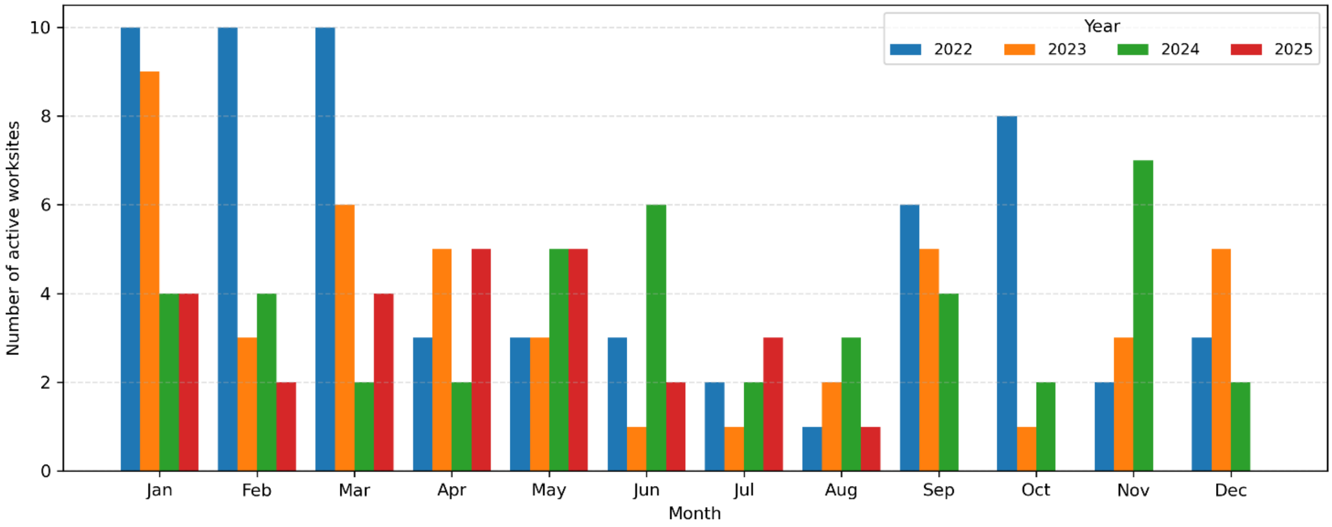

Figure 6. The distribution of matched company worksites, in which month and year they were active.

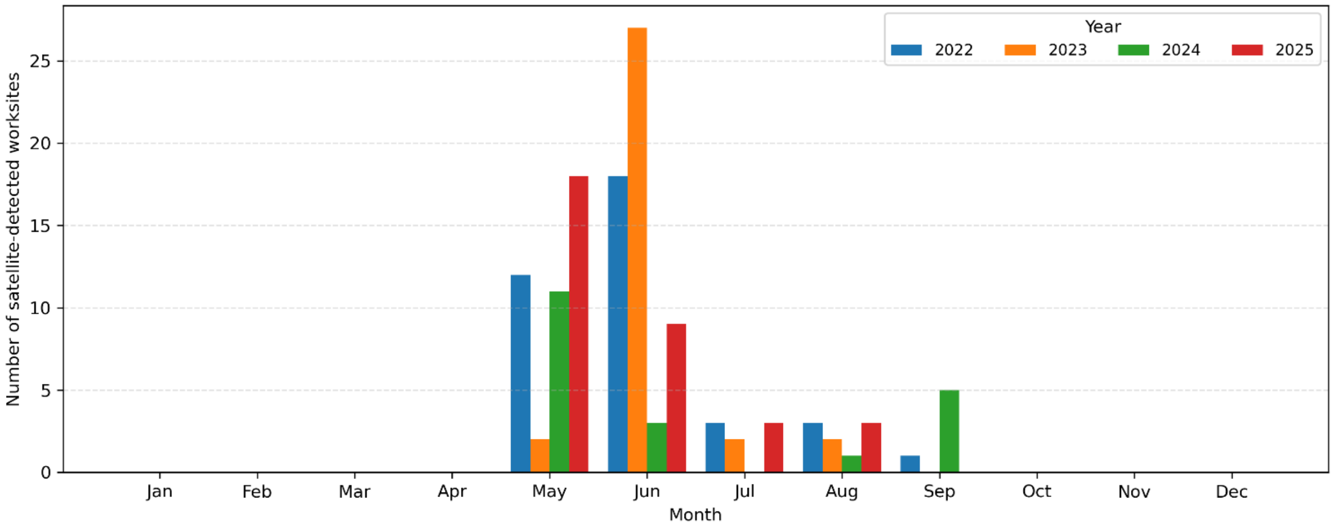

Figure 7. The distribution of dates for the matched SKS-worksites.

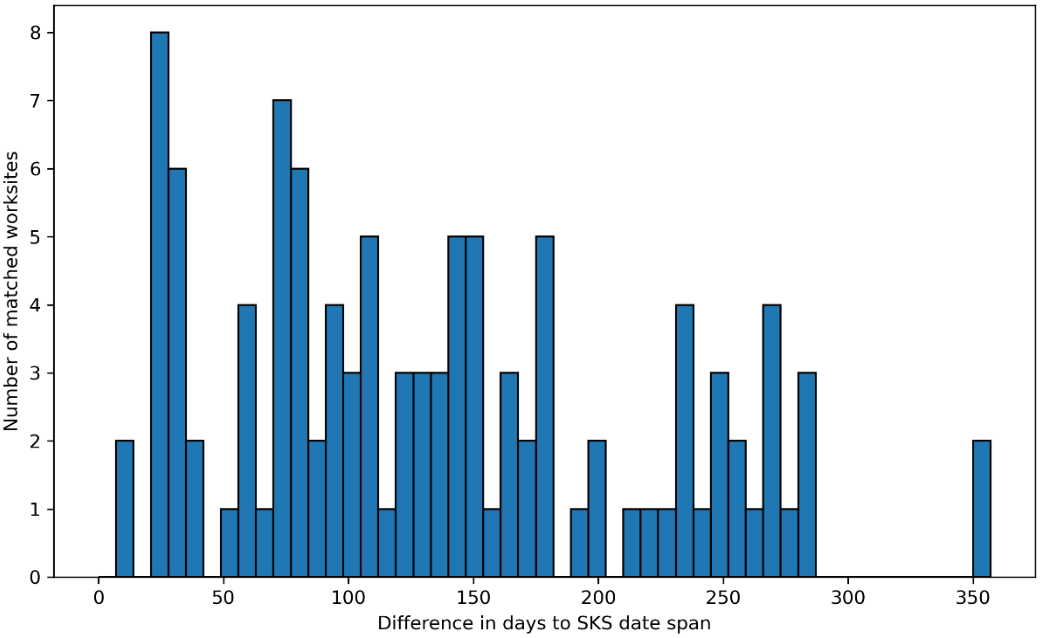

Figure 8. Distribution of the difference in days between the harvesting dates recorded in the company dataset and the corresponding SKS-detected harvesting sites.

When mapping the specific energy demand within a region, the temporal distribution of forestry operations is highly relevant. However, the time differences shown in Figure 8 clearly indicate that the harvesting dates reported in the open-access dataset do not match the actual harvesting dates recorded in the company dataset

Satellite-detected SKS harvesting data for energy supply planning

When assessing the potential energy demand required to support electrified forestry operations, it is important to consider the full range of forestry activities taking place within a region, both spatially and temporally. Previous research has shown that the spatial distribution of charging infrastructure and energy demand is strongly influenced by real-world activity patterns (Dong et al., 2013).

The area comparison presented in this study indicates that the satellite-detected harvesting data corresponds reasonably well with the company dataset and can therefore be considered suitable for further spatial analysis. However, when estimating the overall energy demand associated with a potential transition to electrified forestry machinery, both thinning operations and final fellings need to be considered. Since the satellite-detected harvesting dataset only includes final fellings and does not capture thinning operations, this represents a limitation when assessing the total number of active worksites within a region, both spatially and temporally.

The temporal analysis presented in Figure 6 indicates a relatively even distribution of forestry operations across most months in the company dataset, with lower activity during the summer months. In contrast, the SKS dataset shows a much stronger concentration of detected harvesting events during late spring and summer (Figure 7). This difference suggests that the temporal information derived from the satellite-detected dataset does not reflect the actual timing of forestry operations. This interpretation is supported by information from the Swedish Forest Agency (personal communication, 2026), which confirms that satellite imagery is updated several times per week. However, the availability of usable imagery depends on cloud-free conditions and snow-free ground, which makes it difficult to determine the exact timing of a harvesting event. In addition, the quality of satellite imagery during winter conditions in northern Sweden is often insufficient for reliable detection. As a result, satellite-based detection is primarily possible during snow-free periods.

Overall, the results suggest that the SKS dataset provides a reasonably reliable representation of the spatial distribution of harvesting sites, but the temporal information is insufficiently reliable for the time-based analyses conducted in this study. Consequently, the dataset is suitable for spatial analyses of forestry activities, while its use for detailed temporal analyses remains limited.

4.2 Distance calculations

To provide an overview of the distances relevant for planning future energy infrastructure, Figure 9 illustrates the calculated distances from company worksites to the nearest public charging stations. The figure includes all 226 worksites in the dataset. The results show that the distance between worksites and the nearest charging station ranges from approximately 2 km to about 70 km. The median distance is 32 km, and 50% of the worksites are located within 18–42 km.

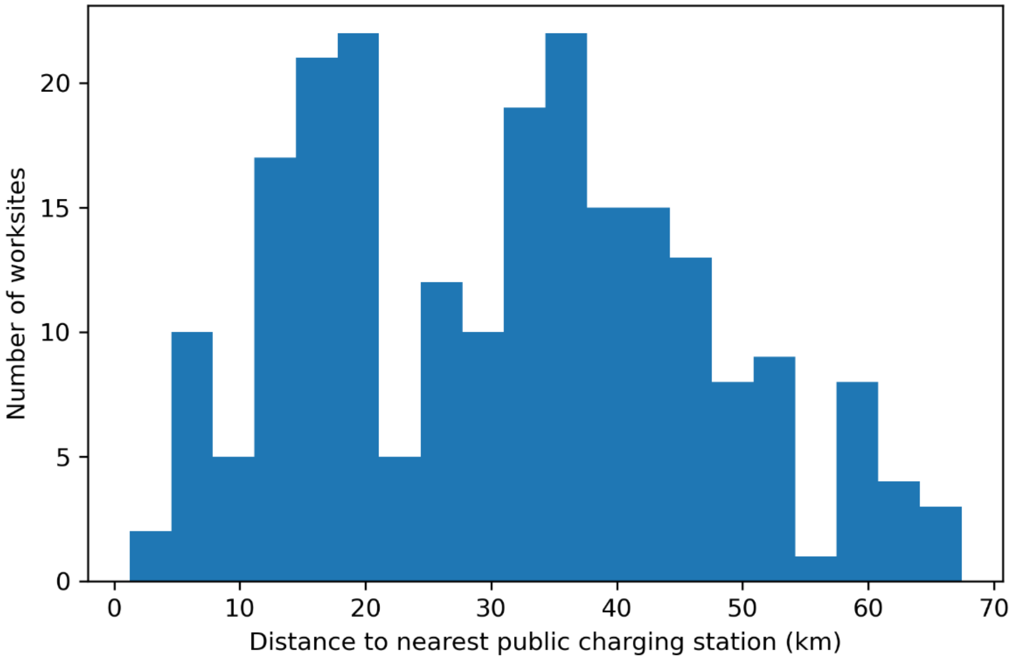

Figure 9. Distance distribution (km) between worksites and the nearest public charging station.

Figure 10 shows the corresponding distribution of distances to the nearest sawmill for the same dataset as in Figure 9, which ranges from approximately 34 km to 118 km. The median distance is 69 km, with 50% of the worksites located within the 57–88 km interval.

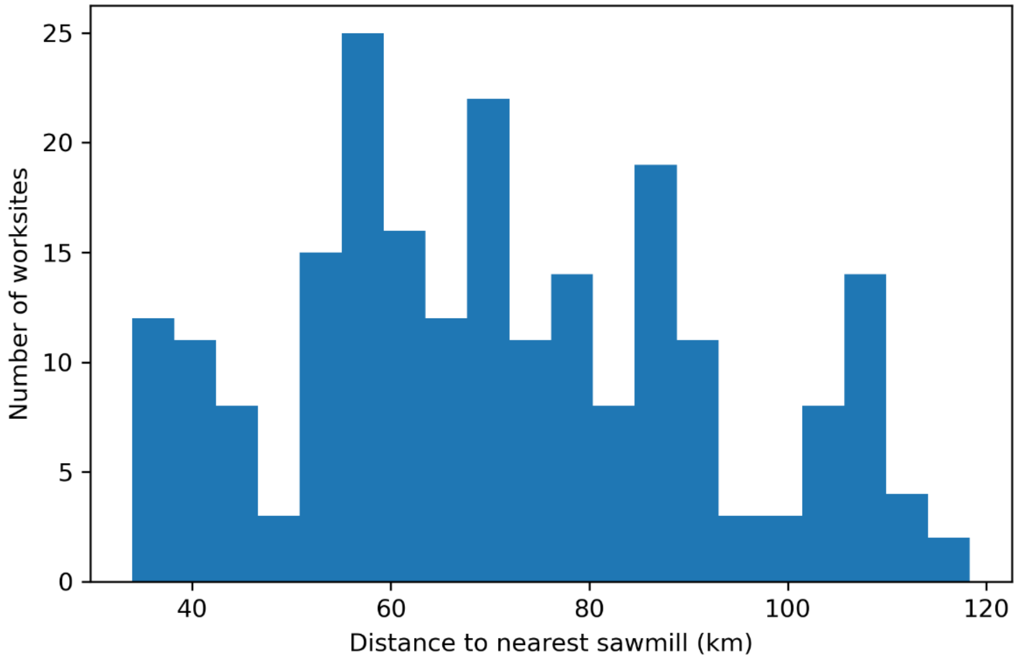

Figure 10. Distance distribution (km) between worksites and the nearest sawmill.

While Figures 9 and 10 describe the distribution of distances for the company dataset, a more comprehensive comparison between datasets is provided through the cumulative, area-weighted analysis presented in Figure 11. The results indicate that the cumulative share of harvested area shows a similar trend across both datasets, with a slight shift towards longer distances in the company dataset. As illustrated in Figure 11, approximately half of the SKS-detected harvested area is located within around 25 km of a public charging station, whereas the corresponding distance to sawmills is around 70 km. For the company dataset, approximately 50% of the harvested area is located slightly above 30 km from the nearest charging station, while the corresponding distance to sawmills is similar to that observed for the SKS-detected harvesting sites.

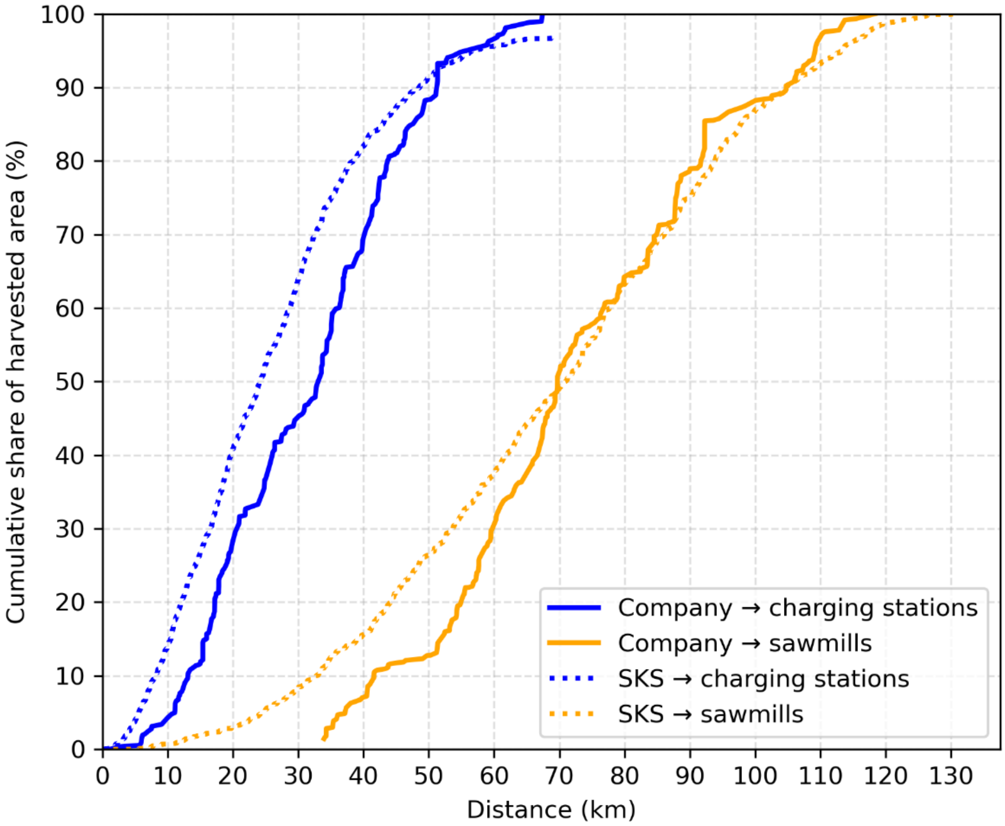

Figure 11. Distance calculations for both the company and SKS datasets. Displaying the harvesting area-weighted cumulative share versus the distance to the nearest charging station and sawmill.

Figure 11 indicates very similar trends for both datasets, indicating a consistent spatial pattern and suggesting that the company dataset is representative of the broader study area. This strengthens the robustness of the analysis, as similar accessibility patterns are observed across the data sources. In this context, area serves as a proxy for the scale of harvesting operations, and thus indirectly reflects the relative energy demand, as larger harvesting sites are generally associated with higher harvested volumes and increased machine activity. The analysis also confirms the previously observed pattern that the distance from worksites to industrial facilities (sawmills) is generally greater than the distance to the nearest public charging station.

According to Davidsson et al. (2023), the average truck transport distance from forest biomass to industry in Sweden is approximately 91 km. In northern Sweden, these transport distances tend to be longer, with average distances of about 130 km for sawlogs. The distances from worksites to sawmills observed in this study are slightly shorter but still fall within a similar range as those reported by Davidsson et al. (2023). In contrast, the distances from worksites to the nearest public charging stations are significantly shorter.

One alternative mentioned by Norouzi (2025) is the use of mobile charging solutions. In such a system, mobile charging units could potentially be charged within the existing network of public charging stations and then transported to the worksites. This would require external transport to and from the harvesting sites. Such transport could potentially be carried out by the machine operators themselves or by external transport. As discussed in Nilsson et al. (2013), the fuel supply for forestry machinery is usually arranged at or near the harvesting site, meaning that diesel must be delivered to the worksite during operations. Similarly, mobile charging solutions could potentially be transported to the worksites as needed. Forestry machines cannot travel long distances to reach charging stations because their energy supply must remain closely connected to the worksite where operations occur.

To conclude, the result in Figure 11 demonstrates a methodological approach that can be used to further estimate the energy demand required to support charging infrastructure. Such estimates could be made more accurate by incorporating harvested volumes at the worksite level. However, this study is limited to using area as a proxy because volume data were available only for the company dataset, not for the open-access harvesting data. Consequently, the area is assumed to represent a corresponding variable for the scale of harvesting operations.

4.3 Spatial Implications for Energy Infrastructure Development

When developing a future energy infrastructure network, several factors must be considered, including the spatial distribution and density of accessible energy supply points. A temporal perspective would also be valuable to understand when forestry activity, and thus energy demand, is at its highest. Based on the results shown earlier in the study, the temporal information in the dataset was not reliable enough to include in the analysis. Therefore, the assessment concentrates on spatial conditions.

The distribution of distances from detected harvesting sites to the nearest charging infrastructure and sawmills is presented in distance classes, with the share of worksites shown in Table 3. It shows that 46% of the harvesting sites are within 20 km of a charging station, while only 4% are within the same distance of a sawmill. In contrast, only 1% of the harvesting sites are situated more than 60 km from a charging station, whereas 58% are positioned at that distance from the nearest sawmill.

Table 3. Distribution of distances, categorized into distance classes, from detected harvesting sites to the nearest charging station and sawmill.

Distance class (Km)	Public charging stations (%)	Sawmills (%)
0-20	46	4
20-40	40	14
40-60	13	23
>60	1	58

To further illustrate the spatial distribution of accessibility within the study area, detected harvesting sites were classified based on their distance to the nearest public charging station, as shown in Figure 12. This approach provides an overview of the actual conditions, reflecting both the spatial distribution of harvesting activities and the distances that would need to be managed in practice. Within the study area, public charging infrastructure is generally accessible within approximately 40 km, as indicated by the light green areas. However, some regions have distances exceeding 40 km, and even 60 km, as indicated by orange and red areas, suggesting limited access to charging facilities.

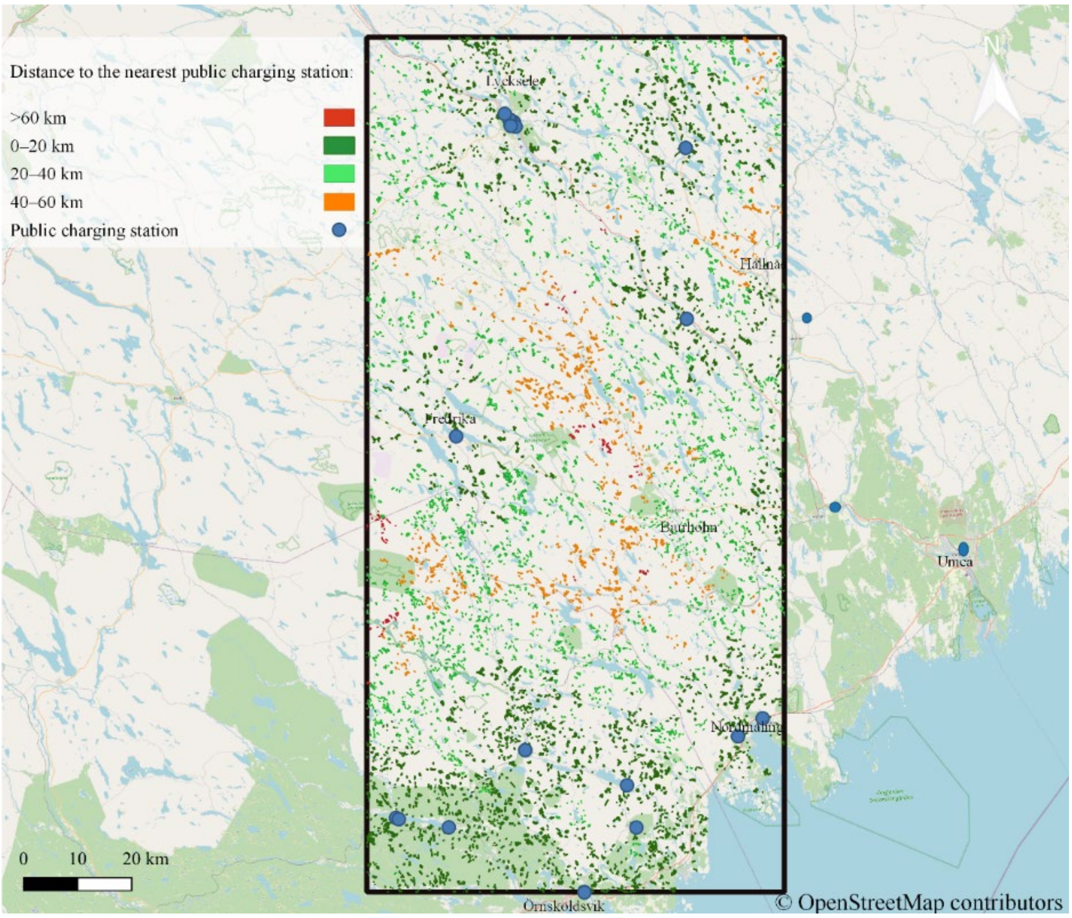

Figure 12. All detected logging sites from the Swedish Forest Agency between 2022 and 2025, classified by distance to nearest charging stations.

As illustrated in Figure 12, harvesting sites located close to existing public charging infrastructure (shown in dark green) highlight locations where these facilities could be expanded to serve as energy supply points for forestry operations. As noted by Norouzi et al. (2025), there is currently no established solution regarding which type of energy supply system should be used. Instead, several potential concepts have been proposed, such as mobile charging stations and battery-swapping systems. It is therefore difficult to determine what would be considered a feasible solution at this stage. Rather, the results primarily indicate the conditions the forestry sector will need to address when developing future energy supply systems.

To further examine the spatial implications of these results, Figure 13 highlights areas with limited accessibility, defined as being more than 40 km from the nearest charging station, shown in orange and red. These harvesting sites represent regions where new energy infrastructure might be needed due to limited access to charging facilities, and they are marked by purple circles.

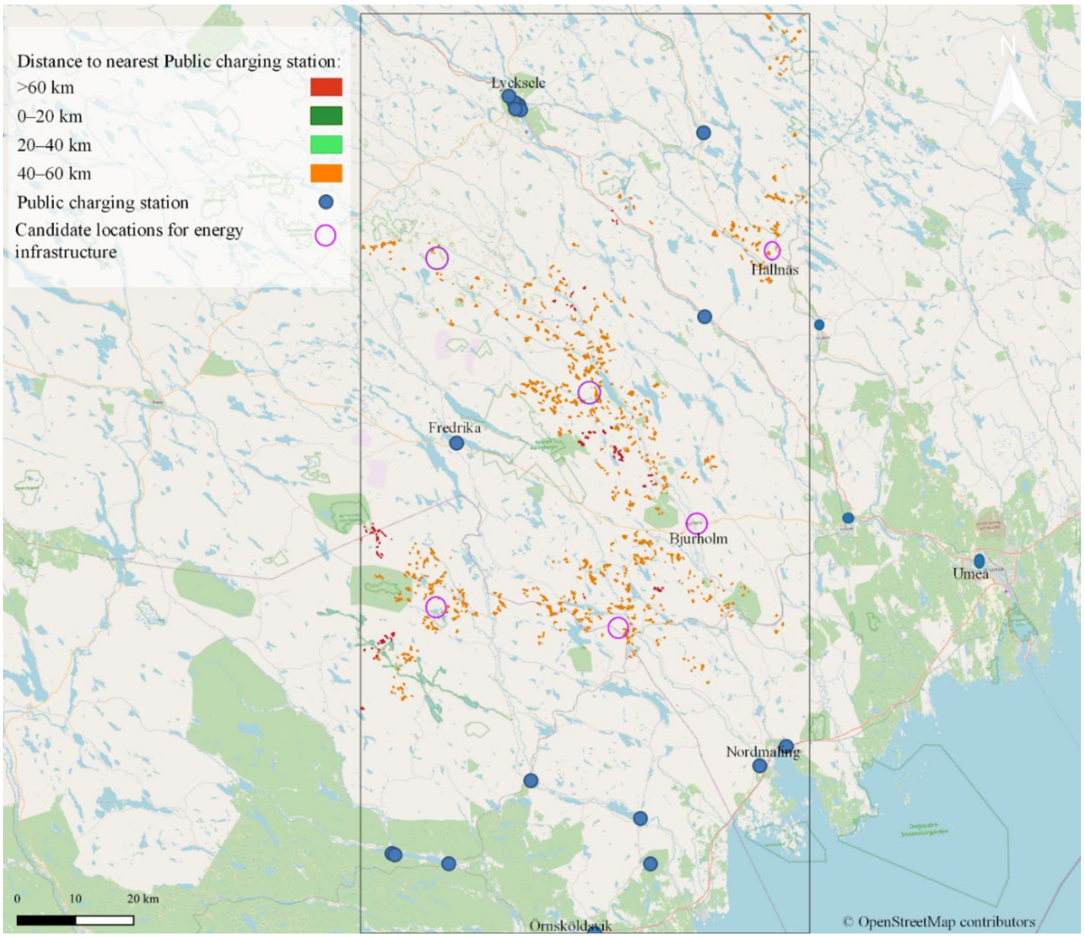

Figure 13. All scanned logging sites from 2022 to 2025 located more than 40 km from a charging station.

As shown in Figure 13, the energy infrastructure in the interior regions of northern Sweden is limited. In areas located far from larger settlements, the distance to the nearest charging station exceeds 40 km. This represents a relatively long distance, as forestry machinery would likely require access to an energy supply near the harvesting site. Considering the high daily energy demand of forestry machinery, estimated at several hundred kilowatt-hours per working day (Norouzi et al., 2025), access to nearby energy supply infrastructure becomes an important factor for the feasibility of electrified forestry operations.

In regions where charging infrastructure is limited, larger settlements are also typically absent. Since northern Sweden contains more remote areas than the south, these regions represent locations where the expansion of energy infrastructure could be justified. At the same time, forestry activities are more prevalent in these areas due to the larger forest-covered land area, which further emphasizes the potential need for energy supply infrastructure. Similar challenges have also been highlighted by Antila et al. (2025), who identify the availability of supporting energy infrastructure as a key barrier to the large-scale implementation of electrified forestry machinery in remote harvesting areas.

To complement this analysis, the accessibility to sawmills was assessed using the same classification approach as for public charging stations. The results show that the distances to sawmills are generally much longer than the distances to public charging stations, as indicated by the large number of red-coloured harvesting sites. Consequently, in remote areas where sawmills are scarce, harvesting sites are overrepresented in the lower-accessibility classes, particularly in the low-accessibility (40–60 km) and very low-accessibility (>60 km) categories. This pattern is illustrated in Figure 14.

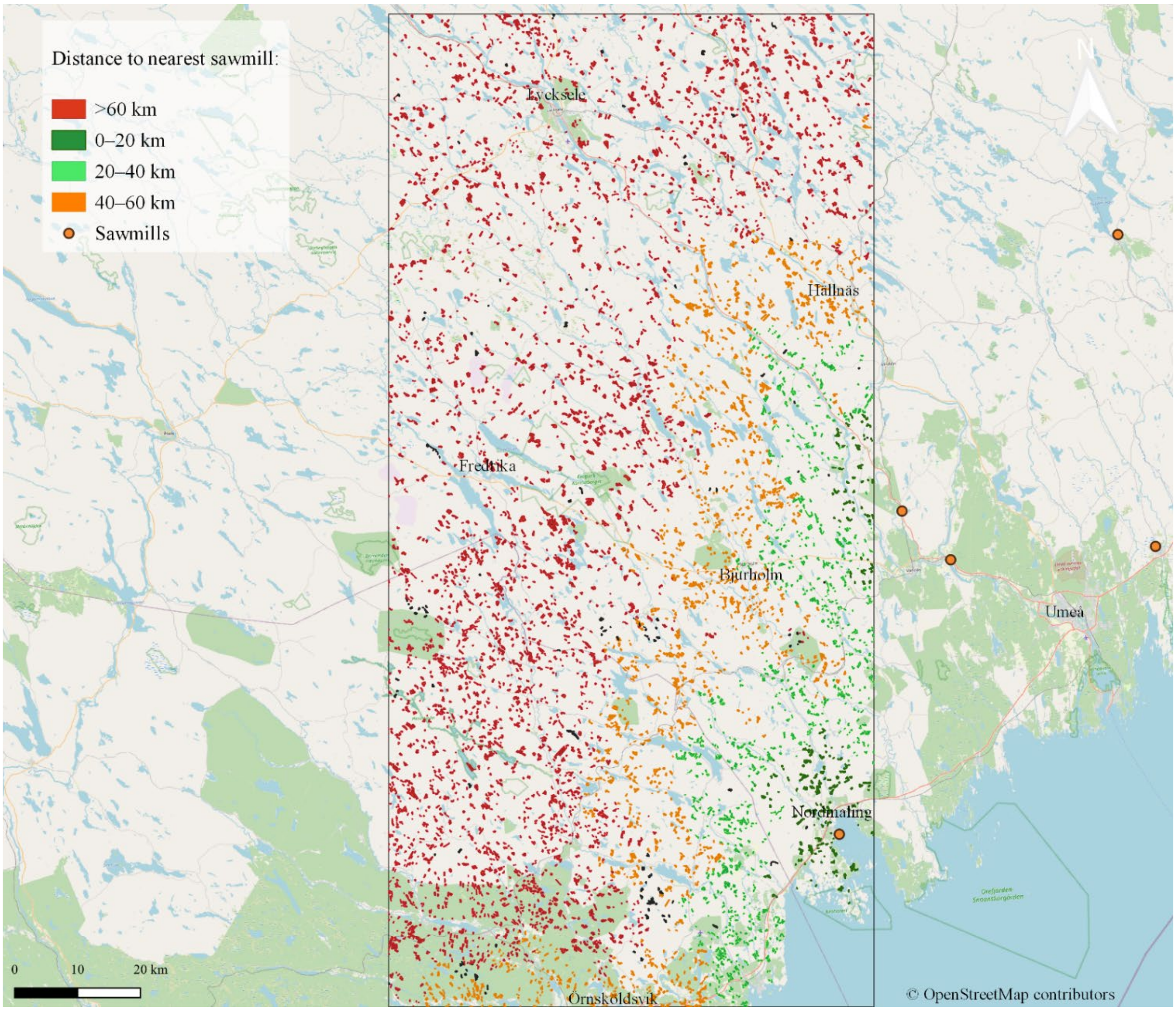

Figure 14. All detected logging sites from the Swedish Forest Agency between 2022 and 2025, classified by distance to the nearest sawmill.

As demonstrated by Davidsson et al. (2024) transport distances for timber in northern Sweden are generally long, consistent with the pattern shown in Figure 15. Considering these distances, sawmills show lower accessibility compared to the harvesting sites. However, since the energy source is assumed to be transported to the harvesting location, sawmills could potentially be modified more specifically to meet the energy needs of the forestry sector. This might make them viable energy supply points despite the longer distances.

As further shown in Figure 14, most industrial facilities are located closer to the coast; therefore, the distances to these facilities are generally longer than those to public charging stations, which are more widely spread across the study area, as shown in Figure 13. Including sawmills in the same calculations as charging stations would not significantly change the overall results. It should be noted that pulp and paper mills were not included in the dataset, which is a limitation of the study. However, they are generally believed to be located near the coast, although some wood-processing industries are found in more remote areas. These facilities could also serve as potential energy supply points and might slightly influence the spatial accessibility results.

Overall, the results indicate that while some potential energy supply points are present, large remote areas still lack sufficient access to energy infrastructure. This implies that developing electrified forestry will likely require a combination of expanding infrastructure and using alternative energy solutions tailored to remote harvesting environments. The analysis identifies remote areas where the need for energy infrastructure is probably greatest. However, the question of which energy supply systems should be used for electrified forestry machinery remains unresolved, making it hard to determine where and at what scale future energy infrastructure should be established.

5. Conclusions

To conclude, this study provides a practical overview based on real harvesting activities within the study area and the existing conditions for energy infrastructure in the region. By analyzing the spatial relationship between harvesting sites and potential energy supply points, the results highlight both the opportunities and limitations of relying on the current infrastructure network to support electrified forestry operations. The future electrification of forestry will likely require not only an expansion of infrastructure, but also adaptation to sector-specific needs and the development of alternative energy solutions, such as mobile energy storage.

Existing public charging infrastructure is present within the study area and provides a spatial basis for supporting a substantial share of harvesting sites. However, accessibility varies considerably, with 46% of the worksites located within 20 km and 14% in more remote areas beyond 40 km. In contrast, sawmills show significantly lower accessibility, with only 4% of the worksites within 20 km and 81% located more than 40 km away, limiting their potential as energy supply points.

The spatial comparison between the Swedish Forest Agency's detected harvesting data and the company dataset shows a substantial level of agreement, with 53% of the sites exhibiting an overlap exceeding 60%. Despite known limitations in the delineation of company polygons, this level of correspondence supports the use of the dataset for spatial analysis. However, the temporal data were too dispersed to capture consistent seasonal patterns of forestry activities. Consequently, the dataset is suitable for large-scale spatial analyses of harvesting activities, while it is not suitable for detailed temporal analyses.

The findings of this study contribute to ongoing and future research by providing an initial methodological framework for modeling energy supply and transportation systems in forestry contexts. While the empirical analysis is limited to a selected region in northern Sweden, the proposed approach is scalable and could be extended to larger geographical areas, such as the entirety of northern Sweden, in future research.

Such applications could support strategic planning of future energy infrastructure by identifying areas where additional energy supply capacity may be required to enable the transition towards electrified forestry machinery.

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Popular science summary

The availability of electric charging infrastructure in northern Sweden is currently limited, which poses a challenge for the future electrification of forestry. The study contributes a method for identifying where the need for charging infrastructure is greatest, based on the spatial distribution of harvesting activities.

The results show that within the study area, located between Örnsköldsvik and Lycksele, 46% of the harvested sites from the years 2022–2025 are located within 20 km of a public charging station, while 14% are situated more than 40 km away. When analyzing proximity to sawmills, 81% of the sites are located more than 40 km away, while only 4% are within 20 km. These findings indicate that public charging stations are generally more geographically accessible than industry, although sawmills could potentially be better adapted to meet the specific energy demands of forestry. The study assumes that mobile charging stations could be charged within the existing infrastructure network and then transported to harvesting sites. In this context, sawmills could function as more specialized energy hubs, while public charging stations may play a broader role in covering geographic demand.

In addition to infrastructure accessibility, the study evaluates whether open-access harvesting data from the Swedish Forest Agency can be used for large-scale spatial and temporal analyses. The results show that the data is well suited for spatial analyses but less reliable for temporal analyses. Satellite-based detection is affected by factors such as cloud cover and snow, which means that estimated harvesting dates do not always reflect actual harvesting times.

The study is based on a combination of data sources, including open-access data from the Swedish Forest Agency, company data from Holmen, public charging station data from NOBIL, sawmill data from the CEForestry project, and road network data from Lantmäteriet. The analyses were conducted in Python, and distances were calculated along the road network using OpenRouteService.

The background of the study is the ongoing need to reduce the forestry sector's reliance on fossil fuels in response to climate change. Electrification is considered a promising solution, with both electric and hybrid forestry machines already under development. However, a key challenge is the limited availability of energy infrastructure in the areas where forestry operations take place.

The study contributes a method for identifying where the need for charging infrastructure is greatest, based on the spatial distribution of harvesting activities.

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I would like to express my sincere gratitude to Holmen for providing access to the harvesting data used in this study. I would also like to thank my friends for their continuous support throughout the work. Finally, I would like to extend my appreciation to my supervisor, Justin Herdegen, for his guidance and support during this project.

Appendix 1: Description of the used Python tools

Table 4. The Python tools that were used for data processing.

Input data	**Library/tools**	**Description**	**Output**
Detected harvesting from the Swedish Forestry Agency from 2022 to 2025	GeoPandas	Data loading, filtering, coordinating system handling, clipping, and exporting geospatial data	Study area
	Shapely	Creation of a rectangular study area	
	Python standard functions	Column validation and data preview	
Company harvesting data (HPR)	OS (Python)	File management and batch processing of input files	Spatial harvesting data in point form (stem points)
	Custom Python function	Loading coordinates for specific stem data from converted harvesting files, cleaning, filtering, and export to GeoPackages	
	GeoPandas	Reading and handling geographic point data	
	Python standard functions	Error handling and data validation	
Spatial harvesting data in point form (stem points)	GeoPandas	Reads input files, buffers points, and merges geometry per worksite ID. Area calculation and export of spatial data	Company harvesting sites polygons
	Pandas	Aggregation and merging of attributes at the worksite level	
	Shapely	Merging geometric attributes	
	Dataclass	Configuration and reproducible control of polygon generation	
	Custom Python functions	Column validation and grouping, creation of worksite-based polygons	

Table 5. The Python tools that were used for the validation of the forest agency data.

Input data	Library/tools	Description	Output
Polygon layer of harvesting sites for both the company and the SKS dataset.	GeoPandas	Spatial overlay, geometry handling, dissolve operations, and export of matched polygon layers	Geometric layer with the matched harvesting sites.
	Pandas	Date handling, table aggregation, filtering, and conflict resolution based on best match	
	Custom Python function	Candidate matching between SKS polygons and company harvesting polygons based on geographic overlap and rule-based selection logic	
	Dataclass	Structuring of matching results	
Converted Harvesting production files from the company, and the SKS detected harvesting sites.	Pandas	Compilation, date comparison, aggregation, pivoting, calculation of statistics, and export to Excel	Figures and statistics of the temporal analysis for both the company harvesting sites and the SKS.
	GeoPandas	Loading matched geodata and SKS detected harvesting sites as input for result analysis	
	Matplotlib	Creation of histograms and bar charts for result visualization	
	NumPy	Numerical processing for figure generation	
	Fiona	Identification of layers in GeoPackage	
	Pathlib	Management of file paths and output files	
	Custom Python module	Standardized export of result tables and metadata to Excel	
Geometric layer with the matched harvesting sites.	GeoPandas	Calculation of area and matching degree, as well as geometric comparison and overlap between company polygons and matched SKS polygons	Figures and statistics for area comparison and overlap between the company and the SKS polygons
	Pandas	Compilation, sorting, and tabulation of area and overlap results	
	NumPy	Calculation of percentage differences, overlap ratios, and summary statistics	
	Custom Python module	Export of area comparisons, overlap tables, and metadata to Excel	
	Pathlib	Management of result files	
	Matplotlib	Visualization of the distribution of the overlap degree	

Table 6. The Python tools that were used for distance calculations of the company and the Swedish forest agency dataset.

Input data	Library/tools	Description	Output
Company harvesting polygons, and SKS detected harvesting polygons	GeoPandas	Loading polygon layers	Representative points for the harvesting polygons in both the company and SKS datasets.
	Pandas	Aggregation and merging of split attributes	
	Shapely	Generation of representative points from polygons	
	Dataclass	Configuration and reproducibility of polygon generation	
Representative points for the company harvesting polygons	GeoPandas	Reading geodata, CRS handling, nearest neighbour analysis, and management of point and line data	Calculated road network distance to charging stations and sawmills for the company harvesting polygons
	Pandas	Table management, data merging, and storage of distance results	
	Shapely	Precise snapping of points to the nearest location on road geometries	
	OpenRouteService	Calculation of road distances between snapped road points and the nearest charging station/sawmill.	
	Custom Python functions	Construction of station datasets, road access analysis, and routing-based distance calculations	
	Python standard library	File handling and API request management	
Representative points for the SKS detected harvesting polygons	GeoPandas	Reading geodata, snapping to the road network, nearest neighbour analysis, and export of results	Calculated road network distance to charging stations and sawmills for the SKS detected harvesting polygons
	Pandas	Batch processing, autosaving, merging of results, and export to Excel	
	NumPy	Grid-based grouping of origin points	
	NetworkX	Identification of connected road components for improved grouping	
	OpenRouteService	Calculation of driving distances to the nearest charging station/sawmill	
	Custom Python functions	Road network matching, station assignment, and routing-based analysis	
	Python standard library	API key management and file handling for restorable batch processing	

Calculated road network distance to charging stations and sawmills from the harvesting polygons for the detected SKS and company data.	Pandas	Compilation of distance results and linkage to area and volume data	Figures for the distance calculations
	GeoPandas	Reading geometries and export of distance-classified geolayers.	
	Matplotlib	Visualization of histograms, boxplots, and cumulative distance distributions	
	NumPy	Calculation of cumulative distributions and numerical handling of distance data	
	Matplotlib tick utilities	Customization of axis ticks in figures	
	Pandas/GeoPandas-based classification	Classification of distances into fixed distance intervals	

Appendix 2: Temporal distribution of satellite-detected final fellings

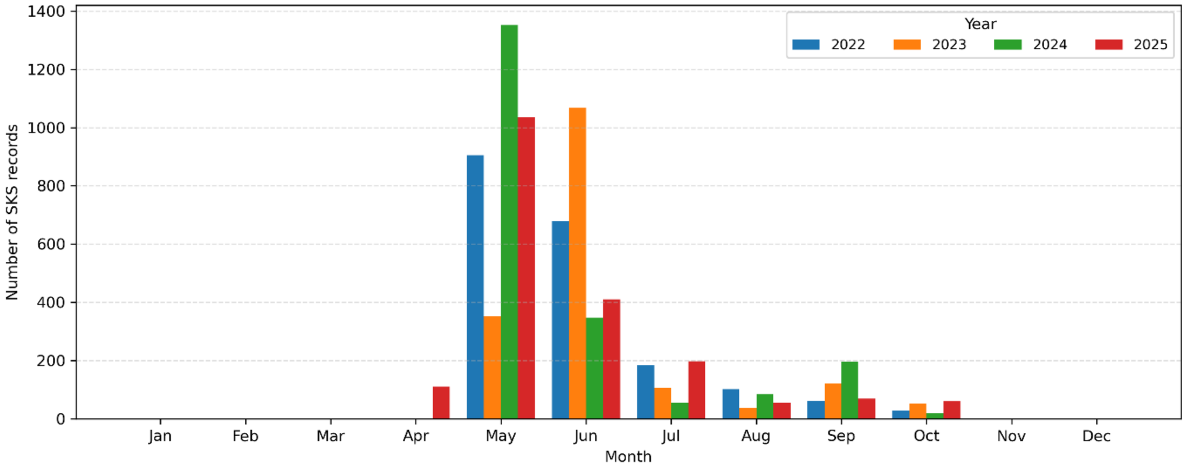

Figure 15. Temporal distribution of all satellite-detected final-fellings from the Swedish Forest Agency for the years 2022–2025, distributed by month and year.

Appendix 3: Routing comparison of the datasets

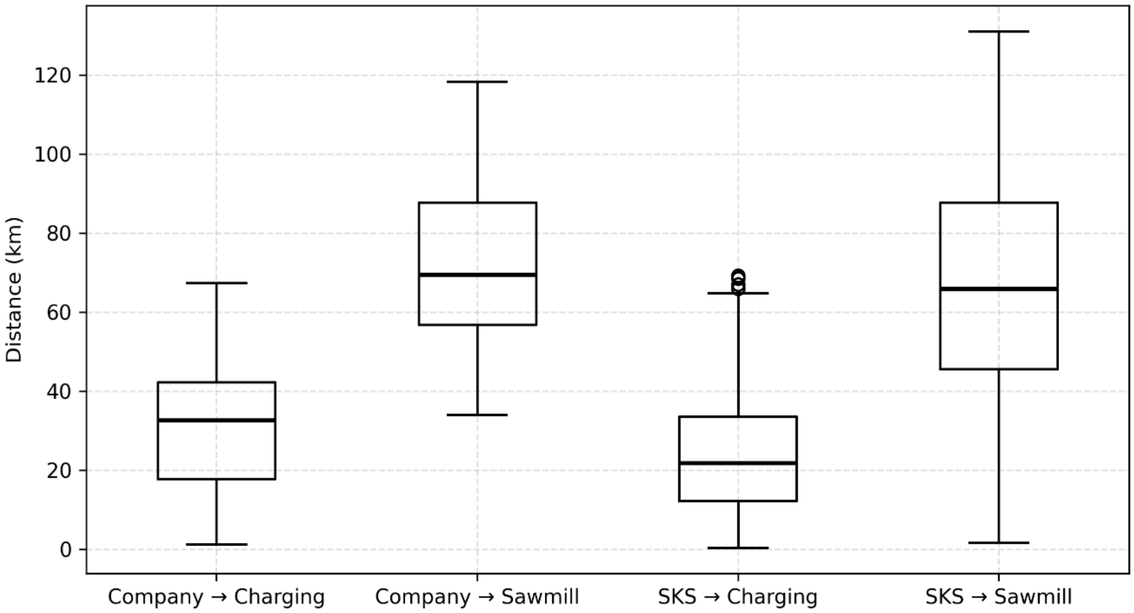

Figure 16. Comparison of distance distributions to public charging stations and sawmills, derived from routing calculations for both the company and SKS datasets.

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