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Supply Potential and Cost of Residual Forest Biomass for New Industrial Applications in Sweden

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ABSTRACT

This work investigates the potential for logging residues (branches and tops that can be extracted during roundwood harvesting) to replace fossil-based feedstocks and energy use in industry, using Sweden as a case study. National and regional supply–demand balances are calculated and costs for extraction and transportation of logging residues to current and future users are estimated. The results show that there is an excess of unutilized logging residues in northern Sweden (just below 10 TWh/y), while the supply potential is already utilized in the south. In southern Sweden, the use of logging residues for district heating is extensive, while simultaneously, the refinery industry is undergoing a transition to renewable feedstocks. This creates a gap between the regional supply and demand of around 15 TWh/year going into the future. Meanwhile, the middle and northern parts of Sweden could be largely self-sufficient and rely on regional logging residues to supply the estimated future biomass demands of around 9 TWh/y. Thus, a regional supply–demand imbalance can be expected in the future, where the excess resource is located in the north, while large demands are expected in the south. With current utilization patterns, the costs for logging residue extraction and transportation are around 50% higher in the north than in the south of Sweden, mainly attributable to the shorter transportation distances. To supply refineries with logging residue-based feedstock from northern Sweden, costs for transportation can be reduced by about 5–10 €/MWh utilizing distributed methanol synthesis before long-distance ship and train transportation. However, the transportation cost reduction is small compared to the cost of the methanol synthesis step, highlighting that the added value for the refinery of receiving methanol compared to chipped logging residues needs to make up the difference to motivate a supply chain based on distributed methanol synthesis.

1 | Introduction

The European Union (EU) is set to attain climate neutrality by Year 2050, and to achieve emissions reductions of 55% (relative to the levels in Year 1990) by Year 2030 (European Commission 2022). To reach these targets, efficient utilization of biomass for the substitution of fossil-based feedstocks and for use as an energy source is important, both as a near-term strategy for fossil fuel replacement and as a long-term strategy for producing carbon-based products, e.g., in refineries and chemical industries (European Commission 2018). In the EU context, the use of biomass is guided by the so-called *cascading principle*, whereby the production of long-lived and highly valued material products should be prioritized over bioenergy applications (Olsson et al. 2016). However, the cascading principle is not obligatory and may be deviated from by Member States on multiple grounds, e.g., to ensure security of energy supply or for forest management reasons (e.g., using wood harvested for wildfire prevention for energy purposes). In theory however, the cascading principle means that EU Member States should guide biomass use according to the following order of priority: (1) production of wood-based products; (2) extending the service lifetimes of wood-based products; (3) re-use; (4) recycling; (5) bioenergy; and (6) disposal (European Commission 2023). In addition, the amendments to the Land Use, Land Use Change and Forestry (LULUCF) regulation have placed stronger emphasis on using forests as natural carbon sinks, aiming to increase the amount of CO_2 that is bound in forest biomass in the Member States (European Parliament 2022). Expanding the carbon sink in the LULUCF sector could limit forest harvesting levels, thereby decreasing the supply of residuals that could be used for bioenergy or feedstock purposes (Skogsindustrierna 2024). There are also limitations associated with sustainability aspects other than climate mitigation to consider in connection with biomass harvesting and bioenergy use, such as the effects of land use and land use change on biodiversity (Black-Samuelsson et al. 2017).

Sweden is a heavily industrialized country and yearly greenhouse gas (GHG) emissions amount to approximately 45 $MtCO_2eq$ (excluding uptakes in the LULUCF sector) (Naturvårdsverket n.d.). Sweden is covered by 28 million hectares (ha) of forests (68% of the country's land area), of which 23.5 million ha are defined as productive forest land (annual increment greater than 1 m^3 per ha) and the total growing stock amounts to 3601 million m^3 today (Roberge et al. 2024). Around one-quarter of the total final energy use in Sweden is supplied by bioenergy (Energimyndigheten 2023), and about 80% of all bioenergy is produced from residuals from the forestry sector (Björheden and Eckerberg 2024). Waste streams from pulp and paper plants (black liquor and bark), sawmills (sawdust and bark), and harvesting operations (damaged roundwood, and logging residues i.e., tops and branches from final fellings) are extensively used for energy purposes today (Energimyndigheten 2023). In terms of total industrial energy use, almost half of the energy supply comes from bioenergy, with 90% of this being internally used within the pulp and paper industry (Energimyndigheten 2023). The Swedish heating sector consists largely of district heating and combined heat and power plants, with an average of 40% of the fuel sourced from forestry and bio-oils (Rydegran 2023). The use of forestry residues for the generation of district heating and electricity has helped the Swedish energy sector to reduce its fossil emissions drastically since the 1980's (Werner 2017). Furthermore, according to estimations made by Parklund (2023), the current unutilized potential of logging residues in Sweden corresponds to approximately 13.7 TWh per year when taking into consideration technical and ecological constraints. This unutilized potential could be used as feedstock or fuel to substitute fossil alternatives in industrial applications and to expand heat and power generation units. To make increased logging residue use feasible, the cost needs to be competitive compared to fossil-based alternatives. Naturally, raw material costs are subject to the market forces of supply and demand, which means that the price of biomass fluctuates with economic trends. Provided that the costs are reasonable, unutilized logging residues are of special interest because they are produced in connection to roundwood harvesting, and have no alternative competing use at the moment.

There exists a large body of research and there is an ongoing debate on the climate effects of utilizing more forestry-based biomass to substitute for fossil feedstocks and fuels, as opposed to leaving forests standing, with discrepant outcomes and interpretations (see for example (Cintas et al. 2016; Colombo et al. 2012; Hammar et al. 2015; Luyssaert et al. 2018; Mathys et al. 2021; McKechnie et al. 2011)). For the purposes of this work, we assume that the growth rate in the forests will outweigh the harvesting rate going forward, and that no further restrictions on biomass use for feedstock and energy purposes are imposed.

Along with the increasing interest in biomass use for climate change mitigation, several studies have estimated the potential future supply of bioenergy on the global (Haberl et al. 2013; Smeets and Faaij 2007), European (Hänninen et al. 2018), and Swedish levels (Börjesson 2021; de Jong et al. 2017; Hansson et al. 2021). Economic estimations on the supply side have also been performed by e.g., Lundmark et al. (2015) who carried out an assessment of the supply potential and costs for several forest biomass assortments and reported average costs for road-side delivery of logging residues as 22.7 €/m^3 and 24.5 €/m^3 for final fellings, i.e., clearcutting of larger areas, and thinnings, respectively. In addition to the supply side, the demands for biomass and bioenergy in Sweden for future applications have been estimated by Börjesson et al. (2017) who projected increases in demand for forest fuels and feedstock for petrochemical industries of just above 40 TWh/year and 60 TWh/year for Year 2030 and Year 2050, respectively, although the estimations come with high uncertainty intervals due to the unknown impacts of electrification and energy efficiency measures. Furthermore, some studies have matched future use scenarios with the estimated supply at both the EU level (Mandley et al. 2020) and nationally in Sweden (Bisaillon et al. 2021; Fossilfritt Sverige 2021; Nwachukwu et al. 2021). However, there is a lack of understanding as to how specific demands for bioenergy and biogenic carbon (e.g., the carbon atoms required for liquid biofuel manufacturing) from multiple sectors can be connected to the supply of different biomass assortments, and how expected supply–demand balances look on a more highly resolved geographic scale.

The aim of this paper is to assess the potential of logging residues to cover future bioenergy and biogenic carbon demands on a regional scale and to calculate the costs for extracting and supplying logging residues, according to current and future industrial usage patterns (focusing on the refinery and iron and steel industries). Additionally, this paper estimates how the timing of implementation in different sectors affects the feasibility of meeting future production and energy demands with logging residues, by varying the demand for logging residues and applying the demands either in the 2030s or the 2040s.

2 | Method

Logging residues are produced during roundwood harvesting (final fellings) and extracted to forest roadside. In this work, they are considered to meet bioenergy or biogenic carbon demands in manufacturing. Only national wood flows have been looked at in this paper, and import as well as export have been ruled out as the focus of the study has been Sweden. An overview of the applied method is presented in Figure 1. To estimate the supply potential of logging residues and the related cost for a

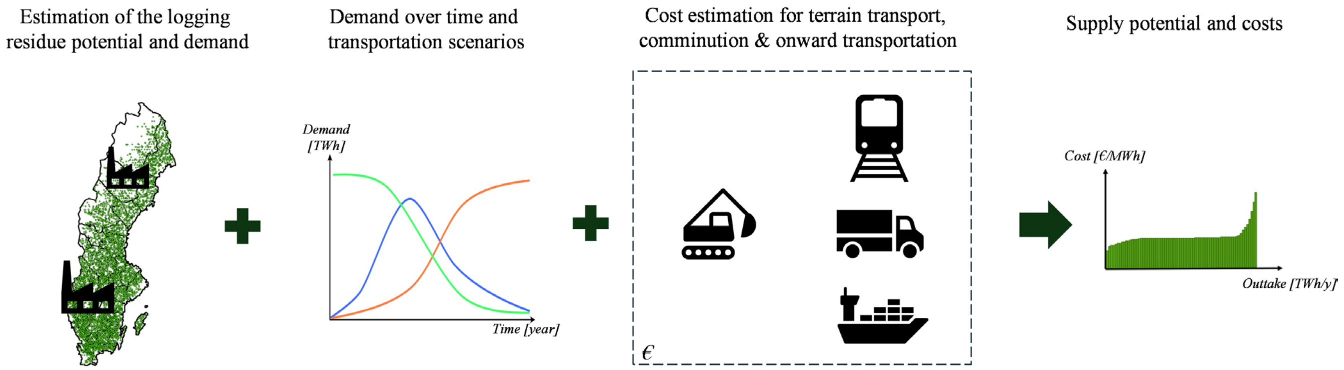

FIGURE 1 | Overview of the method. Logging residue availability is estimated and related to demand scenarios. Cost estimates are calculated for logging residue supply chains. Outputs in the forms of regional logging residues excess/deficit, potential to cover future industrial developments biomass demands with logging residues, and associated logging residue supply costs are generated.

specific energy or carbon demand, the spatially and temporally explicit availability of logging residues is mapped to the spatially and temporally explicit demands. The cost includes logging residue extraction and transportation, considering current and future potential use. The scenarios consider variations in demand between specific sites and across sectors, as well as the configurations of transportation chains. The considered transport chains include the transportation of either chipped logging residues to the final user or local refining to methanol before transportation.

In this work, we apply the following terminology: *biomass* encompasses all bio-based materials; *bioenergy* is biomass used for energy purposes; and *liquid biofuels* are refined fuels, e.g., transportation fuels, produced from biomass.

Figure 2 illustrates the geographic scope of the study, including new and existing demand for bioenergy and biogenic carbon, as well as pulp mills and terminals considered for local logging residue collection and upgrading. Figure 2 also shows the division of Sweden into the four regions: Götaland, Svealand, southern Norrland, and northern Norrland. This division is used to define the regional supply and demand on a more highly resolved scale than nationally, since the conditions for logging residues, in terms of availability, transportation distances, conditions for off-road transportation, and demand, vary across the country.

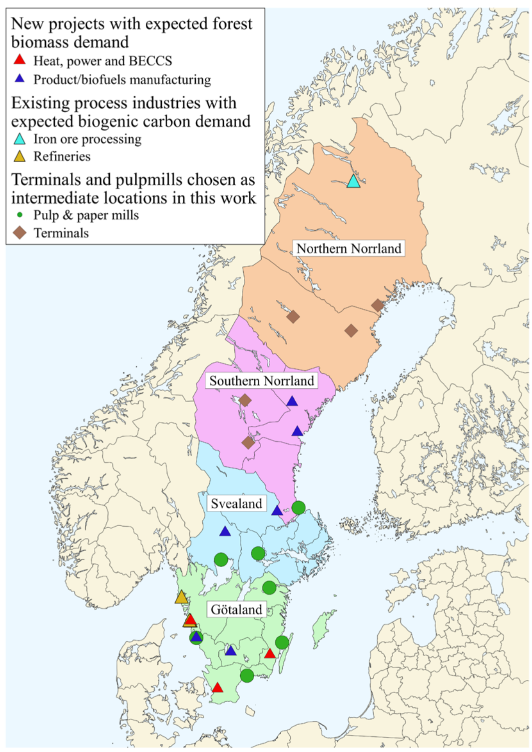

FIGURE 2 | Map of Sweden defining the geographic scope of this study. The expected additional bioenergy and biogenic carbon demands (new projects and in existing industry), as well as the pulp mills and terminals considered as collection points before bulk transportation are shown on the map. Existing bioenergy based heat and power plants (more than 200 plants in total, mainly located in southern Sweden) are omitted for clarity.

2.1 | Estimation of the Logging Residue Potential and Demand

2.1.1 | Mapping of the Biomass Potential From Logging Residues

Forestry data to estimate the time-resolved and spatially explicit volumes of logging residues from final fellings were obtained from the Forest Impact Assessments "SKA15" (Claesson et al. 2015; Skogsstyrelsen 2015). SKA15 uses the Swedish National Forest Inventory (Roberge et al. 2024) covering around 30,000 test areas of productive forest land around Sweden and the Heureka system (The Heureka System, SLU) to simulate the outputs of timber, pulpwood and logging residues from year 2010 to 2110 on productive forest land. We base our analysis on the SKA15 scenario called "Today's forestry", which assumes that the forest is harvested and managed in the same way as in recent years and that climate change corresponds to the IPCC emission scenario RCP4.5. The chosen scenario "Today's forestry" does not consider future changes in the distribution of harvested tree species, dominated by Norway spruce and Scots pine in terms of annual harvest. In this work, the results from three time periods, illustrating changes that occur in the heat and power and industrial sectors induced by Swedish climate targets, are chosen: current situation (2020–2024); short term (2030–2034); and long term (2040–2044).

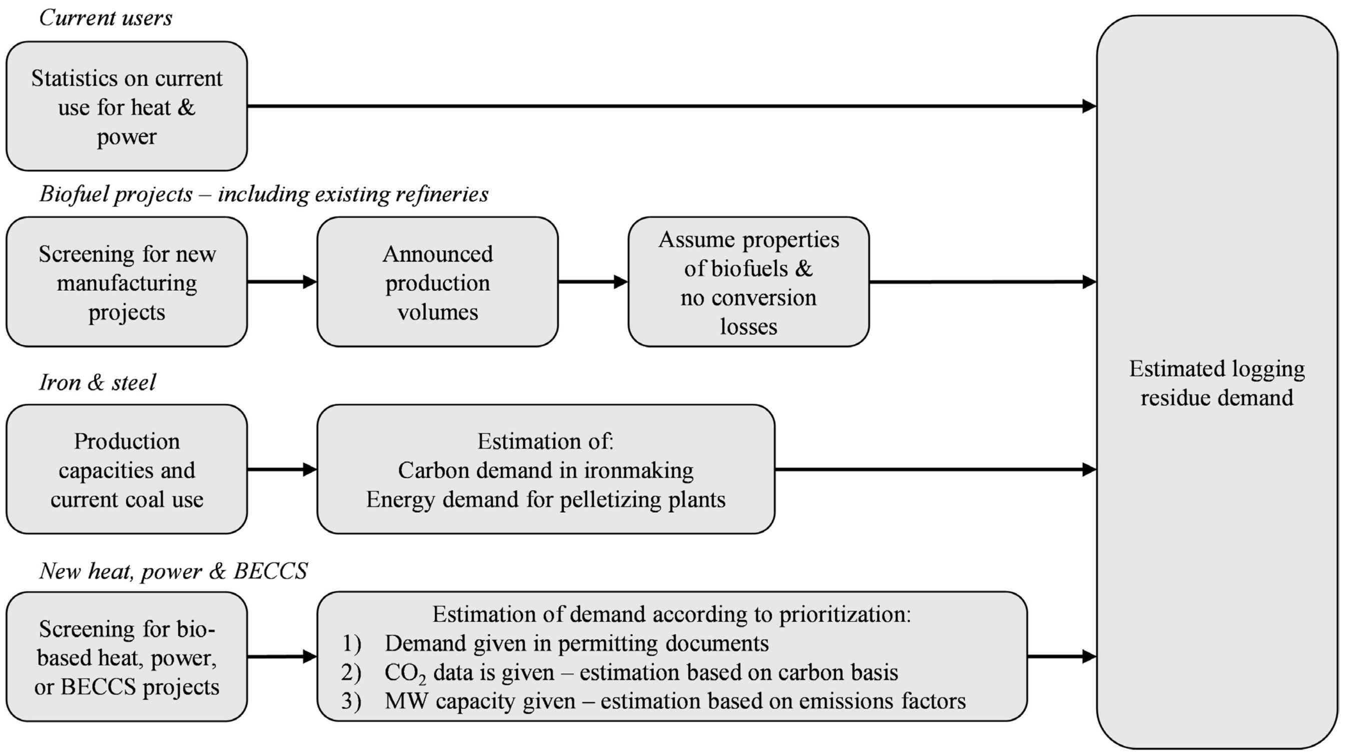

FIGURE 3 | Methodology applied to estimate the demands for bioenergy and biogenic carbon in the different sectors in this work.

In calculating the potential for harvesting logging residues from forestry, ecological restrictions, which exclude the extraction of residues from nature reserves, conservation areas, swamp forests and other forests with wet and moist soils, were applied (Drott et al. 2019). It is assumed that 30% of the potential logging residues are left at the felling site (higher than the 20% prescribed by the Swedish Forest Agency), and that 50% of the needle volume is left or falls off between material handling from the cutting site and chipping at the forest roadside, based on the practical experiences from Eliasson and Nilsson (2015). The WeCalc tool (Nylinder et al. 2016) was used along with the assumptions of 45% moisture content and 2.5% ash content for the chipped logging residues, giving an energy content of 4.8 MWh per dry tonne of logging residues. In the calculations performed in this work, the assumed moisture content of 45% is accounted for. The data used in this work is publicly available at Zenodo (Forestry Research Institute of Sweden 2025).

2.1.2 | Current and Future Demands for Logging Residues

Figure 3 outlines the procedure used to estimate the demands for bioenergy and biogenic carbon in the different sectors in this work. The logging residue demand for current users is taken from the work of Parklund (2023) and is aggregated for the four regions of Götaland, Svealand, southern Norrland and northern Norrland (*cf.* Figure 2). The estimated demand for future liquid biofuel projects, ironmaking, and heat and power projects (including BECCS) is based on announced projects and the resulting estimated demand for the considered future users is shown in Table 1.

In calculating the biogenic carbon demands for liquid biofuels, it is assumed that the produced fuel has similar properties to those of biodiesel, a density of 0.88 g/cm^3 (at 15°C) (Alptekin and Canakci 2008) an energy content of 38 MJ/kg (Energy Education 2024). In estimating the demand for forestry biomass for liquid biofuel production no conversion losses between the logging residues and the biofuel are assumed. Further, it is assumed that the announced production volumes correspond to a demand for logging residues. Thus, the numbers in Table 1 represent a theoretical demand. The actual demand will depend strongly on the chosen production route(s) and the share of the demand that is envisioned to be covered by forest-based biomass. These factors are uncertain, and thus, the numbers in Table 1 should be taken as an indication of the future demands from different projects in energy terms. For ironmaking, we assume an additional bioenergy demand to replace coal, and a carbon demand based on hot briquetted iron (HBI) production with 1% carbon by weight, assuming no carbon losses (i.e., that all carbon content in the logging residues can be transferred to the HBI). In traditional iron and steelmaking, the carbon content in the finished products comes from the use of fossil fuels in the production processes. When fossil fuels are phased out, carbon from other sources needs to be added.

The production levels for existing refineries are based on information from Preem (one of the two oil refining companies in Sweden producing transportation fuels), which is targeting the production of 5 million m^3 of biobased transportation fuels by Year 2035 (Preem 2021). For most of the 5 million m^3, oils and fats are planned to be used as feedstock. However, there is currently no feedstock planned for 1.255 million m^3 of the 5 million m^3 of the future liquid biofuel production. In addition, we assume that St1's refinery (the other oil refining company in Sweden

TABLE 1 | List of announced projects included in this work, their stated year of commissioning and the estimated demand for bioenergy and/or biogenic carbon.

Project	Type	Announced commissioning year	Estimated demand (GWh/year)
Heat, power and BECCS			
Göteborg Energi, new bio-boiler	New bio-fired boiler, potential for BECCS in the future	2026	262
Expansion of Örtofta CHP	Expansion of bio-fired boiler	2028	840
Norbex, Nybro	Gasification followed by electricity generation and BECCS	2028	525
Sum: Heat power and BECCS			*1627*
Manufacturing			
Swestep, Ljungby	Liquid biofuels	2025	74
FerroSilva and Ovako, Hofors	Gasification and direct reduced iron production	2026	175
SkyFuelH2	Aviation fuels	2028	1200
Södra Värö, biomethanol	Biomethanol	Unknown (assumed 2040–2045)	111
Värmlandsmetanol	Biomethanol	Unknown (assumed 2040–2045)	533
Biorefinery, Östrand	Liquid biofuels	Unknown (assumed 2040–2045)	1800
LKAB	HBI production & pelletizing	2030, Pelletizing 2045, HBI	3188 (782 for pelletizing, 2406 for HBI)
Preem	Liquid biofuels	2035	11,657
St1	Liquid biofuels	2035	5829
Sum: Manufacturing			*24,567*

producing fuels) will have a demand corresponding to 50% of the estimated levels for Preem, based on the fact that the St1 refinery currently processes around half of the crude oil, as compared to Preem's refineries. For ironmaking, the current demand for coal in pelletizing plants is taken from the Chalmers Industrial Case Study Portfolio, ChICaSP (for more information, see Svensson et al. (2019)). The carbon estimation for HBI production is based on the maintained production of iron ore, assuming that hydrogen reduction will be implemented for full iron ore production.

New heat, power and BECCS projects include projects that aim to install new bioenergy-based capacity for district heating and power production, with BECCS as a component in one of the listed projects. In addition to the listed projects, there are projects aimed at installing BECCS on existing bioenergy-based heat and power plants. However, the logging residue use from such plants is already included in the estimate for current users, and since it is not certain that BECCS would yield an increased demand for logging residues as opposed to reduced output of electricity or heat, they are excluded from the analysis.

2.2 | Investigated Demand Over Time and Transportation Scenarios

The bioenergy and biogenic carbon demands from Table 1 are applied over time in the different scenarios according to Table 2. The *Other new users* category in Table 2 summarizes announced smaller manufacturing projects, together with heat, power and BECCS plants with individual estimated biomass demands of less than or equal to 1.8 TWh/year. The *Business as usual scenario* assumes a constant demand for logging residues from the current users, as well as unchanged transportation and usage patterns, with no new future users. In the *Planned development* scenario, the demand from new users is allocated to the short- and long-term based on matching the announced commissioning year, as indicated in Table 2, to the closest of the short- or long-term periods. The logging residue demand from the current users in the heat and power sector is maintained. The *Alternative development* scenario investigates a development in which the biofuel production plans are delayed by 10 years in the refinery sector, while the demand for logging residues in the iron and steel industry peaks in the period of 2030–2034. The *Alternative development* scenario covers a situation in which slightly lower demands are included and these demands are more distributed in time.

As shown in Figure 4 this work investigates two process configurations, with the process of gasification and methanol synthesis of logging residues at local collection points (Figure 4a) considered as an alternative to transporting unrefined logging residue chips (Figure 4b). The configuration in Figure 4a is investigated and compared to the supply chain in Figure 4b for refineries specifically, since receiving methanol as opposed to logging residues could provide practical benefits such as requiring storage space on site and easier refining to higher value products. Methanol was chosen in this work as an example of an energy carrier with existing markets and production paths, that could also be used for further refining to other products and transportation fuels. The methanol synthesis performance data are taken from the Danish Energy Agency (2021) and from the paper of Andersson et al. (2014).

2.3 | Cost Estimation

Logging residue supply chain activities consist of forwarding (i.e., transport from the harvesting site to the forest roadside), comminution (chipping), and onward road transportation on a chip-truck, by railway or by ship. It should be noted that no harvesting costs are allocated to logging residues, since logging

TABLE 2 | Bioenergy and biogenic carbon demands applied in the scenarios studied in this work for the current situation, short-term, and long-term timeframes.

Scenario	User	Current demand: 2020–2024 (TWh/year)	Short-term demand: 2030–2034 (TWh/year)	Long-term demand: 2040–2044 (TWh/year)
Business as usual	Current users	7.8	7.8	7.8
Planned development	Current users	7.8	7.8	7.8
	Refineries	*7.8*	17.5	17.5
	I&S: Pelletizing		0.8	0.8
	I&S: HBI		3.1	2.4
	Other new users		*29.2*	5.5
	Total			*34.0*
Alternative development	Current users	7.8	7.8	7.8
	Refineries	*7.8*	0.8	17.5
	I&S: Pelletizing		3.1	5.5
	Other new users		*11.7*	*30.8*
	Total			

Abbreviations: HBI, hot briquetted iron; I&S, iron and steel manufacturing.

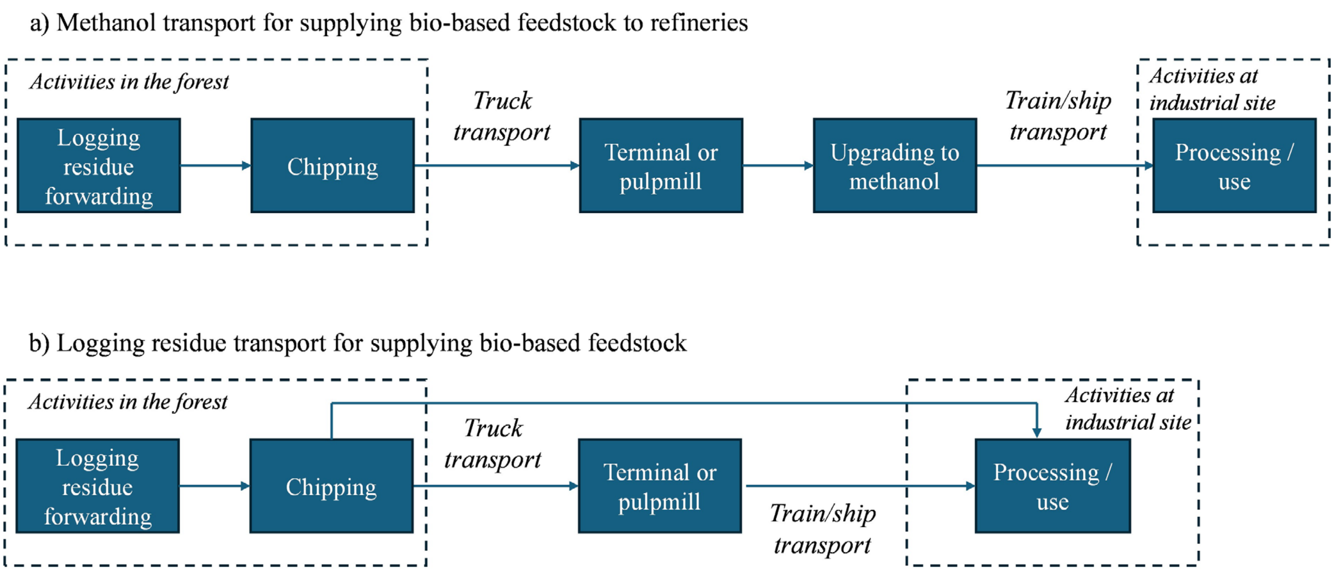

FIGURE 4 | Supply chains considered for supplying logging residues to the refinery sector. In (a), methanol synthesis is performed at the intermediate locations (pulp mills and terminals) before onward transportation to refineries. In (b), the logging residues are transported all the way to the site before further processing or use.

residues are a by-product of timber and pulpwood harvesting activities, which therefore bear the actual harvesting cost. Landowner compensation, administration costs, and a margin for risk and profit are not included in the supply chain costs, since these will vary significantly depending on individual business agreements. Compensation to landowners for extraction of logging residues and "different overhead costs" are included as a constant value by Lundmark et al. (2015), aiming to show the "total supply cost". However, we consider it difficult to include such values due to the diversity in agreements between suppliers and consumers of logging residues. Excluding these costs might also ease comparisons between studies, and if needed, the reader could calculate the 'total supply cost' by using their own values. This means that the costs presented in this work will not directly reflect the market price of logging residues, but rather the physical cost of extraction and transportation.

In this work, we establish regional marginal cost curves, showing the expected cost as a function of the volume of material extracted, chipped and transported if no major changes are made in the industrial landscape. For cases involving large future industrial developments, average costs for specific cases are investigated. The average exchange rate applied is that for the cost year of 2020, i.e., 10.48 Swedish crowns (SEK) per euro (€).

TABLE 3 | Data used for calculations of the costs for terrain transport (forwarding), comminution, and onward transportation in this work.

Parameter	Value	References
Terrain transport cost (forwarding) (€/h)	102.1	
Comminution cost (€/MWh)	4.58	Eliasson 2021
Diesel price in Year 2020 (€/l)	1.38	Drivkraft Sverige 2023
Diesel price in Year 2020 excl. VAT (€/l)	1.06	
Diesel price in Year 2020 excl. VAT, incl. tax deduction for forest contractors (€/l)	0.87	
Electricity price for rail transport in 2020 (€/kWh)	0.042	SCB 2023

2.3.1 | Logging Residue Forwarding, Comminution and Transportation Costs

Table 3 lists the values applied for the calculations of terrain transportation, comminution and onward transportation costs. Table 4 gives the resulting unitary costs for the onward transportation of logging residues (by truck, rail and ship transport) and methanol (ship and rail transport) in the four regions of Sweden studied. In Table 3, the applied price of diesel for truck transport excludes value-added tax (VAT), and the diesel price applied for terrain transport and comminution excludes VAT and includes an energy tax deduction for forest contractors.

For terrain transportation, existing productivity norms were used to calculate the time required to forward logging residues to the roadside, as a function of the logging residue concentration per ha, driving speed, and terrain ("off-road") transport distance (Eliasson and Brunberg 2013). Terrain distance was calculated from the center of the supply point to the nearest forest road and corrected with a regional tortuosity factor using actual terrain distances (Biometria 2022; Brunberg 2017). For the comminution of logging residues, the representative value for Year 2020 was used. For the costs in the short-term (2030–2034) and long-term (2040–2044) timeframes, it is assumed that the price of diesel is doubled.

The cost for rail and road transportation of logging residues was calculated using the model of Fjeld et al. (Fjeld et al. 2021), tailoring the input values to Swedish conditions (Enström and Winberg 2009; Noreland 2020), while railway transportation of methanol was based on data from the Swedish Transport Agency (Trafikverket 2024). It was assumed that the price of electricity for rail transport increases at the same rate as the price of diesel.

For ship transportation, we applied the tonne-km costs for bulk carriers and tanker ships presented by Bernacki (2021a, 2021b) for logging residue shipping and methanol shipping, respectively. For both the bulk carriers and tanker ships, we chose the costs for the smallest ship size, due to the relatively small volumes of goods to be transported over relatively short distances. The costs presented are given in $€_{2019}$, which we adjust to reflect the Year 2020 value by multiplying by a factor of 1.0074, reflecting the change in purchasing power over this interval.

TABLE 4 | Unitary transportation costs for logging residues and methanol for the relevant transport modes, with cost assumptions corresponding to the current situation (2020–2024) for the different regions of Sweden.

	Road transport costs (€/tonne-km)				Train transport costs (€/tonne-km)	Ship transport costs (€/tonne-km)
Product	Northern Norrland	Southern Norrland	Svealand	Götaland	Whole country	Whole country
Logging residues (chipped)	0.204	0.205	0.213	0.215	0.018	0.0021
Methanol	—	—	—	—	0.016	0.0022

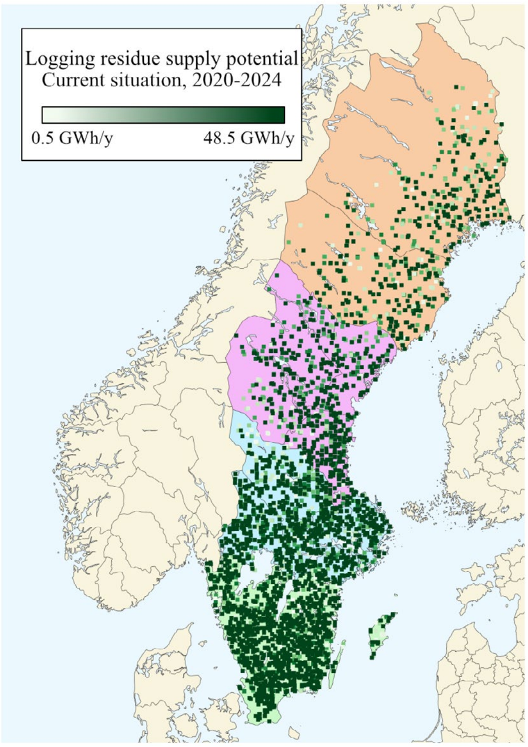

FIGURE 5 | Representation of the logging residue supply potentials in the current situation (2020–2024) at the supply points considered in this work. Each supply point corresponds to the amount of logging residues indicated by the color in the legend. Note that the supply points represent surrounding forest areas, such that the indicated supply potential is not limited to the discrete points displayed in the map.

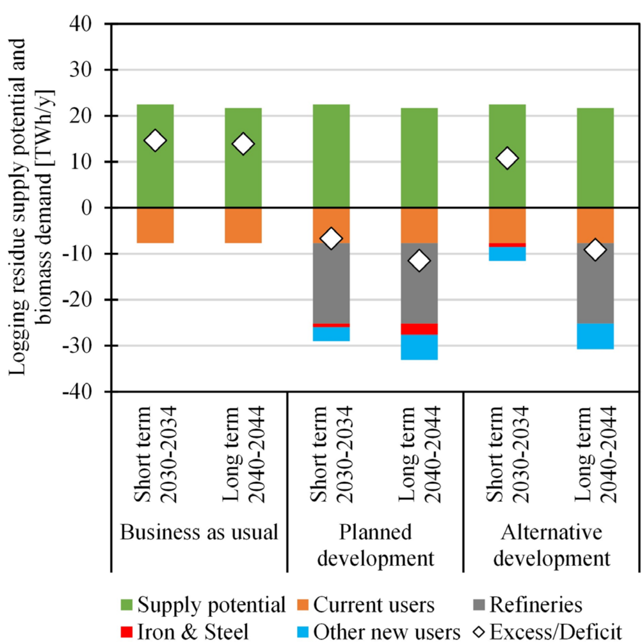

FIGURE 6 | National supply potentials and estimated demands for bioenergy and biogenic carbon in the three scenarios investigated in this work in the short-term and long-term timeframes.

2.4 | Transportation Distances

Transport data for logging residues from Biometria (2018–2020) were used to calculate the average transport distances for logging residues that were being transported either directly to an end-user or to a terminal. For the calculation of transportation distances to new industrial users, the actual transportation distances from the forest, via a terminal or pulp mill, to the new industrial end-user were estimated. Transportation distances from the forest to the terminal (or pulp mill) were calculated as a straight-line distance ("as the crow flies"), corrected with a tortuosity factor of 1.3, which is regarded as representative for road transport of roundwood in Sweden (Dietrichson and Jensen 2010; Nylund and Sundby 2011). For the estimation of train distances from terminals and pulp mills to industrial users, an open access online tool was used that calculates the shortest railway path between two points in the Swedish railway network (Tydal–Distance calculation). For ship transportation, the distances were estimated by measuring the distance between two ports using the measuring tool in the QGIS software.

3 | Results

In the presentation and discussion of the results, the *supply potential* of logging residues is defined as the possible out-take given the constraints (see Section 2.1.1) imposed on logging residue extraction, as applied in this work. An *excess* or *deficit* is defined as the difference between the logging residue supply potential and the bioenergy and biogenic carbon demands in any geographic area.

3.1 | National Logging Residue Supply Potential and Bioenergy and Biogenic Carbon Demands

Figure 5 shows a representation of the calculated logging residue supply potential for the supply points that are currently covered. It should be noted that the supply potential shown in the points represents the volume of logging residues available in a forest area surrounding the supply point, such that logging residues are not limited to the discrete points displayed in the map. From Figure 5 it is clear that the south of Sweden has a large supply potential compared to the north of the country. This is primarily due to differences in forest conditions and harvesting activity between the regions, with the south of Sweden generally having higher growth and harvesting rates. For the current situation, the supply potential of logging residues in Sweden amounts to 21.1 TWh/year, with 27%, 25%, 27% and 21% of the estimated potential in Götaland, Svealand, southern Norrland and northern Norrland, respectively. The differences in logging residue potentials between the regions are attributable to different forest conditions, such as the area of productive forest land, the forest growth rate, and the expected forest management and harvesting activities. The actual extraction of logging residues was equivalent to 7.8 TWh in Year 2020 Swedish Energy Agency Eliasson 2024b, which corresponds to 37% of the calculated potential. The differences in extraction of logging residues are also substantial between the regions: 83% of

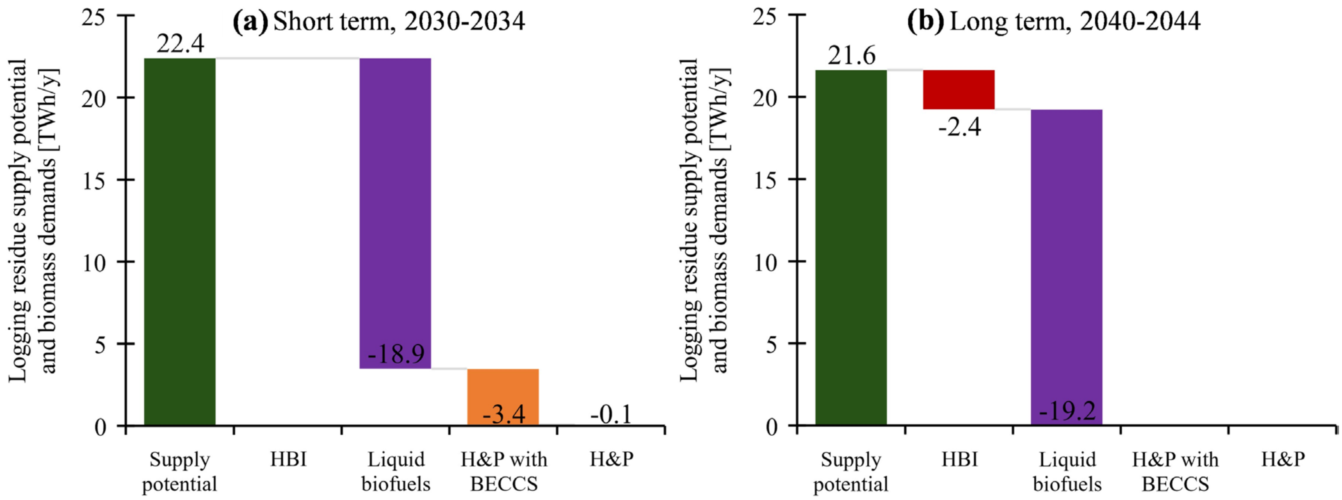

FIGURE 7 | Logging residues supply potentials and biomass demands, cascaded according to the prioritization order of: (1) Ironmaking (HBI); (2) Liquid biofuel manufacturing (Liquid biofuels); (3) Heat and power production with BECCS (H&P with BECCS); and (4) Heat and power production without BECCS (H&P), in (a) the short-term and (b) the long-term timeframes.

the supply potential is used in Götaland, 48% in Svealand, 7% in southern Norrland, and 1% in northern Norrland.

Figure 6 presents the short- and long-term national supply potentials of logging residues, along with the estimated demands from the industries considered in the three scenarios. In the short term, the *Business as usual* scenario supply potential greatly exceeds the demand, as no new demand is introduced, and the logging residue excess amounts to around 15 TWh/year. In the *Planned development* scenario, the demand from the refinery sector to meet the planned liquid bio-fuel production targets outweighs the possible supply, and there is a deficit of 7 TWh/year. In the *Alternative development* scenario, the demand from the refinery sector is first seen in the long term and there is a short-term logging residue excess of roughly 11 TWh/year. In summary, depending on the realization and the rate of implementation of liquid biofuels production, logging residues have the potential to cover the short-term needs for bioenergy and biogenic carbon. However, if the demands from the refinery industries are realized during the early 2030s, the levels of logging residues are not sufficient even in the short term, so other biomass assortments, import of biomass or alternative low-emissions fuel production pathways (for instance, electro-fuels) should be considered.

In the long term, the *Planned development* scenario shows greater demands, specifically in the iron and steel sector and other new demands from biofuel and BECCS projects, and the deficit reaches around 12 TWh/year. In the *Alternative development* scenario, the demand from the iron and steel sector is phased out towards the long-term timeframe, while the demand from the refinery sector appears, and the deficit is reduced to 9 TWh/year. Due to the relative sizes of the demands, where the demand from biofuel manufacturing, specifically in the existing refinery sector, drastically exceeds all the remaining demands, changes made in other sectors have only a marginal impact on the overall supply–demand balances.

Figure 7 shows how the supply potential of logging residues would be prioritized in the *Planned development* scenario when applying an interpretation of the cascading principle, whereby carbon for HBI is assigned the highest priority (longest-lived product), liquid biofuel production is the second-highest priority, heat and power generation with BECCS is the third-highest priority, and heat and power generation without BECCS is the fourth-highest priority. Thus, Figure 7 takes the full supply potential and cascades it according to this order of prioritization. The rationale here is that some applications will be easier to decarbonize without the use of biomass than others. For instance, heating and electricity generation are in principle not dependent upon the use of carbon-based fuels; electricity could be supplied by wind, solar and nuclear power without any demand for carbon, and heating could then be provided by heat pumps (and possibly electric boilers). However, considering those industries whose products rely on the presence of carbon in the products, such as the refinery and iron and steel industries, there is an inherent demand for carbon to produce the products. Heat and power production with BECCS is prioritized over heat and power generation without BECCS due to the added climate value provided by carbon dioxide removal (CDR). Heat and power plants with plans for BECCS are estimated to have a future demand of roughly 3.4 TWh/year, including large current users of logging residues with plans for BECCS at existing sites, and announced projects in Table 2.

The results in Figure 7 show that if the demand increases according to the planned development scenario, there would be sufficient logging residues to supply the demand for biofuel production in the short term, while also fulfilling an estimated 3.4 TWh demand for heat and power applications with BECCS, leaving a negligible excess of logging residues for heat and power applications without BECCS. In the long term, the demand for carbon in ironmaking is also met, and the full supply potential of logging residues is used for either the iron and steel industry or the production of liquid biofuels. The full demand for biogenic carbon for liquid biofuels (around 21 TWh/y) cannot be met in the long term. This means that concomitant demands for logging residues from carbon in ironmaking and the planned biofuel production projects cannot be delivered by the national logging residue supply potential, even without any logging

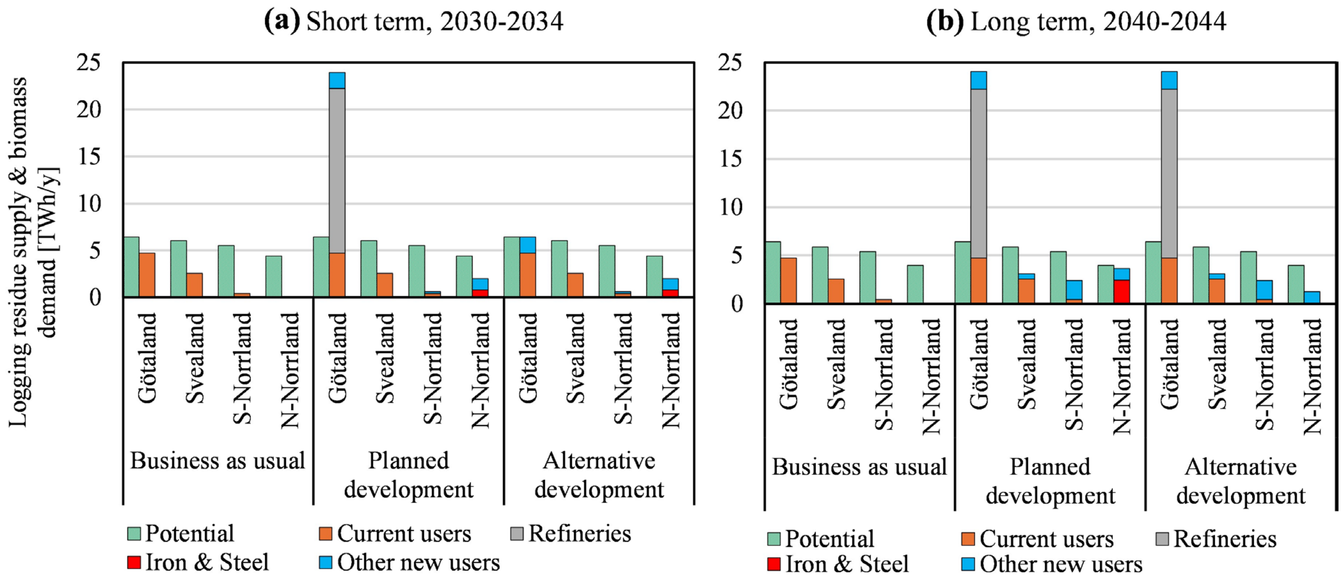

FIGURE 8 | Regional logging residue potentials (dashed green bars) and biomass demands (solid bars) for the three scenarios studied in this work, in (a) the short-term and (b) the long-term timeframes.

TABLE 5 | Excess logging residues in Svealand and Norrland for the long-term timeframe, 2040–2044, in the scenarios investigated in this work.

Scenario	Excess logging residues in Svealand and Norrland in the long-term timeframe [TWh/year]	Deficit in Götaland in the long-term timeframe [TWh/year]	Share of deficit in Götaland that can be covered by excess logging residues from Svealand and Norrland
Business as usual	12.2	—	—
Planned development	6.1	17.6	35%
Alternative development	8.5	17.6	48%

residues being used for heat, power and BECCS, further highlighting the need for other carbon sources.

3.2 | Regional Supply and Demand Balances

Figure 8 breaks down the supply and demand for the four regions in the short-term and long-term time perspectives. In the short-term (Figure 8a), the regional supply potential is larger than the demand, with the exception of the refinery demand in Götaland in the *Planned development* scenario. This implies that the current logging residue transportation infrastructures (mainly trucks) are likely to be sufficient to supply the demands in three out of the four studied regions. Naturally, with the demand for biogenic carbon from the refineries, the regional demand in Götaland is severely unbalanced (17.5 TWh/year demand relative to a 6.5 TWh/year supply), such that the excess logging residues from other regions might be transported to Götaland. Although more demands arise in the long-term (Figure 8b) in the *Planned development* and *Alternative development* scenarios, a logging residue excess can still be observed in three out of the four studied regions.

In the *Planned development* scenario, the magnitudes of the excess of logging residues in Svealand and Norrland are smaller than in the *Alternative development* scenario. In the case of the *Planned development* scenario, this is due to the higher demand assumed from the iron and steel sector. Table 5 further highlights this by showing the excess logging residues potentials in Svealand and Norrland and the deficit in Götaland, along with the share of the deficit that could be covered by the excess in the long-term timeframe. The results show that the *Planned development* scenario presents a worst-case situation in terms of being able to cover the deficit in Götaland with the excess from Svealand and Norrland; in this scenario, only 35% of the deficit could be covered. In the *Alternative development* scenario, the excess from Norrland and Svealand can cover 48% of the deficit in Götaland. This trend shows that although the demand for bioenergy and biogenic carbon in Götaland is higher than the excess logging residues on a national level, the extent of the demand in other sectors has a significant impact on the ability of the logging residue excess to cover the demand from the refineries.

3.3 | Cost of Supplying Logging Residues to Current and Future Users

3.3.1 | Marginal Cost of Supplying Logging Residues According to Current Use Patterns

Figure 9 presents the marginal cost curves for logging residues in the *Business as usual* scenario (in which the current industrial

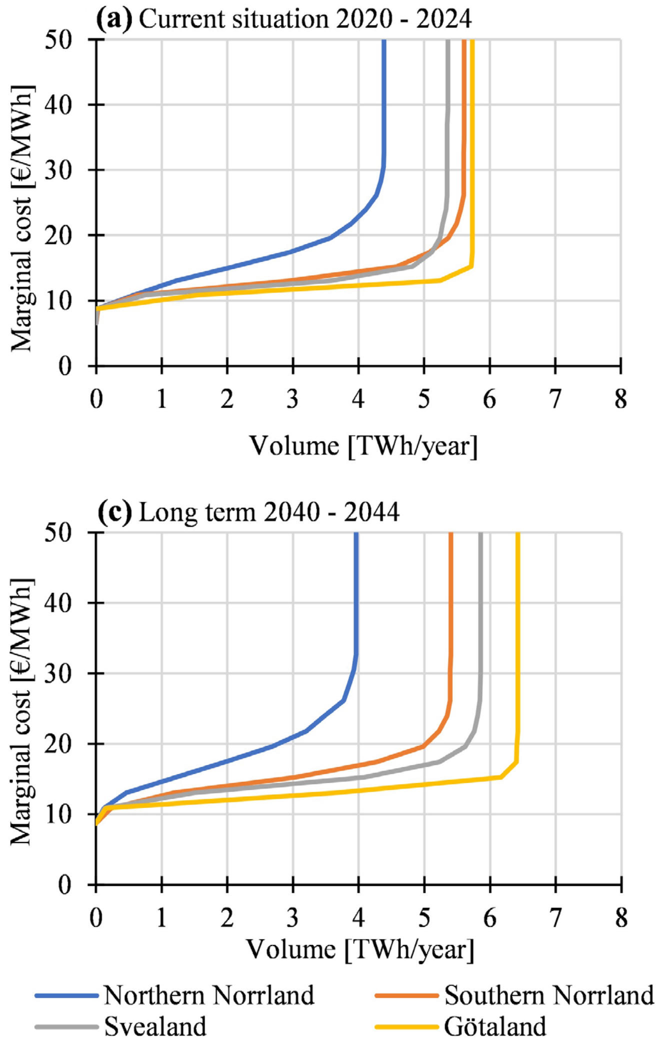

FIGURE 9 | Calculated marginal costs for logging residues in the Business as usual scenario for the (a) current situation, (b) short-term and (c) long-term timeframes. Note that the marginal costs only consider costs for the physical extraction and transportation of logging residues according to current usage patterns, and do not reflect the market price, which in addition includes, for example, administration costs and profit margins that can vary depending on the business agreement.

landscape is assumed to be maintained without any changes), for the three studied time periods in this work (current situation, short term, and long term). The marginal cost curves present the unit costs (€/MWh) of the logging residues in these regions, as a function of the volume of logging residues (TWh) that can be taken out of the forest each year.

The logging residue cost increases from south to north, mainly due to the longer transportation distances from the forest to the railway terminal or end-user. The supply potential of logging residues is greatest in Götaland, where the costs for extraction and transportation are also the lowest with current usage patterns. In Götaland and Svealand, logging residues are currently used extensively for district heating and power production (Svebio 2021), and the transportation distance between the forest and the end-user is relatively short compared to northern Sweden. In Year 2020, the average road distances for logging residues were 59, 64 and 70 km for Götaland, Svealand, and Norrland (northern and southern Norrland combined), respectively, according to Davidsson et al. (2023). A difference in transportation distance of 11 km between (the difference between the average in Norrland and Götaland) contributes to a difference in cost of just above 1 €/MWh, indicating that road transport costs will increase significantly if road transportation distances are increased in the order of 100 km or more. Today's annual extraction logging residues corresponding to 7.8 TWh would give a predicted marginal supply cost of about 13.2 €/MWh, with terrain transport accounting for 31%, comminution for 35%, and road transport for 34% of the cost. The predicted marginal cost of 13.2 €/MWh for Year 2020 is in line with the actual supply cost reported in the survey of Eliasson (2021) and, as expected, it is below the average market price for wood chips paid by heating plants in Sweden, i.e., 19.2 €/MWh in Year 2020 (Swedish Energy Agency 2024a).

The results imply that it is cost-effective to prioritize the mobilization of logging residues close to new users, in order to keep the costs down. Due to the low current usage of logging residues in northern Norrland, the physical costs for mobilizing regional logging residues to the existing iron and steel industry are expected to be in line with the regional marginal costs in both the short and long terms. However, looking more closely at the expected regional distribution of the supply and demand in Figure 8, large parts of the new demands are expected to be located far from the excess logging residues; therefore motivating the deployment of new transportation infrastructures.

3.3.2 | Transport From Supply to Demand Regions

As established by the regional supply and demand balances for logging residues, it should be possible to supply regionally the demands in Svealand and Norrland. However, the refineries in Götaland create a much larger demand than can be supplied regionally. Figure 10 presents the costs of forwarding, chipping and transporting the logging residues to the closest terminal (in northern and southern Norrland) or pulp mill (in Götaland and Svealand), methanol synthesis (in the case of distributed methanol synthesis), and onward transportation in the form of either logging residues or methanol to the refineries in Gothenburg (in Götaland) for the long-term time frame. The transportation chain is based on trucks to terminals or pulp mills, followed by trains in the case that the terminal or pulp mill is landlocked with railway access, or ships in the case that the terminal or pulp mill is located on the coast. The costs presented in Figure 10 differ from the marginal costs presented in Figure 9, which are based on the current use and transportation patterns without any consideration of new industrial establishments and transportation chains. The most significant part of the costs presented in Figure 10 is the ones related to methanol synthesis in the case of methanol transport. This means that the value for the refinery, in terms of practicality and ease of further processing, of receiving methanol compared to logging residues, needs

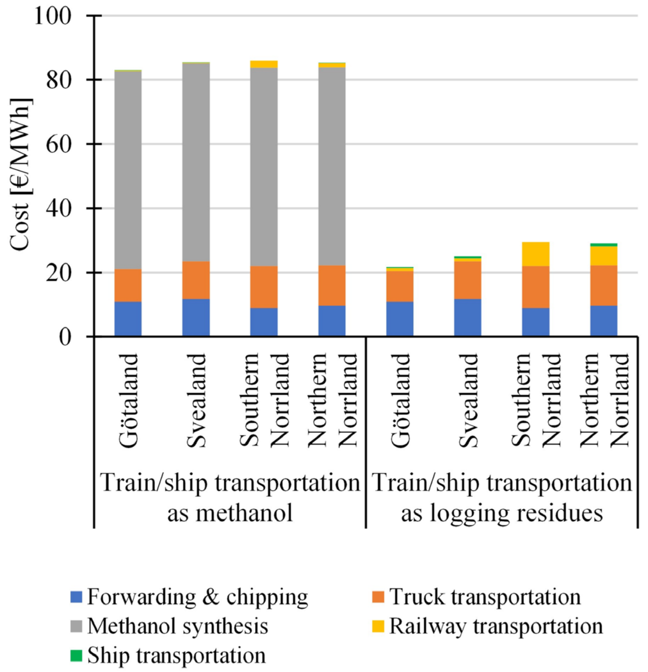

FIGURE 10 | Regional costs for forwarding and chipping, and the transportation of logging residues to the closest terminal/pulp mill, with onward transportation as either logging residues or methanol to refineries for the long-term time frame. Note that the costs are levelized against the energy content in the processed logging residues, to allow for comparison between the cases.

to outweigh the additional cost incurred by the methanol synthesis. If distributed methanol synthesis is not considered, the train transport of logging residues from Norrland to the refineries makes up a significant fraction of the total supply cost and a reduction in cost for transporting methanol instead of logging residues is seen, primarily for long transportation distances.

Looking into the transportation cost, for transport from Norrland to Gothenburg, which is 700–1600 km by train depending on the terminal and 1700 km by ship, the cost of transporting methanol is around 5–10 €/MWh lower than the cost of transporting chipped logging residues. This is a significant difference, but not enough to outweigh the cost of methanol synthesis, again highlighting that the added value for the refinery of receiving methanol compared to chipped logging residues needs to make up the difference in order to motivate the distributed synthesis supply chain.

4 | Discussion

The results show that considering the current and future demands for biomass, there will be a deficit if logging residues are to be applied to all future demands assumed in this work. Thus, it is possible that the market price for logging residues will increase in the future, or that roundwood could see an increased demand for other end products compared to today, as the demands from more sectors increase. In the absence of policies that regulate the allocation of biomass resources, the willingness to pay for the resource will ultimately determine to which sectors it is allocated, and it is reasonable to assume that the added value of liquid biofuels will be higher than that of district heating. However, if a high value is placed on CDR, BECCS may also outcompete other uses.

Due to the massive demand for biogenic resources that will come from the refinery sector if it transitions away from its reliance on fossil fuels, other biomass resources than logging residues will be necessary to explore. It should be noted that the production levels of liquid biofuels at refineries investigated in this paper entail a significant downsizing compared to current fossil production capacities. Even with that, the ambitions of the refineries would be difficult to achieve using logging residues. In comparison, the demands from other sectors are relatively modest, meaning that even if they are reduced, the demand from the refineries will still be difficult to supply. Looking at alternative biomass streams, Börjesson (2021) estimates that around 38–58 TWh/y of forestry-based, aquatic and agricultural biomass assortments other than logging residues could be made available nationally in Sweden by 2050. Enabling these streams to be used for manufacturing and energy purposes could help bridge the gap between the demand and supply observed in this work. It is also possible that additional demands will arise in the future, such as those for BECCS, biofuels or other chemical production projects that are yet to be announced. This further highlights the importance of investigating several different biomass and carbon resources as feedstocks for the refineries, as well as furthering the development of electrofuels or non-carbon fuels for aviation, heavy road transport and maritime applications in parallel with the ongoing electrification of the transport sector.

Utilizing captured CO_2 to produce e-fuels is an alternative fuel production pathway that would not compete with current uses for logging residues, and the Swedish pulp and paper industry and heat and power sector present several large point sources of biogenic CO_2. Yet, this will obviously require electricity for which there will be a high demand from electrification of the industry and transport sectors. In addition, lignin from pulp mills and sawdust from sawmills could be used as alternative feedstocks for biofuels. Currently, lignin extraction at pulp mills is not performed on a large scale, so there is no competition with existing users. On the other hand, lignin extraction would require investments in additional process units at relevant pulp mills, and the operators of the mills would need to be convinced that there is a good business case before investing in such technology. Lignin extraction is performed at one pulp mill in Finland, producing around 50 kt/year of lignin. If the same proportion of lignin in relation to pulp production would be extracted from the 10 largest pulp mills in Sweden this would result in roughly 700 kt/year of lignin, which is a small amount relative to the expected future biomass demands.

Regarding sawdust, roughly 6 million tonnes are generated in sawmills around Sweden, although the majority of this is already in use for heat generation, both for district heating generation and in small-scale heating applications, and the resource is spread over many sawmills across the country (Eriksson and Parklund 2023). Since most of the generated sawdust is already in use, competition for this resource can be expected in the future, as the demand for residual biomass streams increases. Sawdust is a potential feedstock for pyrolysis oil, and the Swedish company Pyrocell (jointly owned by the wood product company Setra and the Preem refining company) produces around 25 kt/year of pyrolysis oil from sawdust for use in Preem's refinery. It could be argued that the production of materials and transportation fuels should be priority areas for biomass use, as opposed to district heating and power generation, since this could reduce the reliance on more energy-intensive production pathways for biofuels, such as e-fuel production and since there are alternatives for the production of heat and electricity. In this work, an analysis re-prioritizing logging residues as feedstock for the process industry is carried out, and it is shown that logging residues are not sufficient to cover simultaneously the demands for carbon in ironmaking and liquid biofuel manufacturing.

Furthermore, the results show that from a transportation cost perspective, there is an advantage in transporting methanol rather than chipped logging residues over distances between 750 and 1500 km (around 5–10 €/MWh less transportation cost in the studied case). This is not enough to outweigh the cost of methanol synthesis, which means that the added value for the refinery of receiving methanol compared to chipped logging residues needs to make up the difference in order to motivate the distributed synthesis supply chain. The availability of space at industrial sites such as refineries is usually quite limited, and space is a valuable asset for the company. It is, therefore, unlikely that there will be space for a large wood chip storage on site, as such storage would take up significantly more space than chemical tanks that could be used for methanol storage. Thus, even if the additional cost of distributed methanol synthesis is not outweighed by the lower transportation costs, it might make sense to pay the premium.

Since the supply potential of logging residues is inherently tied to the harvesting of roundwood, developments that influence harvesting rates either positively or negatively will indirectly influence the logging residue supply. For instance, increasing the carbon sink in the LULUCF sector in Sweden could lower the amount of logging residues that is available for industrial and heat and power applications, resulting in a higher demand for other biomass assortments or fuel production pathways. Moreover, other trends in the transition of silvicultural systems, from today's rotation forestry-dominated system towards a larger share of continuous cover forestry, can also lower the amount of available logging residues in similar ways, as present thinning operations do not allow logging residue extraction.

The assumption regarding maintained harvesting activity made in this work presents an uncertainty, since the direction of future forest management strategies is unknown. Furthermore, only considering logging residues, and excluding other biomass assortments from the analysis is one major limitation of the work. Nonetheless, the analysis performed in this work shows that there is a need to establish new and efficient supply chains to connect regions of high biomass availability with regions of high supply to enable the transition away from fossil fuel-based industry. Transitioning the refinery industry towards utilizing more forest residues would provide substantial climate benefits compared to the fossil feedstocks that are used today. It would also likely have an impact on the existing logging residue market, where the current dominating use is for bio-based heat and power generation, which is likely to have a lower added value than liquid biofuels. This could also impact the demand for other biomass assortments, that are currently used for other end purposes than energy products.

5 | Conclusions

The work presented in this paper highlights the importance of connecting biomass supply and demand regions to enable the transition of fossil-based processes to bio-based alternatives, and to enable the establishment of new bio-based processes. Currently, logging residues are primarily extracted in the southern parts of Sweden, where the supply potential is strongest. Within the current industrial landscape, the costs for extraction and onward transportation of logging residues increase on a gradient from south to north, primarily due to increasing transportation distances. For an expected out-take of 3 TWh/year, the calculated supply costs are 12.9, 13.8, 14.4, and 19.3 €/MWh progressing from the southernmost to the northernmost region.

With the increasing demand for bio-feedstock by refineries, estimated as 17.5 TWh/year in the Swedish case study, regionally sourced excess logging residues will not be sufficient to cover the demand. The high local demand in southern Sweden and the high local supply in northern Sweden illustrate the importance of establishing efficient transportation routes for low-grade biomass or intermediate carbon carriers. Reducing the gap between the logging residue supply and demand for biogenic feedstock at the refineries could be achieved by transitioning the heat and power sector so that it utilizes waste heat and electrified heating sources, thereby reducing the reliance on logging residues. Re-prioritizing the use of logging residues to ironmaking and liquid biofuel production, it is shown that logging residues could satisfy around 90% of the estimated future demands for HBI production and liquid biofuels.

The results presented in this work highlight that logging residue transportation patterns will need to change going forward to enable a higher utilization of the resource where the demand is expected to be high. Furthermore, although the supply potential of logging residues estimated in this work is large, due to the high expected demands from future users, specifically in the refinery sector, there is a need to explore the utilization of other biomass and carbon sources and establish supply chains that enable their utilization.

Author Contributions

Sebastian Karlsson: formal analysis, investigation, methodology, visualization, writing – original draft. **Anders Eriksson:** formal analysis, investigation, methodology, writing – review and editing. **Raul Fernandez-Lacruz:** formal analysis, investigation, methodology, writing – review and editing. **Johanna Beiron:** supervision, writing – review and editing. **Fredrik Normann:** conceptualization, supervision, writing – review and editing. **Filip Johnsson:** conceptualization, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.17689223.

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