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Environmental Impact Assessment of Logging Residue Utilization for Increased Bioenergy Production from Scots Pine Forest Stands in Lithuania Using a Life Cycle Approach

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Abstract

The strategic importance of forest biomass as a renewable energy source is growing across the EU, driven by climate goals, energy security, and the abundance of logging residues. While logging waste offers considerable potential for bioenergy production, its life cycle environmental impacts remain insufficiently understood. This study evaluates the impacts of utilizing Scots pine (*Pinus sylvestris*) logging residues for energy production in Lithuania using a comparative life cycle assessment (LCA). Two harvesting scenarios were assessed at midpoint and endpoint levels: one excluding and one including logging residues. The results show that about 173.2 tons of biofuels can be produced from one hectare of Scots pine forest over a 100-year cycle, generating up to 513.6 MWh of energy when residues are utilized. The LCA revealed improvements in 9 of 18 impact categories, with greenhouse gas avoidance increasing from –52 to –89.5 t CO_2 eq, and overall endpoint impacts decreasing by nearly 39%. The novelty of this study lies in applying established LCA methods with region- and species-specific data, partly obtained through monitoring, for Scots pine residues in Lithuania, while extending system boundaries to include soil degradation, storage losses, and ash management—providing a more holistic and Northern Europe-relevant perspective.

Keywords: solid biofuel; biofuel supply chain; forest residues; life cycle assessment

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1. Introduction

The importance of solid biofuel as an energy source is likely to increase during the coming years not only because of European Union (EU) environmental policies, but also as it is available in all the EU countries [1]. Scientists assessed the availability of forestry residues that could potentially be used for advanced biofuel production. They claim that most EU Member States are likely to have more than enough sustainably available feedstock to meet the advanced biofuel requirement, and a majority may have more than 10 times the necessary amount [2]. This is important, as EU Member States aim to fulfill the goals of the latest amendment to the Renewable Energy Directive—Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023—which sets a renewable energy target of at least 42.5% by 2030, significantly higher than the previously stated target of 32% by 2030 in Directive (EU) 2018/2001 [3]. Moreover, the current geopolitical context has prompted several authors to emphasize the strategic importance of forest biomass as an alternative to support the renewable energy transition [4,5].

According to the Official Statistics Portal [6], in 2023 Lithuania's gross inland energy consumption amounted to 301,698 TJ. The share of renewable energy sources (RESs) in final consumption was 32.23% [7]. Solid biofuels dominated RES consumption, accounting for 70.7%. By 2030, the demand for wood biofuels in Lithuania is expected to rise further, as up to 90% of heat energy is projected to be produced from RESs [8]. The annual potential of firewood and wood waste in Lithuania is estimated at 8500 thousand m^3, of which 6351.3 thousand m^3 was consumed in 2023 [6]. In addition, up to 1690 thousand m^3 of forest logging residues could be generated annually, with around 50% usable for energy, though currently only 30% of this potential is exploited [9]. As similar logging residue potential can be expected from forests across other EU countries, this also indicates untapped potential and growing interest. In particular, biomass exchange markets (e.g., Baltpool) show increasing demand for logging waste at the EU level [10].

Harvesting all logging residues from Scots pine stands over a 100-year rotation could raise solid biofuel recovery by 15–20% compared with conventional practices [11]. The modeling results presented by Miksis et al. [11] showed potential biomass removals amounting to 88 t ha^{-1} of stem wood biomass from Scots pine stands during thinnings at 30, 50, and 70 years, and sanitary cuttings at 80–90 years. Moreover, including tree crown biomass (e.g., branches and needles) would allow an additional 23.5 t ha^{-1} of solid biomass to be recovered during thinnings and sanitary cuttings, of which 18 t ha^{-1} comes from branches and 5.5 t ha^{-1} from needles. However, the feasible collection rate may be only around 80%, as it is not practical to collect logging residues such as small branches or stumps [11]. On the other hand, innovative, less disruptive stump-removal technologies are emerging, indicating future potential to recover biomass from stumps as well.

Although biofuel is considered a source of green energy, in practice there are cases where biofuels are produced without regard to climatic and technical criteria, which raises reasonable doubts as to whether firewood and harvesting residues can be considered environmentally friendly fuels. It was revealed that removing residues from the forest can have some negative effects. Although there were no significant effects on wood productivity when the residues were removed for the first time, during the second rotation with residue removal, wood productivity reduced by 15% even with high rates of fertilizer application. Further, a 40% reduction in microbial biomass and soil respiration was noted with forest residue removal [12]. In recent years, the problem of mineral loss due to the removal of biomass from the forest has been highlighted [13,14]. However, it is revealed that if the logging waste is dried before shredding and leaves and needles are allowed to fall, the loss of minerals will be greatly reduced. In additional, to compensate for the loss of minerals, the ash after firewood and the wood waste burning process may be returned to the forest [15].

The impact on climate change of the energy sector can be reduced by using forest biomass instead of fossil fuels, incl. natural gas, if biogenic carbon is excluded [16]. The inclusion of biogenic carbon reduces the estimated climate benefit, since total greenhouse gases (GHGs) are ultimately 46–47% higher than in cases of natural gas. While forest biomass has certain advantages, it cannot be considered an emission-free energy source.

Energy production from wood biofuel chain covers different technological stages: land preparation and planting, harvesting of wood biomass (timber wood, firewood), logging of biomass to chipping, pelletizing, or briquetting (in case of pellet or briquette production), wood biofuel transportation to boiler houses or power plants, biofuel storage, burning in combustion plants (CPs) or large combustion plants (LCPs), and waste (ashes) management [5,17,18]. Environmental impact of wood biofuel production depends on different aspects, e.g., the intensity of widely used diesel fuels, lubricant/oil consumption, machine repair, replacement of components, proportion of different harvesting systems and their productivity, and use of different harvesting types [19,20]. Electricity and diesel fuel are also used in wood biofuel combustion plants in additional and main processes, and thus direct and indirect impacts on air quality due to air emissions (NO_x, CO, PM, SO_x, NMVOC) and on climate change due to GHGs (CO_2, CH_4, N_2O) are generated [21].

However, there is a lack of research in the scientific literature focused on the estimation of environmental impacts from energy production of the wood biofuel chain, analyzing all stages of wood biofuel production from forest cultivation to harvesting and wood biofuel combustion for energy production. Despite the steady increase in LCA studies on forest biomass management, significant knowledge gaps remain when broader system boundaries are considered [17]. For example, studies covering the entire forest system from site preparation to final utilization are still rare, especially for specific locations or regions [17]. Moreover, the number of studies significantly decreases when the valorization of forest and timber processing residues is taken into account [18].

The aim of this research was to evaluate and compare two forest solid biofuel management scenarios to determine whether the utilization of logging waste for energy recovery has significant life cycle environmental impacts under Lithuanian conditions.

The objectives of the research are as follows:

- To monitor pine biomass harvesting operations, both with and without forest residue collection, to obtain empirical data for life cycle inventory.
- To determine the cumulative energy demand of woody biomass utilization from one hectare of forest as a fuel source for combustion plants, under scenarios with and without forest residue collection.
- To estimate life cycle inventory data that are not directly measurable, such as emissions from forest soil degradation, ash generation, and thermal energy production impacts.
- To compare the two biomass management scenarios through a life cycle analysis to assess their overall environmental impacts.

2. Materials and Methods

2.1. Overall Flowchart of the Research Framework

Figure 1 presents a general flowchart of the research framework. Each stage is further explicitly defined in the following chapter of the methodology.

2.2. Research Conditions

The experiment was carried out in Lithuania from 2017 to 2019, during the monitoring of wood biomass preparation in six fertile areas (Šakiai State Forest Enterprise). The average values from these areas were used in the assessment. Analyzed biomass was from pine (*Pinus sylvestris*) forest stands where the soil types were Arenosols and Luvisols. For the research, scotch pine (*Pinus sylvestris*) forest stands were selected, which are the dominant tree species in Lithuania (34.6% of the stands) [22].

2.3. Research Boundaries and Function Unit

The research boundaries include processes from land preparation for forest planting to thermal energy generation. The following processes were analyzed: forest soil degradation, forest land preparation, planting, harvesting, forwarding from felling sites, chipping (shredding), wood processing processes, sawn timber production, transportation of solid biofuel to CPs and LCPs, solid biofuel storage, biofuel combustion in CPs and LCPs for energy production, and ash management (storage and transportation for use and/or landfilling). Timeframe—100 years or one rotation.

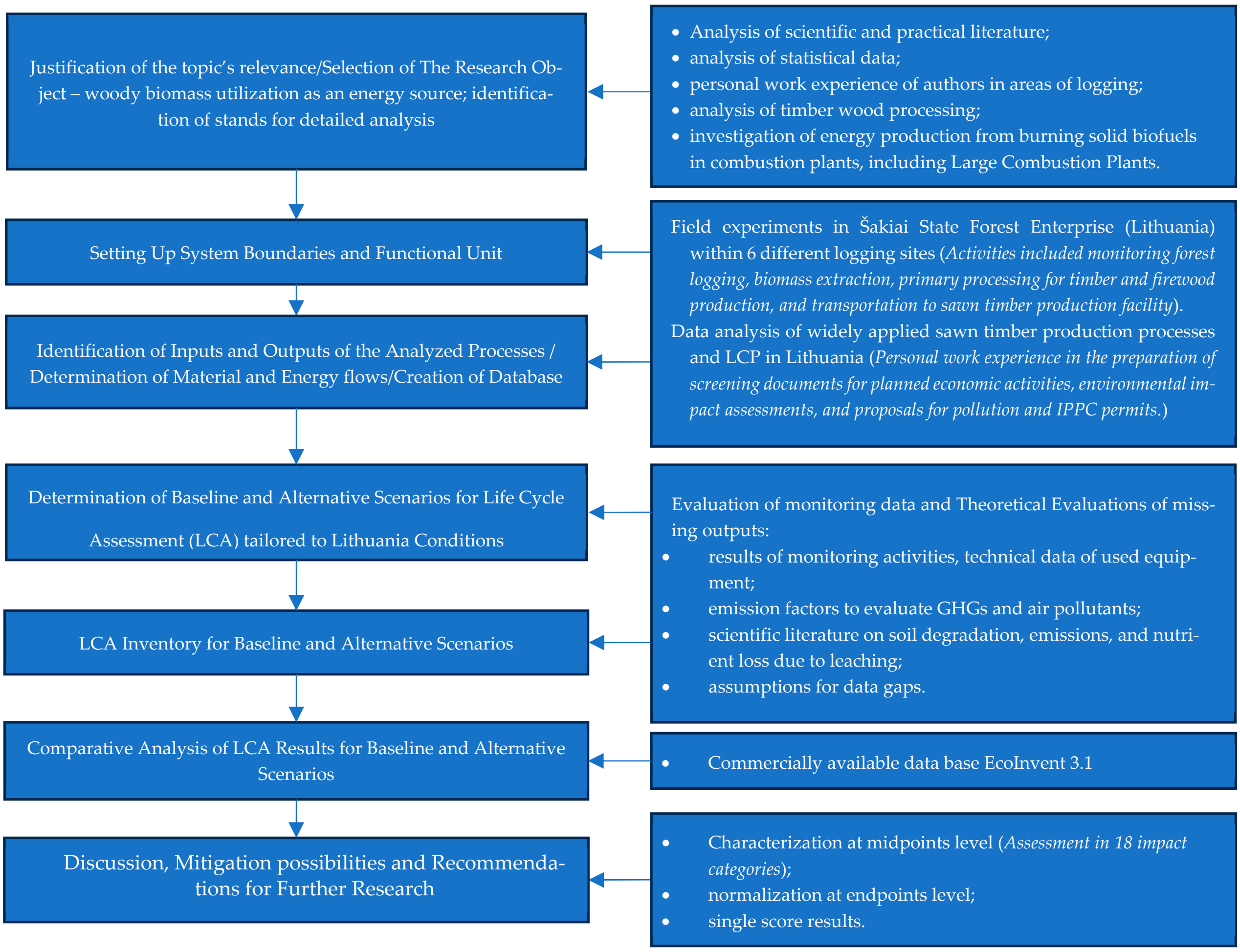

Figure 1. General flowchart of the research framework.

The following functional unit was used in the research—megawatt-hours of thermal energy produced from wood biomass harvested per hectare of forest stand (MWh ha^{-1}).

In the research, two scenarios of forest stand biomass management for energy recovery were analyzed:

- Utilization of firewood and approximately 40% of wood residues generated during log processing (including bark, sawdust, and cuttings).
- Utilization of logging waste, firewood, and approximately 40% of wood residues generated during log processing (including bark, sawdust, and cuttings).

The research stages are presented in Table 1.

Table 1. Expected results at each research stage.

Nr.	Stage	Achieved Results
1	Monitoring the felling and log processing life cycle stages: identification of inputs and outputs for life cycle inventory	• Diesel fuel consumption (t y^{-1}) and wood biomass production (m^3 or/and t y^{-1}) were estimated for the following processes: land preparation, planting, logging (harvesting), loading of wood biomass (incl. logging waste), chipping, transportation. • Volume and mass of by-products (wood waste: bark, sawdust, and cuttings) in timber processing were evaluated following monitoring data from a timber processing plant in Lithuania. The evaluated mass of by-products acts as inputs to CPs and LCPs (t y^{-1}).

Table 1. *Cont.*

Nr.	Stage	Achieved Results
2	Evaluation of inputs and outputs for LCI: analysis of data obtained through practical consulting experience and scientific literature	• Energy balances of CPs and LCPs (MWh y^{-1}) were made to obtain data on electricity consumption and thermal energy production in a CP and LCP. • The ash volume (bottom ash and fly ash) from the combustion of log processing residues (RW1), firewood chips (SM1), and shredded logging waste (SM3) were calculated using data from the ISO 17225-1:2021 [23] solid biofuel standard and the Baltpool system. • The efficiency coefficient (%) of energy recovery from biomass combustion in LCPs was based on a typical LCP installation in Lithuania. • The assessment of soil organic carbon (C) and nitrogen (N) degradation, including their release as air pollutants such as volatile organic compounds (VOCs), CH_4, CO, NH_3, and N_2O, as well as through leaching as total organic carbon (TOC), nitrogen (N), ammonia (NH_4^+), and nitrates (NO_3^-), was conducted using emission factors from the relevant literature source. • Air pollutions and GHG emissions were evaluated at various stages, from the cultivation of the forest stand to the final combustion of solid biomass residues of varying quality, classified as RW1, SM1, and SM3 according to Baltpool nomenclature (in tonnes or kg per hectare).
3	Evaluation and comparison of the scenarios by applying LCA approach	Environmental impacts of two scenarios were assessed by applying LCA approach
4	Interpretation of results from analysis of the chosen alternatives	Recommendations regarding the use of logging waste residues and the application of prevention or compensation measures.

2.4. Experimental Conditions and Used Equipment

Experimental sites were selected based on suitable harvesting and extraction conditions—specifically, areas with Luvisol and Arenosol soils, which provide the dry conditions required for the chosen technique. The most widely used method to harvest pine stands in Lithuania is cut-to-length technology—making timber assortments in the site area with harvesters and extracting wood products from harvesting sites to temporary storage areas with forwarders. The average distance from harvesting sites to the temporary storage of wood products is up to 700 m. From an economic point of view, the maximum distance for timber wood delivery to temporary storage site could be less than 1 km [20]. The most widely used brand for this operation in Lithuania is the Finnish machinery company—Ponsse. In Lithuania, harvesting, delivery of timber, firewood, and logging residues are usually conducted with the same equipment for all kinds of wood products.

During the experiment, the logging of pine forest stands was conducted with a Ponnse FOX harvester (2014; engine power—150 kW); extracting (loading) of wood products was carried out with a Ponsse Wisent forwarder (2012, engine power—150 kW); chipping of biomass was conducted with a MUS-MAX 10 blade chipper (2010; the caterpillar engine power is 515 kW), within a MAN truck (2012; engine power is 294 kW). Transportation of wood biofuel was carried out with DAF XF 105 trucks (2011, engine power—340 kW, Euro 5 standard) with a biofuel capacity of 36 m^3 (wood chips) or approx. 28 tonnes per trailer (per cycle). In the analyzed area, land preparation (plowing) was performed by a tractor (2007; engine power—93 kW).

For the evaluation of environmental impact during transportation, it was estimated that the maximum distance from wood and wood biofuel storage to primary wood processing facilities or biofuel combustion plants in Lithuania is 100 km. Since, in Lithuania, SM3-grade biofuel is widely burned in LCPs with a furnace, which can be flat or inclined with a moving grate type, the technical characteristics of such LCPs were used when evaluating inputs and outputs.

For the evaluation of environmental impact during wood biofuel combustion, the following assumptions were made:

- Average efficiency of widely used wood biomass CPs in Lithuanian sawn timber production companies (with maximum power of thermal energy—up to 10 MW)—85% [24];
- Average efficiency of widely used wood biomass LCPs in Lithuania (with power of thermal energy production—≥50 MW)—96–100%; such a high efficiency is achieved due to the use of flue gas-condensing economizers [21];
- Average efficiency of fabric filter in CPs—86% [21];
- Average efficiency of electrostatic participators in LCPs—99% [21].

2.5. Evaluation of Air Emissions and GHGs

GHGs from mobile and stationary sources were based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 2 "Energy" [25]:

$$E_{GHG,\ fuel} = B_{fuel} \times Q_{fuel} \times EF_{GHG}, \quad (1)$$

where

B_{fuel} –volume of combusted fuel (t y^{-1});
GHGs: CO_2, CH_4, N_2O;
Q_{fuel}—fuel lower heating value (TJ t^{-1}).

(1) For solid biofuel (see Table 2);

Table 2. Characteristics of different biofuels (pine) were adopted from ISO 17225-1:2021 solid biofuel standard [23] and Baltpool system [26].

	Moisture Content, %	Ash Content, %	Lower Heating Value, MJ kg^{-1}		
			Q	Q, Min.	Q, Max.
Chips from log processing plant (RW1)	≤20	≤2	14.87	14.31	15. 91
Chips from firewood (SM1)	≤35	≤1	11.56	11.17	12.01
Chips from logging waste (SM3)	≤40	≤3	10.54	10.12	11.32

(2) For other fuel—from Lithuanian National GHG emissions inventory document [27]:
  - For diesel fuel: Q = 42.91 TJ t^{-1};
  - For natural gas: Q = 34.62 TJ 1000 m^{-3};

EF_{GHG}—default emission factor of a given GHG by type of fuel (t TJ^{-1}). In the case of CO_2, national EF is used according to data presented in the Lithuanian National GHG emissions inventory document [27]:

(1) For solid biofuel: EF_{CO2} = 104.01 t TJ^{-1};
(2) For diesel fuel: EF_{CO2} = 72.950 t TJ^{-1};
(3) For natural gas: EF_{CO2} = 55.59 thousand m^3 TJ^{-1}.

Evaluation of air pollution from mobile and stationary sources was based on the EMEP/EEA Air pollution emission inventory guidebook (2023) [28]:

$$E_{pollutant} = AR_{production} \times EF_{pollutant}, \quad (2)$$

where

$AR_{production}$—the activity rate for the specific technology, e.g., volume of fuel for transport (kg y^{-1}); energetic volume of combusted fuel (GJ y^{-1});

$EF_{pollutant}$—the emission factors of the specific pollutant (g GJ^{-1} of combusted fuel in CPs (combustion in manufacturing industry), in LCPs (energy industries), in g kg^{-1} of fuel (in road transport), or in g t^{-1} of fuel (in non-road mobile machinery):

- Ozone precursors (CO, NO_x, NMVOC);
- Acidifying substances (NH_3, SO_2);
- Particulate matter mass (PM).

2.6. Quantification of Soil Degradation Emissions

Total carbon and nitrogen loss due to the removal of logging waste was estimated by multiplying the total C and N pools by the nutrient removal rates reported by James et al. [29]. Soil C and N pool data were obtained from literature sources and are presented in Table 3.

Table 3. Forest soil C and N pool data as well as their degradation rates.

Parameter	Value	Unit	Reference
Soil organic carbon pool in pine forests	141.2	Mg C ha^{-1}	[30]
C loss after removal of logging slash	8.5	%	[29]
N pool in Arenosols	2300	kg ha^{-1}	[14]
N loss after removal of logging slash	3.5	%	[29]

After assessing total carbon loss, the distribution of degraded soil carbon into carbon compounds was evaluated. The distribution percentages were obtained from the scientific and practical literature, and the values are presented in Table 4.

Table 4. Distribution of degraded soil C into carbon compounds.

Carbon Form	% Total C Losses
CO_2–C [31]	95
CH_4–C [31]	3.12
CO–C [31]	0.08
VOC–C [32]	1.2
Leachate C losses [31]	0.6
Total C loss	100

Similarly, after assessing nitrogen loss due to the removal of logging waste, the distribution of organic nitrogen among different nitrogen forms was evaluated based on data from the scientific and practical literature. Since exact data on forest soil degradation products were unavailable, emission factors and their distribution were adopted from composting processes. This assumption was made by taking into account the intensive microbial activity present in both the composting process and forest soil degradation immediately after harvest. The values used to calculate nitrogen loss via different nitrogen compounds are presented in Table 5.

Table 5. Distribution of degraded soil N into nitrogen compounds.

Form of N Losses	Value	Basis	Comment
N leaching losses [33]	19.6	% N	Maximum value
NH_4^+–N losses [33]	87.15	% of N leaching losses	Average value
NO_3—N [33]	1.15	% of N leaching losses	Average value
Unaccounted N losses	11.7	% of N leaching losses	Evaluated value
N losses as gas	80.4	% N	Evaluated value
NH_3-N [34]	83.3	% from gas emissions	Average value
N_2O-N [34]	1.23	% from gas emissions	Average value
Unaccounted N losses	15.47	% from gas emissions	Evaluated value

2.7. Data Collection and Evaluation for Life Cycle Inventory of Forest Biomass Management

Table 6 presents life cycle inventory data from monitoring activities for various stages of wood processing, from forest planting to the transport of finished products and logging waste. It provides insights into diesel fuel usage across different technological processes—such as land preparation, felling, forwarding, and transportation—while distinguishing between logs, firewood, and logging residues. Note that a significant part of the PM emission factors for wood mechanical processing was taken from Chapter 12 "Woodworking production" of the methodology *Key emission factors of the formation of harmful substances emitted into the atmosphere from the main types of technological equipment used in machine building*, created by Kharkiv State Design Institute [35]. This methodology is included in the list of methodologies approved by the Minister of the Environment of the Republic of Lithuania.

Table 6. Life cycle inventory data for technological processes, fuel consumption, and operational assumptions.

No.	Technological Process	Energy Consumption	Remarks
1	**2**	**3**	**4**
1	Land preparation and other forest planting stages (D_0)	Diesel fuel: up to 13 L per hour	Up to 4 h per hectare. 100% fuel allocated for growing logs and firewood (excluding logging residues). Portion allocated to logging residues (D_{03})—0.
	Portion allocated to logs (D_{01})	Diesel fuel: up to 11.24 L per hour	86.46% of D_0
	Portion allocated to firewood (D_{02})	Diesel fuel: up to 1.76 L per hour.	13.54% of D_0
2.	Felling (D_1)	Diesel fuel: 0.6–1.0 L per m^3 of logs	Assumed for evaluation—0.7 L per m^3 of logs. Portion allocated to logging residues (D_{13})—0.
	Portion allocated to logs (D_{11})	Diesel fuel: 0.605 L per m^3 of logs	86.46% of D_1
	Portion allocated to firewood (D_{12})	Diesel fuel: 0.095 L per m^3 of logs	13.54% of D_1
3.	Forwarding (D_2): forwarding to loading site—logs (D_{21})	Diesel fuel: 15 L per 25 m^3 of logs	Capacity: 1 cycle equals 25 m^3 of logs
	Forwarding (D_2): forwarding to loading site—firewood (D_{22})	Diesel fuel: 12 L per 20 m^3 of logs	Capacity: 1 cycle = 20 m^3 of firewood
	Forwarding (D_2): forwarding to loading site logging residues (D_{23})	Diesel fuel: 10.8 L per 6 m^3 of logs	Capacity: 1 cycle = 6 m^3 of logging residues

Table 6. *Cont.*

No.	Technological Process	Energy Consumption	Remarks
1	**2**	**3**	**4**
4.	Transport of logs to processing (D_4)	Diesel fuel: 30 L per 100 km	Capacity: 1 cycle (1 truck): 24–36 m^3 (assume 30 m^3) Transport distance up to 100 km under Lithuania conditions
	Portion of diesel allocated to final product (logs) (D_{41})	63% from D_4	The typical yield of the final product ranges between 50% and 80% of the log volume, depending on the wood product. A value of 63% was assumed based on monitoring data for sawn timber [35].
	Portion of diesel allocated for the waste fraction—wood bark, waste from wood-processing operations (D_{42})	37% from D_4	Waste from wood processing facility was assumed based on monitoring data [35]: • Wood scraps, bark—16% by volume, incl. bark—6 to 9% of the timber wood (average value assumed); • Wood shavings: up to 11% by volume; • Sawdust: 10% by volume.
5.	Log processing	Energy allocated to log processing waste: Electricity: 5% Thermal energy: 5%	Thermal energy is used to the debarking process and dry wood products (sawn timber), and it is produced in a combustion plant by burning processing by-products (bark and sawdust) (in the case of Lithuania). The processing of wood produces particulate matter (PM) [35]: • 0.5–1% of bark DM (an assumption of 0.6% was used, since bark DM can be up to 60%); • 0.2452 t t^{-1} sawdust. PM is collected by cyclones and sent to the incineration plant of the processing company (Lithuanian case). η cyclone—95 to 99% [35] (accepted average—up to 97%).
6.	Shredding of processing residues before transport to the LCP (D_{31})	Diesel Fuel: up to 1.5 L per m^3	Monitoring data shows up to 1.5 l of diesel per m^3 of logs. Density of chips (approx. 20% moisture content [36]: 600–750 kg m^{-3} [26]; assumed from monitoring results—683 kg m^{-3}. Density of chips, shavings (about 20% moisture content [36] 250–350 kg m^{-3} [26]; 350 kg m^{-3} was assumed based on monitoring results. During shredding, PM (<200 µm) is formed [35]: 125–360 g kg^{-1} of waste (without bark) (average of 242.50 g kg^{-1} is accepted). This PM is collected in cyclones and then sent for incineration in the company's combustion plant (Lithuanian case). η cyclone—95 to 99% [35] (assumed average value—up to 97%).

Table 6. *Cont.*

No.	Technological Process	Energy Consumption	Remarks
1	**2**	**3**	**4**
7.	Loading operations (D7) of biofuel (bark and sawdust) intended for incineration at a log processing company	Diesel Fuel: up to 1 L ton^{-1}	Monitoring data: • Losses during biofuel handling and storage range from 1 to 5% [35] (up to 1% in Lithuania; this is achieved by stacking in storage areas enclosed on three sides and covered with awnings) (Lithuanian case). • Sawdust (around 40–50% moisture [36]) density: 350–450 kg m^{-3} [37]; 350 kg m^{-3} according to monitoring results. • Typical density of pine bark at the specified moisture content (about 35%): 680 kg m^{-3} [36].
8.	Firewood shredding into chips (D_{32})	Diesel Fuel: up to 1.5 L per m^3	Up to 1.5 L per m^3 according to monitoring data. Up to 3% losses (by weight) during crushing and loading into transport (1 to 5% [35]) are losses due to direct emissions to ambient air (without cyclones), wind, etc. Using modern chippers can reduce consumption to 0.18 L per m^3.
9.	Transportation of wood chips from firewood to the LCP (D_{52})	Diesel Fuel: 30 L per 100 km	1 cycle—23 t of biofuel Transportation—up to 100 km Density of chips (approx. 20% moisture content [36]: 600–750 kg m^{-3} [26]; assumed based on monitoring results—683 kg m^{-3} Transportation of wood chips from firewood, including shredded offcuts, to the LCP (D_{42})
10.	Shreddings of logging residues SM3 (D_{33})	Diesel Fuel: 1.6 L per m^3	Monitoring data show up to 1.6 L per m^3 (assumed figure for the analysis); Chips from logging waste (SM3 fuel) moisture content up to 40%; density between 832 and 852 kg m^3 [26]; we assume an average of 0.842 t m^{-3}; Up to 2% of soil, pebbles (by weight) and up to 3% loss (due to direct emissions to ambient air (in case of no cyclones present), wind, etc.) during shredding and loading into transport.
11.	Transport of logging residues to LCP (D_{53})	Diesel Fuel: 30 L per 100 km	23 t of biofuel per cycle Transport up to 100 km in Lithuanian conditions
12.	Biofuel loading operations at LCP: RW1 chips (D_{61}) SM1 chips (D_{62}) SM3 logging waste (D_{63})	Diesel Fuel: up to 2 L per tonne	According to the data presented by LCPs: up to 1% (up to 5% [35]) of losses are incurred during the handling and storage of biofuels (this is achieved by stacking in granaries closed on 4 sides) (Lithuanian case).

2.8. Life Cycle Assessment Methodology

The environmental impacts of the baseline and alternative forest biomass management scenarios were calculated and compared using the LCA method. The ReCiPe method at the midpoint and endpoint levels was used to perform the impact assessment based on ReCiPe2008 by Goedkoop et al. [38] and an updated version ReCiPe2016 by the National Institute for Public Health and the Environment [39]. In terms of the environmental impact categories at the midpoint, all 18 impact categories were calculated, and characterization was used to present the results. The LCA Ecoinvent Database v3.1. (2023) [40] was applied as the background source for life cycle impact analysis. The potential environmental impacts of management scenarios were calculated using the LCA software SimaPro 9.6.0.1 [41].

3. Results

3.1. Inventory of Forest Biomass Management Scenarios

Figure 2 depicts the baseline forest biomass management scenario. This scenario is built around two main biomass fuel sources (logs and firewood) under typical conditions in Lithuania. It encompasses various inputs and outputs, such as diesel fuel, electricity, thermal energy, fly ashes, bottom ashes, combustion emissions, and storage losses. The inputs and outputs were attributed to log processing residues (RW1) and shredded firewood (SM1). It is worth noting that soil degradation emissions are set to zero in the baseline scenario to enable easier comparison with the alternative scenario where logging waste is collected.

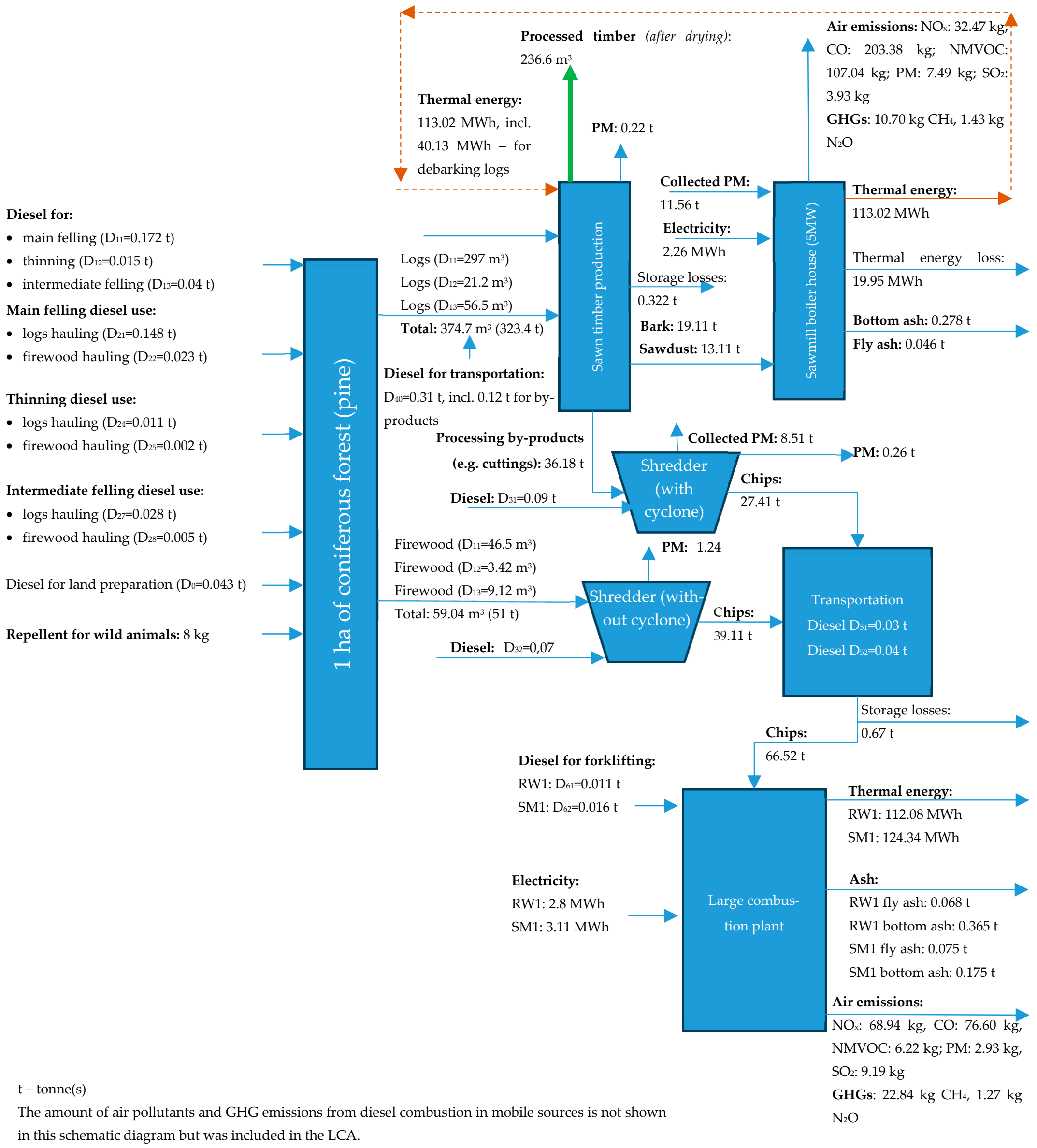

Figure 2. Baseline forest biomass management scenario without utilization of logging residues for energy production, in units of ha^{-1}.

The thermal energy produced in the LCP is supplied to the centralized heat supply system for industrial use and domestic hot water production year-round. Therefore, in the analysis, it was assumed that all wood biomass substitutes natural gas for heating purposes.

In the log processing stage (within sawn timber production), 95% of the inputs and outputs were allocated to product (sawn timber) and 5% to processing residues (RW1). All thermal energy produced (113.02 MWh) in the boiler house of a log processing plant (sawmill capacity: 50–70 tonnes per day) is used for log debarking, drying sawn timber, and heating the facility. During the LCA analysis, life cycle data specific to Lithuanian conditions were used whenever available.

Since combustion plants in Lithuania aim to separate fly ash and bottom ash and manage these streams individually, it is assumed that fly ash is sent to landfills, while bottom ash is used for land farming.

Storage losses are not reflected in SimaPro waste streams, as some of the materials are likely to be blown away by the wind, dry out, enter the stormwater runoff, or decompose. However, quantifying storage losses is ultimately reflected in the overall renewable energy production.

The figure below (see Figure 3) depicts the alternative forest biomass management scenario. The major difference is the inclusion of an extra biofuel source: logging waste. Changes are marked by a green color in order to easily spot the differences between scenarios.

Table 7 presents the main inputs and outputs of the scenarios investigated for quick and easy comparison. In the alternative forest biomass management scenario, energy production increases from 349.45 to 513.55 MWh per ha compared to the baseline, representing a total increase of 31.95%. Moreover, thermal energy production increases to the extent that the actual diesel consumption required to generate an additional unit of energy decreases from 35.41 to 29.87 kWh per MWh per ha. In terms of electricity consumption, the baseline and alternative scenarios show similar usage per unit of thermal energy—23.38 and 23.90 kWh per MWh, respectively. However, as the actual mass of biofuel burned increased in the alternative scenario, the ash generation increased from 2.88 to 4.15 kg MWh^{-1}. The logging waste volume (78.6 m^3) presented in Table 4 represents only the portion of total logging residues that is economically feasible to collect from the felling site. Residues such as stumps and pine needles are left onsite to mitigate negative effects on soil fertility caused by additional organic carbon removal. Some authors suggest that leaving around 16% DM of logging residues at nutrient-poor Scots pine forest sites helps retain a considerable portion of key nutrients and does not compromise soil productivity [42]. Since stumps alone already represent 14.9% [43] of the total felling residues, it can be concluded that the 16% threshold is largely accounted for.

3.2. Comparison of Two Forest Biomass Management Scenarios Based on LCA Approach

After the LCA analysis at the midpoint, positive results were observed in 9 impact categories from a total of 18 (See Figure 4). The major aspect contributing to these positive results was avoidance of natural gas usage due to increased bioenergy production from logging waste. Negative impacts of the scenario utilizing logging waste emerged in the following impact categories: stratospheric ozone depletion, ionizing radiation, particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, human non-carcinogenic toxicity, and water consumption.

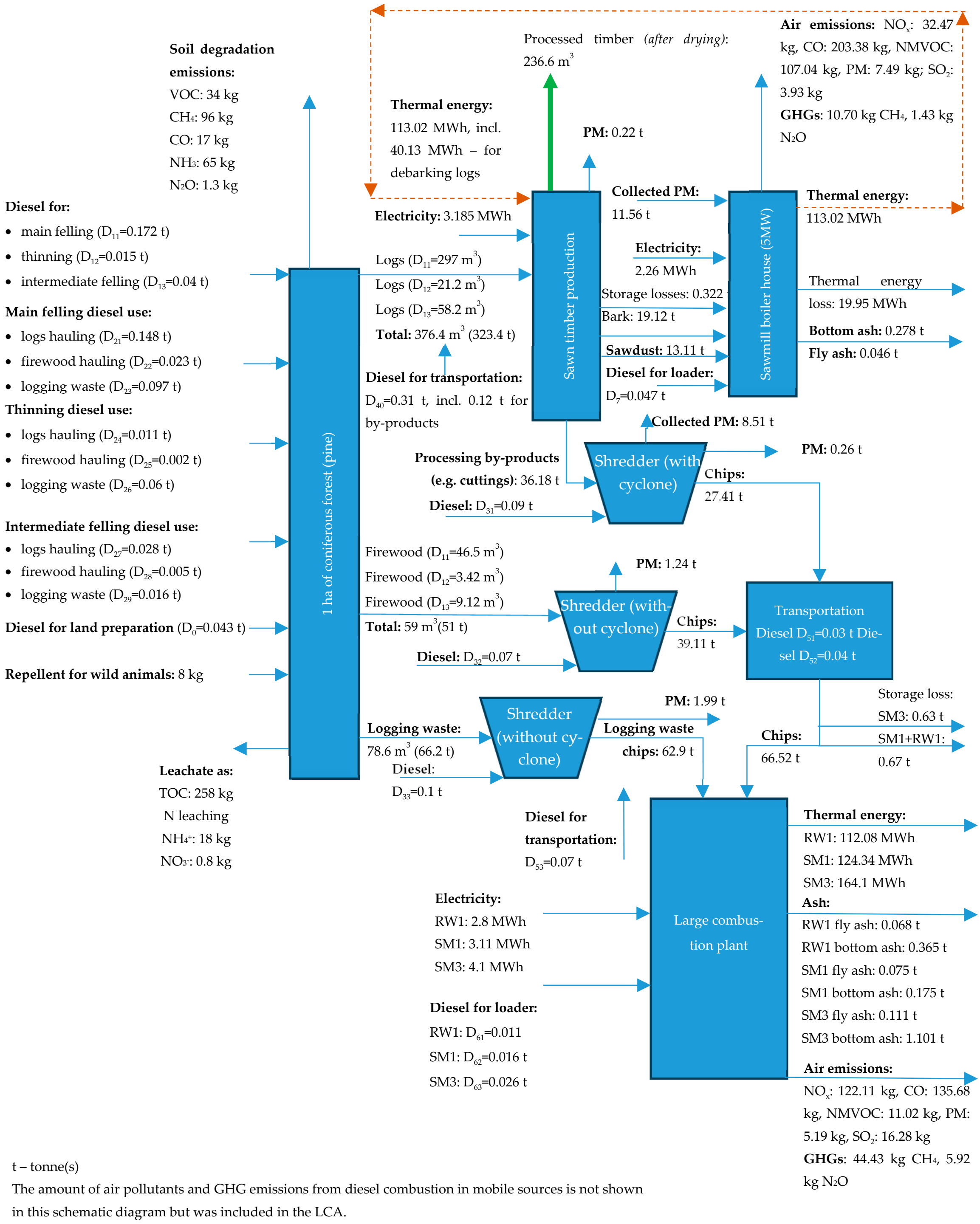

Figure 3. Alternative forest biomass management scenario with logging residue utilization for energy production, in units of ha^{-1}.

The alternative scenario performed worse in the stratospheric ozone depletion and ozone formation (terrestrial ecosystems) impact categories, primarily due to increased consumption of diesel and electricity. When considering the influence of uncertainties in these categories, they would not be significant enough to shift the results in favor of the alternative forest biomass management scenario, since more energy is inherently required to extract felling residues. Furthermore, uncertainties have an equal influence on both scenarios, leaving the difference between them largely unaffected.

Table 7. Main inputs and outputs for the baseline and alternative forest biomass management scenarios.

Main Inputs and Outputs	Dimension, units ha^{-1}	System Level: Solid Biofuel Production and Combustion for Heat Energy Production	
		Baseline Without Logging Waste	Alternative with Logging Waste
Pine forest logging yield			
Timber	m^3	374.70	374.70
Firewood	m^3	59.04	59.04
Extracted logging waste	m^3	0.00	78.6
Total:	m^3	433.74	512.34
Biofuel production yield (inputs for combustion plant)			
Timber processing residues used in sawn timber production company's CP	t	43.78	43.78
RW1 chips from timber processing to LCP	t	27.41	27.41
SM1 chips from firewood	t	39.11	39.11
SM3 logging waste	t	0	62.89
Total:	t	110.30	173.19
Energy yield of system			
Thermal energy at CP	MWh	113.02	113.02
Thermal energy at LCP	MWh	236.43	400.53
Total:	MWh	349.45	513.55
Energy consumption for thermal energy production			
Diesel fuel	kWh MWh^{-1}	35.41	29.87
Electricity	kWh MWh^{-1}	23.38	23.90
Total:	kWh MWh^{-1}	58.79	53.77
Other outputs:			
Ash	t	1.01	2.13
	kg MWh^{-1}	2.88	4.15

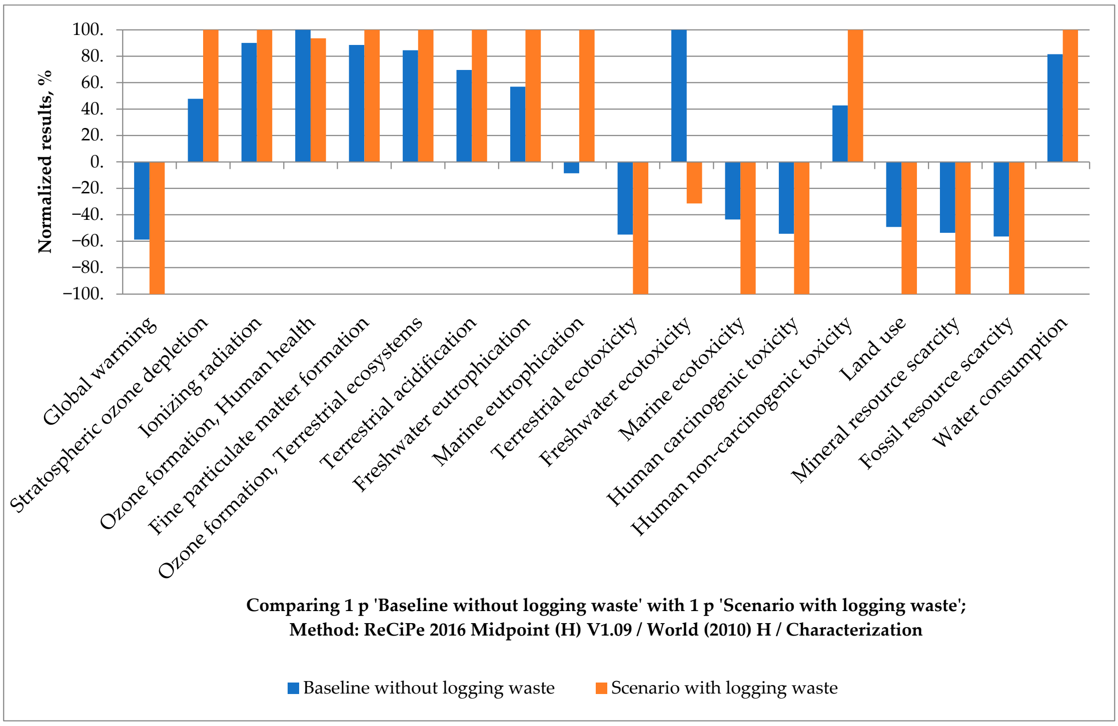

Figure 4. Comparative results of environmental impact of baseline and alternative forest biomass management scenarios at midpoint levels.

The environmental impact in the ionizing radiation category is influenced by uranium processing, which is required for electricity production in nuclear power plants. Since the alternative forest biomass management scenario requires more electricity to handle the additional stream of felling residues, the impact in this category is higher. However, the difference in this impact category between the baseline and alternative scenarios is relatively small. The particulate matter formation impact category is explained simply by the chipping process of logging waste in the forest, which is performed without any PM reduction measures like cyclones. However, this issue could be addressed by technological changes to improve results in this impact category. In the alternative scenario, the terrestrial acidification category performs significantly worse than in the baseline scenario due to additional SO_2 emissions and electricity consumption in the logging waste management process.

In the impact categories of freshwater eutrophication, marine eutrophication, and human non-carcinogenic toxicity, the main contributor to the increased impact was the increased volume of wood biomass ash that was diverted to land farming and landfill. This is one of two processes in the EcoInvent database which reflects ash management and are relevant to the case. In terms of the impact of uncertainties on the results, the situation could only worsen, since harvesting residues may have a higher ash content (more than 3%, reaching up to 5% under Lithuanian conditions [35]) than assumed in this investigation. However, the impact could be reduced by diverting bottom ash to the composting process and returning the nutrients present in ash via nutrient-balanced material like compost. Lastly, water consumption increased due to barite production, which is used in oil and gas upstream activities (relates to increased diesel consumption due to forest residue utilization in the alternative scenario).

The environmental impact of the remaining impact categories is lower in the alternative scenario with logging waste, primarily due to the avoidance of natural gas usage for thermal energy production. For example, the avoidance of greenhouse gas emissions (global warming potential) increased from approximately −52.6 t CO_2 eq to −89.5 t CO_2 eq.

In the alternative scenario which includes the utilization of logging waste, the environmental impacts are lower in all endpoint normalization categories (minus values mean that the impacts are avoided). The endpoint normalization chart (see Figure 5) shows that human health is the most significantly affected impact category in both scenarios, and all the positive offsetting results from the avoidance of natural gas use by substituting this fossil fuel with renewable biomass. This indicates that, in pursuing energy independence and fossil fuel substitution, the main beneficiaries are the broader population. When both scenarios are compared in normalized units, the human health impact is offset from −1.43 in the baseline scenario to −2.33 in the alternative scenario (this indicates that more negative impacts are avoided). Meanwhile, ecosystems and resource impact categories are less pronounced compared to the human health impact category. However, the situation in the alternative scenario improves in these categories as well.

Figure 6 presents a comparative analysis of the environmental impacts of the two scenarios, expressed in single score values using the ReCiPe 2016 Endpoint method. The chart clearly depicts that the scenario with logging waste provides benefits in all impact categories, but especially in human health. Avoidance of total negative environmental impacts increases from −0.66 kPt in the baseline scenario to −1.08 kPt in the alternative scenario which utilizes logging waste.

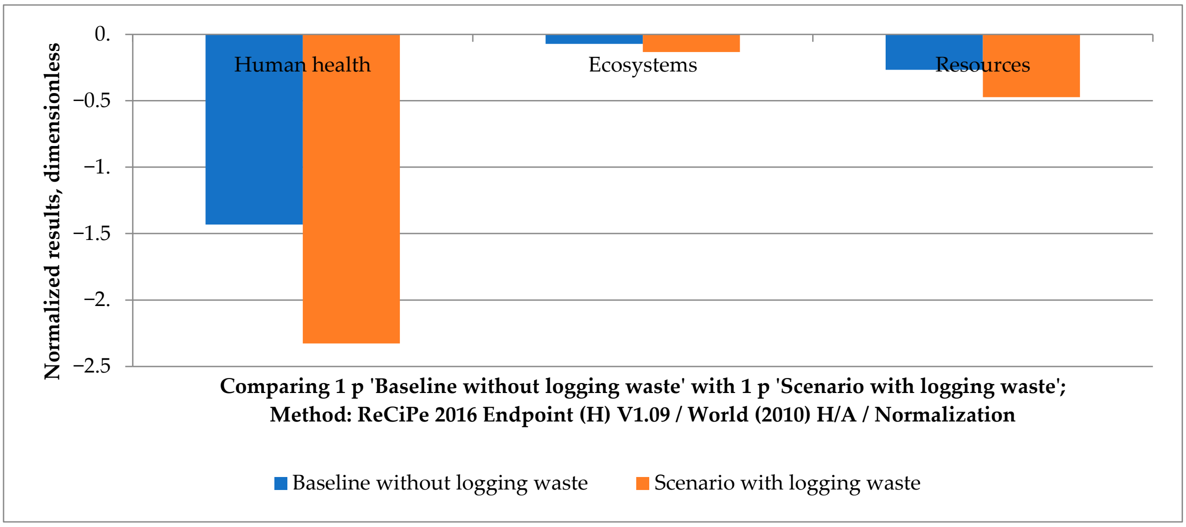

Figure 5. Comparative results of environmental impact of baseline and alternative forest biomass management scenarios at endpoint levels (normalization).

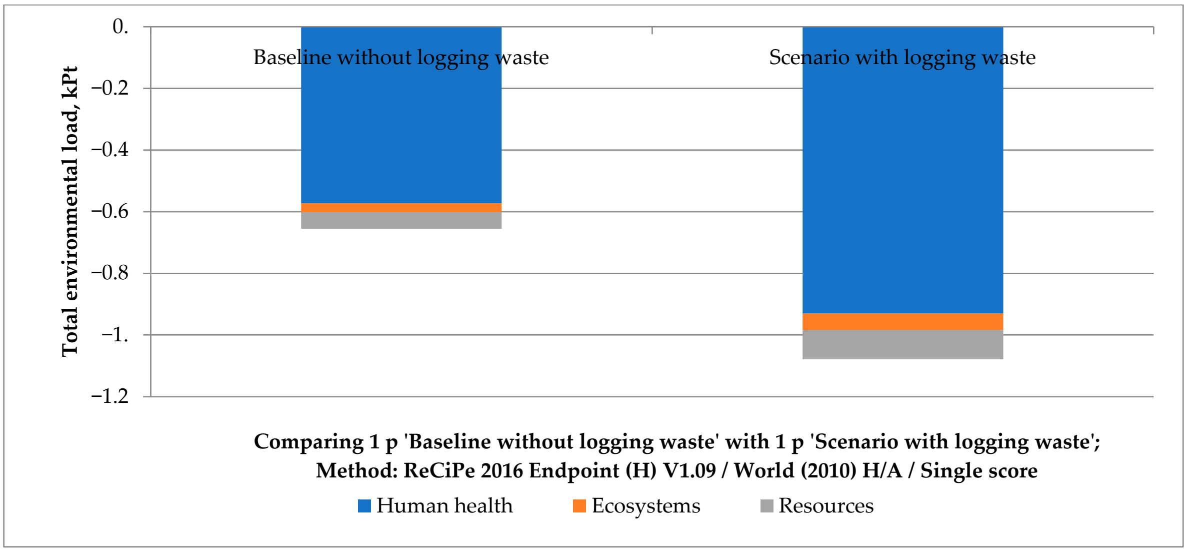

Figure 6. Comparative results of environmental impact of baseline and alternative forest biomass management scenarios at endpoint levels (single score).

3.3. Recommendations

Additional midpoint impact categories could be improved over the baseline scenario through the advancement of more sophisticated ash management practices. The current results indicate that increased ash volume negatively affects freshwater and marine eutrophication, as well as human non-carcinogenic toxicity. Recycling ash nutrients through co-composting with other heavy metals unpolluted biodegradable waste streams (e.g., green waste, source-segregated food waste, sewage sludge of small towns, etc.), and their application to clear-cut forest areas could improve these midpoint impact categories, enhance the appeal of logging residue utilization, and help mitigate future productivity losses caused by extra carbon extraction amounting to 78.6 m^3 of logging residues. Alternatively, fly ash can be used in construction (mixed with cement) and in road building, which is how some companies in Lithuania handle non-hazardous ash.

Other impact categories showed worse performance than the baseline scenario, primarily due to increased electricity and diesel consumption in the scenario that utilizes logging residues. Therefore, improvements are difficult to achieve, as the addition of an extra biofuel stream will inevitably increase overall energy consumption. However, the impacts in both scenarios could be reduced by optimizing traffic flows and adopting more modern cutting, harvesting, loading, and transportation techniques. Since the analyzed harvesting and transportation equipment was relatively old (over 10 years), replacing it with newer machinery could lower fuel consumption and associated emissions.

4. Discussion

Several studies have investigated the environmental implications of replacing fossil fuels with forest biomass in energy systems through LCA. For example, Balcioglu et al. [44] evaluated various technologies for converting forest residues into energy, demonstrating significant greenhouse gas reductions alongside positive economic outcomes. Their findings highlight the diverse technological pathways that enhance the sustainability of forest residue utilization [44]. Similarly, Franzen et al. [45] explored the greenhouse gas emissions associated with forest residue use across multiple energy and product pathways, confirming their considerable climate mitigation potential when managed effectively. Nevertheless, regional and species-specific assessments remain limited, particularly for Scots pine (*Pinus sylvestris*) forests common to Lithuania and Northern Europe—a gap addressed by Rincione et al. [46], who emphasized the value of localized LCAs through detailed case studies on wood chips from residual biomass, which improve the relevance and accuracy of environmental impact evaluations.

In terms of scope, Klein et al. [17] conducted a comprehensive LCA of biomass supply chains for raw wood in Bavaria, Germany, encompassing processes from site preparation to the combustion plant gate and including key impact categories such as global warming potential, non-renewable primary energy consumption, and particulate matter emissions. Building on this work, the present study applies similarly broad system boundaries but advances the analysis by incorporating emissions linked to forest soil degradation due to logging residue extraction—an often-overlooked factor critical for assessing long-term ecosystem impacts. Moreover, the present study addresses 18 environmental impact categories to obtain a clear view of environmental hot spots, which can in turn inform the development of impact mitigation strategies. A distinctive contribution is the comprehensive inclusion of all biomass extracted per hectare, enabling quantification of additional bioenergy derived from log processing residues and thus providing a more holistic system perspective.

This expanded scope aligns with prior findings on environmental trade-offs associated with residue removal. Havukainen et al. [47] reported that replacing natural gas with felling residues in CHP plants reduces global warming potential but can increase local acidification and eutrophication, a trend mirrored here along with additional impacts in ozone depletion, photochemical ozone formation, ionizing radiation, and particulate matter formation. Consistent with this, Scrucca et al. [48] identified human health and ecosystem quality as sensitive categories in woodchip bioenergy systems, with human health emerging as the most adversely affected category under the alternative biomass management scenario, signaling the need for mitigation measures.

The present study also highlights particulate matter emissions tied to wood residue chipping, echoing Proto et al. [18], who highlighted the lack of particulate controls such as cyclones as a key driver, suggesting opportunities for technological improvements [18]. Moreover, research by Brassard et al. [49] revealed similar trends in freshwater eutrophication, terrestrial acidification, and ozone depletion when comparing residue utilization to leaving residues onsite, underscoring the consistency and robustness of environmental trade-off patterns in forestry residue management.

Logistics substantially influence environmental profiles, with Zhang et al. [19] focusing on the impacts of feedstock transport, while Raghu et al. [50] incorporated seasonal biomass demand, storage, and advanced GIS and agent-based modeling to optimize supply chains and reduce global warming potential. Hájek et al. [51] further recognized forest road maintenance as a major contributor to impacts in timber harvesting LCAs of Norway spruce stands. Building on these perspectives, the present study contributes to system comprehensiveness by examining broader factors in the biomass supply chain—including timber preparation, residues generated in log processing facilities, storage losses (in combustion plants), and emissions and ash generation from various wood residue types (timber processing residues [RW1], firewood [SM1], and logging waste [SM3]).

The inclusion of these diverse factors emphasizes significant research potential as more variables are integrated into future analyses. Greater attention should be given to the biofuel combustion stage, as operators increasingly report that poor biofuel quality, characterized by high ash content, leads to more frequent maintenance shutdowns due to slag solidifying in the furnace.

5. Conclusions

It was calculated that about 173.19 t of different biofuels (such as chips, bark, cuttings, sawdust, or logging waste) can be produced from 1 ha of fertile area during forest thinning and intermediate and main felling (after 100 years), and up to 513.55 MWh ha^{-1} of thermal energy can be the main output of the system, incl. 164,10 MWh ha^{-1} due to utilization of 78.6 m^3 (66.2 t) of logging waste. The diesel fuel and electricity consumption of this system was 53.77 kWh per produced MWh of energy.

A comparative analysis of two forest solid biomass management scenarios (with and without logging waste utilization), using a life cycle assessment (LCA) approach at midpoint levels, showed positive results in 9 out of 18 impact categories. The major aspect contributing to these positive results was avoidance of natural gas usage due to increased bioenergy production from logging waste. This significantly affected the global warming impact category, resulting in an increase in greenhouse gas emission avoidance from approximately −52.6 t CO_2 eq in the baseline scenario to −89.5 t CO_2 eq. in the alternative scenario with logging waste.

Although the goal of utilizing logging waste in the alternative scenario was a reduction in global warming and therefore resource usage, the analysis at endpoint levels (normalization) showed that the most dominant impact category was human health. This indicates that, in pursuing energy independence and fossil fuel substitution, the main beneficiaries are the broader population. When environmental impacts were converted to single score values, the avoidance of total negative environmental impacts increased from −0.66 kPt in the baseline scenario to −1.08 kPt in the alternative scenario that utilizes logging waste, representing an improvement of nearly 39%.

This study has several limitations that should be considered when interpreting the findings. Some limitations arise from data uncertainties, such as reliance on literature values to estimate carbon and nitrogen losses through emissions and leaching. Additionally, certain emission factors for soil degradation were adapted from composting processes, as specific emission factors for forest soil degradation are currently unavailable. Assumptions regarding transport distances were also made based on regional averages. Scope limitations include the focus on a single region (Lithuania) and one forest type; however, these conditions are prevalent across Northern Europe, making the results broadly transferable to other countries.

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Abbreviations

The following abbreviations are used in this manuscript:

CPs	Combustion plants
EU	European Union
GHGs	Greenhouse gases
LCA	Life cycle assessment
LCPs	Large combustion plants
RESs	Renewable energy sources
TOC	Total organic carbon
VOCs	Volatile organic compounds

References

1. Álvarez, A.; Pizarro, C.; García, R.; Bueno, J.L. Spanish Biofuels Heating Value Estimation Based on Structural Analysis. *Ind. Crops Prod.* **2015**, *77*, 983–991. [CrossRef]
2. Searle, S.Y.; Malins, C.J. Waste and Residue Availability for Advanced Biofuel Production in EU Member States. *Biomass Bioenergy* **2016**, *89*, 2–10. [CrossRef]
3. The European parliament and the council of the European union Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council. Available online: https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng (accessed on 4 August 2025).
4. Kożuch, A.; Cywicka, D.; Górna, A. Forest Biomass in Bioenergy Production in the Changing Geopolitical Environment of the EU. *Energies* **2024**, *17*, 554. [CrossRef]
5. Rafael, S.; Tarelho, L.; Monteiro, A.; Sá, E.; Miranda, A.I.; Borrego, C.; Lopes, M. Impact of Forest Biomass Residues to the Energy Supply Chain on Regional Air Quality. *Sci. Total Environ.* **2015**, *505*, 640–648. [CrossRef]
6. STAT GOV Official Statistics Portal. Indicator Database. Topic: Energy. Available online: https://osp.stat.gov.lt/energetika (accessed on 4 August 2025).
7. STAT GOV Statistics Lithuania. The Share of Energy from Renewable Sources. Available online: https://osp.stat.gov.lt/statistiniu-rodikliu-analize?indicator=S1R098#/ (accessed on 4 August 2025).
8. Seimas of the Republic of Lithuania. National Energy Independence Strategy. Available online: https://enmin.lrv.lt/public/canonical/1740735085/5963/NENS2024-2.12_EN.pdf (accessed on 4 August 2025).
9. Nagevičius, M. Biofuel Supply in Lithuania, the Road to 2025. Available online: https://www.ena.lt/uploads/PDF-AEI/TMT-ataskaitos/2013-1A-80-biokuras-galutine-ataskaita3.pdf (accessed on 4 August 2025).
10. Baltpool Baltpool Biomass Exchange Results in 2024: Market Dominated by Logging Residue Wood Chips and Short-Term Contracts. Available online: https://www.baltpool.eu/en/baltpool-biomass-exchange-results-in-2024-market-dominated-by-logging-residue-wood-chips-and-short-term-contracts/ (accessed on 30 August 2025).
11. Mikšys, V.; Varnagiryte-Kabasinskiene, I.; Stupak, I.; Armolaitis, K.; Kukkola, M.; Wójcik, J. Above-Ground Biomass Functions for Scots Pine in Lithuania. *Biomass Bioenergy* **2007**, *31*, 685–692. [CrossRef]
12. Zhu, Z.; Wu, L. Fertilization and Residue Management Improved Soil Quality of Eucalyptus Plantations. *Forests* **2023**, *14*, 1570. [CrossRef]
13. Ozolinčius, R.; Armolaitis, K.; Mikšys, V.; Varnagiryte-Kabašinskiene, I. Recommendations for Compensatory Fertilization with Forest Fuel Ash. Available online: https://gamtosknyga.lt/wp-content/uploads/2017/10/Leidinys_kompensuojamo....pdf?x13947 (accessed on 4 August 2025).
14. Armolaitis, K.; Varnagirytė-Kabašinskienė, I.; Stupak, I.; Kukkola, M.; Mikšys, V.; Wójcik, J. Carbon and Nutrients of Scots Pine Stands on Sandy Soils in Lithuania in Relation to Bioenergy Sustainability. *Biomass Bioenergy* **2013**, *54*, 250–259. [CrossRef]

15. Varnagirytė-Kabašinskienė, I.; Armolaitis, K.; Stupak, I.; Kukkola, M.; Wójcik, J.; Mikšys, V. Some Metals in Aboveground Biomass of Scots Pine in Lithuania. *Biomass Bioenergy* **2014**, *66*, 434–441. [CrossRef]
16. Giuntoli, J.; Caserini, S.; Marelli, L.; Baxter, D.; Agostini, A. Domestic Heating from Forest Logging Residues: Environmental Risks and Benefits. *J. Clean. Prod.* **2015**, *99*, 206–216. [CrossRef]
17. Klein, D.; Wolf, C.; Schulz, C.; Weber-Blaschke, G. Environmental Impacts of Various Biomass Supply Chains for the Provision of Raw Wood in Bavaria, Germany, with Focus on Climate Change. *Sci. Total Environ.* **2016**, *539*, 45–60. [CrossRef] [PubMed]
18. Proto, A.R.; Bacenetti, J.; Macrì, G.; Zimbalatti, G. Roundwood and Bioenergy Production from Forestry: Environmental Impact Assessment Considering Different Logging Systems. *J. Clean. Prod.* **2017**, *165*, 1485–1498. [CrossRef]
19. Zhang, F.; Johnson, D.M.; Wang, J. Life-Cycle Energy and GHG Emissions of Forest Biomass Harvest and Transport for Biofuel Production in Michigan. *Energies* **2015**, *8*, 3258–3271. [CrossRef]
20. Virbickas, L.; Galickaja, I.K. Analysis of Air Emissions and Greenhouse Gases in Woody Biomass Production Chain. *Environ. Res. Eng. Manag.* **2017**, *73*, 41–51. [CrossRef]
21. Staniškis, J.K.; Stasiškienė, Ž.; Kliopova, I.; Varžinskas, V. Sustainable Innovations in Lithuanian Industry: Development and Implementation; 2010; ISBN 9789955258155. Available online: https://aleph.library.lt/F?func=direct&=&=&doc%5Fnumber=000102931&local%5Fbase=KTU01&pds_handle=GUEST (accessed on 4 August 2025).
22. Ministry of Environment Lithuanian Statistical Yearbook of Forestry. Available online: https://amvmt.lrv.lt/lt/atviri-duomenys-1/misku-statistikos-leidiniai/misku-ukio-statistika/2017-m-1/ (accessed on 4 August 2025).
23. *ISO 17225-1:2021*; Solid: Biofuels—Fuel Specifications and Classes Part 1: General Requirements. International Organization for Standardization: Geneva, Switzerland, 2021.
24. LITBIOMA Lithuanian Biomass Energetic Association. Available online: https://www.biokuras.lt/en/ (accessed on 4 August 2025).
25. Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies Hayama: Kanagawa, Japan, 2006.
26. Baltpool Technical Specifications of Wood Chip Products. Available online: https://www.baltpool.eu/en/biomass-exchange/products/ (accessed on 4 August 2025).
27. Konstantinavičiūtė, I.; Byčenkienė, S.; Kavšinė, A.; Birgiolas, V.; Juška, R.; Žiukelytė, I.; Vaitiekūnienė, J.; Kairienė, E.; Balčius, M.; Mačiulskas, M.; et al. LITHUANIA'S NATIONAL INVENTORY DOCUMENT. Available online: https://aaa.lrv.lt/public/canonical/1746791508/3570/NID_2025.pdf (accessed on 4 August 2025).
28. Agency, E.E. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023—Technical Guidance to Prepare National Emission Inventories. Available online: https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023 (accessed on 4 August 2025).
29. James, J.; Page-Dumroese, D.; Busse, M.; Palik, B.; Zhang, J.; Eaton, B.; Slesak, R.; Tirocke, J.; Kwon, H. Effects of Forest Harvesting and Biomass Removal on Soil Carbon and Nitrogen: Two Complementary Meta-Analyses. *For. Ecol. Manage.* **2021**, *485*, 118935. [CrossRef]
30. Diers, M.; Weigel, R.; Culmsee, H.; Leuschner, C. Soil Carbon and Nutrient Stocks under Scots Pine Plantations in Comparison to European Beech Forests: A Paired-Plot Study across Forests with Different Management History and Precipitation Regimes. *For. Ecosyst.* **2021**, *8*, 47. [CrossRef]
31. Andersen, J.K.; Boldrin, A.; Christensen, T.H.; Scheutz, C. Mass Balances and Life Cycle Inventory of Home Composting of Organic Waste. *Waste Manag.* **2011**, *31*, 1934–1942. [CrossRef]
32. Büyüksönmez, F. Full-Scale VOC Emissions from Green And Food Waste Windrow Composting. *Compos. Sci. Util.* **2012**, *20*, 57–62. [CrossRef]
33. USDA-NRCS, C. *Part 637 Environmental Engineering-National Engineering Handbook*; United States Department of Agriculture: Washington, DC, USA, 2000; Volume 2.
34. Chen, P.; Cheng, W.; Li, S. Optimization Strategies for Mitigating Nitrogen Loss in the Aerobic Composting of Pig Manure and Microbial Changes Revealed by Metagenomic Analysis. *Process Saf. Environ. Prot.* **2023**, *169*, 270–284. [CrossRef]
35. Kharkov State Design Institute. *Key Emission Factors of the Formation of Harmful Substances Emitted into the Atmosphere from the Main Types of Technological Equipment Used in Machine Building [Udielnyjie Pokazatieli Obrazovanija Vriednych Vieščiestv, Vydieliajuščichsia v Atmosfieru Ot O*; Kharkov State Design Institute: Kharkiv, Ukraine, 1997.
36. Kask, Ü.; Varesm, V. Marten Saareoks Wood Fuel User Manual. Available online: https://www.trea.ee/wp-content/uploads/2021/02/Wood-Fuel-User-Manual.pdf (accessed on 4 August 2025).
37. Stasiak, M.; Molenda, M.; Bańda, M.; Wiącek, J.; Parafiniuk, P.; Lisowski, A.; Gancarz, M.; Gondek, E. Mechanical Characteristics of Pine Biomass of Different Sizes and Shapes. *Eur. J. Wood Wood Prod.* **2019**, *77*, 593–608. [CrossRef]
38. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; Schryver, A.; Struijs, J.; Zelm, R. ReCiPE 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level; 2008. Available online: https://www.scirp.org/reference/referencespapers?referenceid=1292666 (accessed on 30 August 2025).

39. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
40. Ecoinvent Database v3.10. Swiss Centre for Life Cycle Inventories. Available online: https://www.ecoinvent.org/ (accessed on 30 August 2025).
41. PRéSustainability. SimaPro-LCA Software for Fact-Based Sustainability. Available online: https://simapro.com/ (accessed on 30 August 2025).
42. Spulak, O.; Kacalek, D. How Different Approaches to Logging Residues Handling Affected Retention of Nutrients at Poor-Soil Scots Pine Site after Clear-Cutting? A Case Study. *J. For. Sci.* **2020**, *66*, 461–470. [CrossRef]
43. Dzenajavičienė, E.F.; Kveselis, V.; Tamonis, M. Modeling of Forest Biofuel Resource Potential and Production. *Energetika* **2013**, *59*. [CrossRef]
44. Balcioglu, G.; Jeswani, H.K.; Azapagic, A. Energy from Forest Residues in Turkey: An Environmental and Economic Life Cycle Assessment of Different Technologies. *Sci. Total Environ.* **2023**, *874*, 162316. [CrossRef]
45. Franzen, K.; Favero, A.; Milliken, C.; Wade, C. Assessing GHG Emissions Implications of Forest Residue Use for Energy Production. *GCB Bioenergy* **2025**, *17*, e70045. [CrossRef]
46. Rincione, R.; Longo, S.; Cellura, M.; Guarino, F.; Brunetti, A. Life Cycle Assessment of Wood Chips from Residual Biomass: A Case Study. *Int. J. Sustain. Dev. Plan* **2023**, *18*, 2253–2258. [CrossRef]
47. Havukainen, J.; Nguyen, M.T.; Väisänen, S.; Horttanainen, M. Life Cycle Assessment of Small-Scale Combined Heat and Power Plant: Environmental Impacts of Different Forest Biofuels and Replacing District Heat Produced from Natural Gas. *J. Clean. Prod.* **2018**, *172*, 837–846. [CrossRef]
48. Scrucca, F.; Barberio, G.; Cutaia, L.; Rinaldi, C. Woodchips from Forest Residues as a Sustainable and Circular Biofuel for Electricity Production: Evidence from an Environmental Life Cycle Assessment. *Energies* **2024**, *17*, 105. [CrossRef]
49. Brassard, P.; Godbout, S.; Hamelin, L. Framework for Consequential Life Cycle Assessment of Pyrolysis Biorefineries: A Case Study for the Conversion of Primary Forestry Residues. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110549. [CrossRef]
50. KC, R.; Aalto, M.; Korpinen, O.-J.; Ranta, T.; Proskurina, S. Lifecycle Assessment of Biomass Supply Chain with the Assistance of Agent-Based Modelling. *Sustainability* **2020**, *12*, 1964. [CrossRef]
51. Hájek, M.; Pulkrab, K.; Purwestri, R.C.; Tichá, M.; Paduchová, M. Life Cycle Assessment Approach of Silviculture and Timber Harvesting of Norway Spruce—A Case Study in the Czech Republic. *Front. For. Glob. Chang.* **2024**, *7*, 1276740. [CrossRef]