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Feedstock and supply chain-oriented comparative cradle-to-gate life cycle assessment of torrefied pellets, case study: Finland

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Abstract
Life cycle assessment (LCA) is used to compare global warming potential of torrefied pellets made of different feedstock materials, namely energy wood of birch and pulpwood of birch, pine and spruce. In addition, five different supply chain alternatives for each feedstock type are also evaluated. It is assumed that all of the biomass originates in the South Savo region of Finland and the pellets are used for co-firing with coal in a large-scale power plant in Helsinki, Finland. The results show that the torrefied pellets made of pulpwood of birch have the lowest global warming potential, whereas energy wood of birch impose the greatest environmental burden. Of the supply chain alternatives considered, biomass chipped with an electrical chipper in the torrefaction plant yard in South Savo has the lowest global warming potential. Consequently, torrefied pellets of birch chipped in an electric chipper in the torrefaction plant yard have the lowest environmental impact of all feedstock material and logistics alternatives. On the other hand, energy wood torrefied on-site in Helsinki results in the greatest environmental impact of all the raw material and logistics alternatives assessed. Furthermore, logistics with roadside mobile chipping generates 5-17% lower greenhouse gas (GHG) emissions than terminal crushing. Similarly, moving the torrefaction plant from South Savo to Helsinki would cause up to 6.5% additional GHG emissions depending on the raw material. Alternatively, chipping at the plant yard in a stationary electric chipper instead of crushing with a diesel-powered crusher would cause up to 18% fewer GHG emissions depending on the raw material.

Keywords: Biomass; Bioenergy; Torrefaction, pellets; Logistics; LCA.

1. Introduction
Bioenergy is considered a key element of efforts to meet the mandated Paris climate agreement target of keeping global warming to less than 2˚C above pre-industrial levels [1]. If grown sustainably, bioenergy has zero net CO_2 emissions to the atmosphere as the CO_2 released during the energy production is from carbon that the biomass absorbed in the first place [2-4]. Biomass, the source of bioenergy, is challenging as a source of renewable energy due to unfavorable physical and chemical properties such as low heating value, high moisture content, low energy density and hygroscopicity [5, 6]. These properties have a great impact on the logistics of biomass use for energy production. Treatment of the biomass prior to its

utilization is thus required to address limitations arising out of the intrinsic characteristics of biomass and to enable large-scale use of biomass for energy production. One of the many ways to improve biomass quality is torrefaction [7].

Torrefaction is a thermochemical treatment of biomass in which the biomass is heated at 200-300° C in an oxygen deficient environment. During the treatment, the biomass partly decomposes releasing different types of volatiles.

Torrefied biomass contains up to 90% of the initial energy content while reducing weight to about 30% of the initial weight [2, 3, 5, 7] The torrefaction process also enhances physical and chemical properties such as calorific value, grindability, and hydrophobicity. Pelletization of the torrefied biomass further improves the volumetric energy density, which plays an important role in reducing logistics cost as well as energy use during transportation [8]. A further benefit arising from the high-energy content and grindability of torrefied pellets is that they can be co-fired with other fuels in existing power plants, for example, with coal in a coal-fired power plant [7]. Moreover, pulverized coal furnaces can be converted to 100% torrefied pellets mode, which provides an opportunity for coal-fired power plants to reduce their emissions [9].

About 50% of the energy used in Helsinki, Finland is met from coal and about one-third of total energy comes from natural gas. The remaining energy demand is produced by nuclear and renewables with hydropower covering the majority of renewable energy. As a part of efforts to reduce fossil fuel use, the combined head and power (CHP) plants in Salmisaari (160MW_e, 300MW_{th}) and Hanasaari (220 MW_e, 420 MW_{th}) have started to blend white wood pellets with coal, thus increasing the share of renewables in the energy system [10]. Additionally, there are plans for the construction of more heat plants firing biomass after the eventual closure of the Hanasaari facility [11]. However, the energy use of forest biomass is already high in areas in the vicinity of Helsinki (i.e. Uusimaa region), leading to intense competition for resources and potentially higher biomass feedstock prices [12]. On the other hand, approximately 200–300 km from Helsinki, the South Savo region has abundant forest biomass [13]. In 2017, a greater amount (~7 solid-m^3 out of total 62.9 solid-m^3) of industrial round wood was harvested from this region than any other region in Finland [14], and since the area lacks biomass-processing industries, the harvest potential could be considered higher than the current energy wood use in the region. Circumstances such as these make South Savo a possible location for biomass processing industries and Helsinki a possible location for large-scale final biomass use.

The aim of this research is to evaluate the environmental performance of torrefied pellets originating from four different feedstock types using life cycle assessment (LCA). In order to refine the research further, five different logistics alternatives for each feedstock type are evaluated. It is assumed that the delimbed stem wood biomass originates in the South-Savo region and that the power plants in which the pellets are used are located in Helsinki. Different feedstocks (energy wood of birch and pulpwood of birch, spruce and pine) are compared because dissimilar properties such as energy density, volumetric density and forest machine productivity play an important role in determining the environmental performance of the supply chain. Similarly, different supply chains are evaluated because biomass fuel terminal concepts are evolving and terminal type and processing method affect costs and production efficiency [15]. Thus, it is worthwhile to evaluate traditional and innovative logistics solutions in terms of environmental performance. This study will highlight the different elements of biomass supply chain in terms of GHG emissions related to bioenergy and help understand the hotspots along the supply chain. In addition, the study will also identify the better alternative of biomass supply chains that are currently in practice.

2. Materials and methods

2.1 Life cycle assessment (LCA)

According to SFS-EN ISO 14040 [16], life cycle assessment (LCA) is an environmental management technique that helps identify the possible environmental impacts of a product or service through its various life cycle phases. It can assist in identifying improvement possibilities and inform decision makers in industries as well as governing bodies. There are four phases of LCA:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation.

The purpose of the study, intended application and audience are defined in the goal and scope definition phase. Additionally, the product system to be studied is clarified as well as the system boundaries and functional units. LCI comprises collection and validation of the input/output flows in each process as per the defined goal and scope definition. In the LCIA phase, LCI results are assigned to impact categories such as global warming potential (GWP), acidification etc. Finally, in the interpretation phase, the LCI and LCIA results are evaluated and interpreted in terms of the scope of the study. As illustrated in Figure 1, LCA is an iterative process where information is exchanged and modified throughout the process.

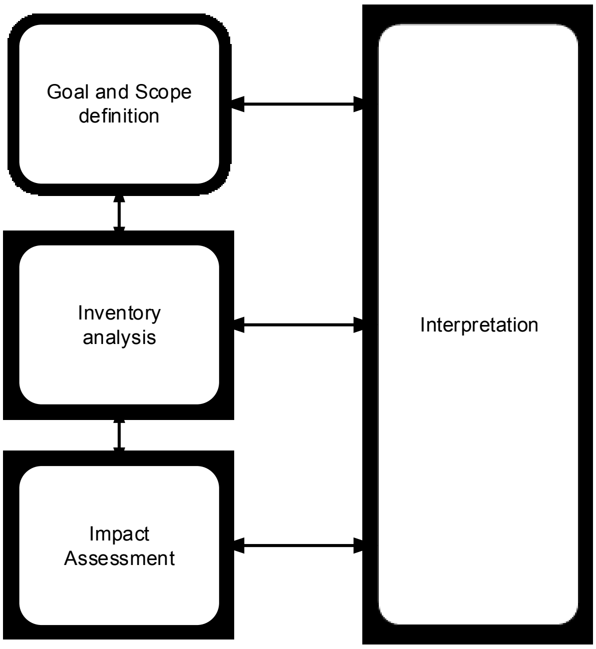

Figure 1. Life cycle assessment framework [16].

In this study, the LCA modelling is done using GaBi Professional (version 8) software with the integrated databases GaBi International and Ecoinvent v3.1. Concerning impact assessment, a sole impact category *global warming potential (GWP) with 100 years of time frame* is presented based on the methodology developed in CML 2001 (2016 version). The characterization factor for two major GHGs, methane and nitrous oxides are 28 kg CO_2 eq. and 265 CO_2 eq., respectively. In addition, the biogenic carbon emissions are excluded from the evaluation. Finally, sensitivity analysis is done for different moisture content of the raw material and different energy content of the torrefied pellets.

2.2 Goal and scope of the study

The aim of this research is to analyze comparative cradle-to-gate LCA of torrefied pellet production including supply chain alternatives for different feedstock biomasses. Four types of feedstock, namely, energy wood of birch (a mix of *Betula pendula* and *Betula pubescens*) and pulpwood of three tree species, i.e., birch (mix of *Betula pendula* and *Betula pubescens*), spruce (*Picea abies*) and pine (*Pinus sylvestris*) are studied. The primary location of the torrefaction plant is assumed to be in the South-Savo region of Finland and the torrefied pellets are assumed to be co-fired with coal in a large-sized power plant in Helsinki, Finland. The corresponding locations are shown in Figure 2. For the sake of comparison, one of the scenarios assesses location of the torrefaction plant in Helsinki. The functional unit of the study is identified as: *kg CO_2 eq. per 1 MWh of torrefied pellets*

2.3 System boundary

A typical cradle-to-gate LCA describes a system that includes upstream inputs and effects resulting from the origin of the raw material and the production phase, and downstream inputs and effects to the gate of the final destination of product usage, which in this case is the power plant where the pellets are co-fired with coal. Furthermore, emissions from diesel and electricity production are taken into account.
Similarly, emissions from forest machinery, trucks, biomass crushers and wheel loaders are included in the analysis but the infrastructure and production of vehicles, trains and machinery are excluded from the system. Potential GHG emissions from biomass decay during storage are outside the boundaries of the system. The system boundaries are illustrated in Figure 3.

2.4 LCI

2.4.1 Biomass properties

In this study, it is assumed that the production of torrefied pellets occurs in a hypothetical torrefaction plant with a production capacity of 200,000 t per year. In terms of feedstock, biomass from delimbed stems of various tree species is compared. For the sake of consistency, it is assumed that the biomass is dried naturally to 30% moisture content. Further explanation of the assumption of moisture content and its impact on transportation are given in Section 2.5.1. The moisture content of the torrefied pellets is kept constant at 6% for the sake of comparability. The major difference between energy wood and pulpwood is that energy wood (4-6cm) generally has a smaller top diameter than pulpwood (6-16cm) [17]. The purpose of using pulpwood as a feedstock is to analyze whether it has the same environmental impact as energy wood from a logistics point of view. The properties of the biomass and torrefied pellets are presented in Tables 1 and 2. The heating value of the torrefied pellets of the pulpwood of different species and energy wood is taken from Ranta et al. [18]. The heating value of the torrefied pellets as received (Q_{ar}) is calculated based on dry-basis lower heating value (Q_d) and moisture content (m) using Equation 1 from Alakangas et al. [19]:

$$Qar = \mathrm{Qd} \times \left(\frac{100-\mathrm{m}}{100}\right) - 0.02443 \times m, \tag{1}$$

where: Q_{ar} is heating value (as received), Q_d is lower heating value (dry basis), m is moisture content % and 0.02443 is the coefficient for enthalpy of vaporization at constant pressure and 25˚C, MJ/kg per 1 % moisture.

The total mass of fresh biomass required is calculated based on the moisture content and Q_d of the fresh biomass, as shown in Table 2. Once the total energy in the torrefied pellet ($Q_{ar,pellet}$) has been calculated, the required amount of energy in the feedstock is calculated based on the assumption that 10% of the energy is lost during the torrefaction process [20]. The calculation is shown in Equation 2:

$$Q_{ar,raw} = \frac{Q_{ar,\ pellet}}{0.9} \tag{2}$$

The moisture content of pulpwood is assumed to be 51.5% as in Föhr et al. [21]. The values of $Q_{d,\ raw}$ of birch, spruce and pine are taken from Alakangas et al. [19], the $Q_{d,raw}$ of energy wood is assumed to be the same as that of the birch pulpwood, and the moisture content is assumed to be 52.2 % [18]. The volumetric ratio of loose to solid biomass is assumed to be 2.5 [22].

Figure 2. Locations of biomass origin and use.

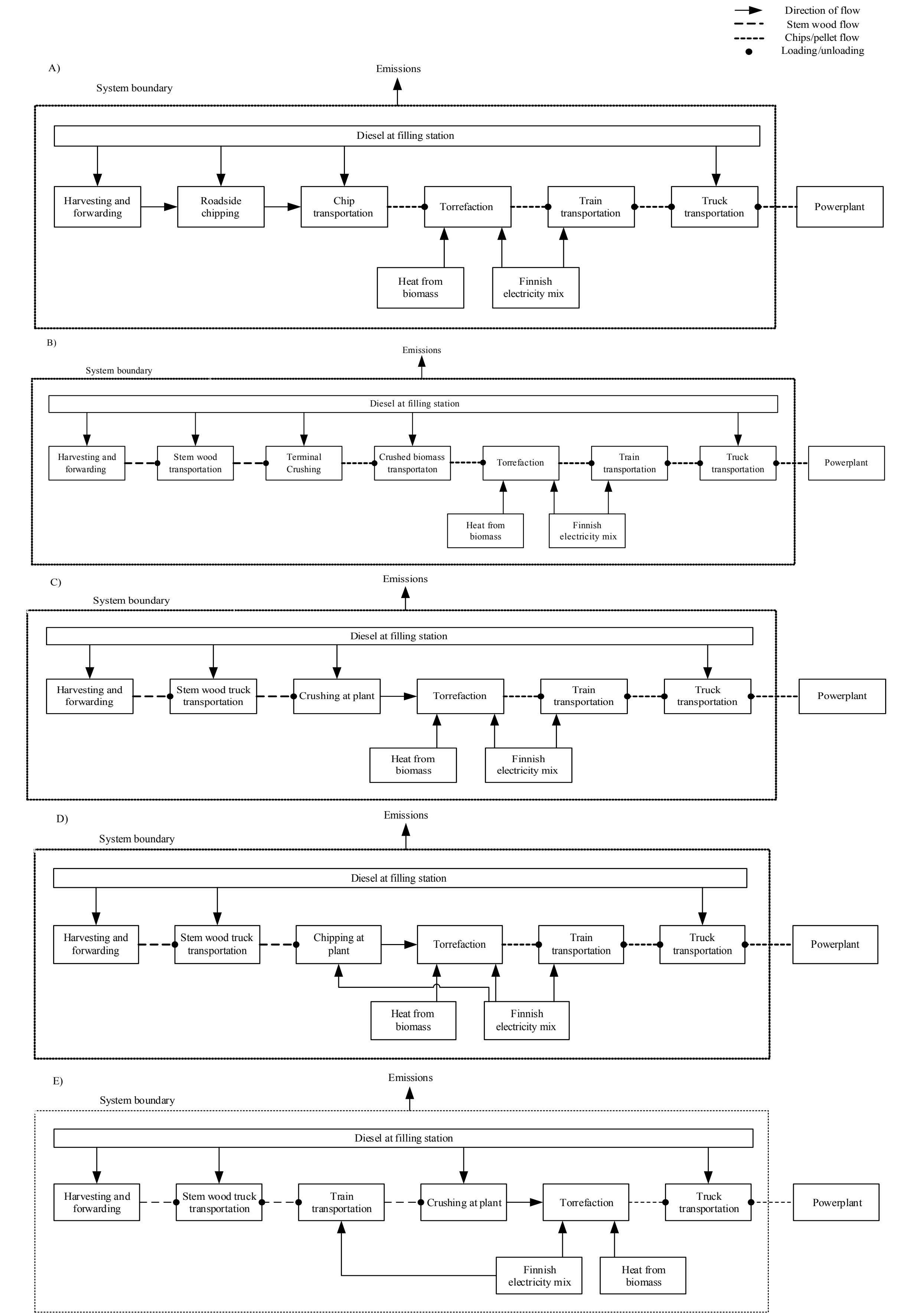

Figure 3. System boundary with supply chain scenarios depicted as Scenario (A): Roadside Chipping (RSC), Scenario (B): Terminal Crushing (CRT), Scenario (C): Crushing at the Plant (CRP), Scenario (D): Chipping at plant (CHP), Scenario (E): Torrefaction plant in Helsinki (TPH).

Table 1. Properties of the torrefied pellets [18].

Species	$Q_{d.\ pellet}$ MJ/kg	Moisture (m) %	$Q_{ar,\ pellet}$ MJ/kg	$Q_{ar,\ pellet}$ MWh/t	Total $Q_{ar,\ pellet}$ MWh/yr	Density kg/m^3
Birch	19.37	6	18.06	5.02	1,003,401	678
Spruce	18.47	6	17.22	4.78	956,401	699
Pine	19.96	6	18.62	5.17	1,034,212	682
Energy wood	19.15	6	17.85	4.96	991,912	696

Table 2. Properties of raw materials.

Species	$Q_{d,\ raw}$ MJ/kg	Moisture (m) %	$Q_{ar,\ raw}$ MJ/kg	$Q_{ar,\ raw}$ MWh/t	$Q_{ar,\ raw}$ MWh/yr	Fresh Mass t/yr
Birch	19.19	51.5	8.05	2.24	1114890	498656
Spruce	19.02	51.5	7.97	2.21	1062668	480217
Pine	19.33	51.5	8.12	2.25	1149125	509668
Energy wood	19.19	52.2	7.90	2.19	1102125	502398

2.4.2 Supply chain alternatives

A flow chart of the five different supply chain alternatives for each feedstock type is shown in Figure 3. In this study, it is assumed that the average truck transport distance is 100km. However, in scenario CRT where biomass is stored and comminuted at the biomass terminal, a surplus of 20km from the terminal to torrefaction plant is added. Similarly, in scenario TPH, where the torrefaction plant is assumed to be in Helsinki, the torrefaction plant is considered to be 20km from the power plant. The process heat required in the torrefaction process is assumed to be produced from biomass. However, electricity is an average Finnish grid mix, shown in Table 3. Long-distance transport is modeled as freight train transportation pulled by an electric locomotive and the distance is set as 300km in all scenarios. Currently, power plants in Helsinki have no railway access so biomass is considered to be handled at a harbor rail-yard 20 km from the powerplant. A brief outline of the scenarios is given below.

Roadside chipping (RSC): Delimbed stem wood is harvested and then forwarded to the roadside storage for natural drying. After drying, it is chipped with a diesel-powered mobile chipper straight to chip trucks (full truck-trailer). The chips are transported to the torrefaction plant. After torrefaction, the torrefied pellets are loaded into an electric freight train for transport to Helsinki and unloaded at the biomass handling harbor rail yard and transported to a power plant in a semitrailer.

Terminal crushing (CRT): After the forest procurement, the delimbed stem wood is immediately transported in trailer-trucks to the biomass terminal. After drying at the terminal, the delimbed stems are crushed with a diesel-powered terminal crusher. The crushed biomass is then loaded into chip trucks for transport to the torrefaction plant. After torrefaction, the torrefied pellets are loaded into the electric freight train for transport to the harbor rail yard, where the pellets are unloaded. The pellets are then loaded onto semi-trailer trucks and transported to the powerplant.

Crushing at the plant (CRP): Similar to RSC, harvested logs are left at the roadside storage for drying. The dried stems are then transported directly to the torrefaction plant and crushed at the plant yard in a diesel-powered crusher. The crushed biomass is torrefied and the finished product delivered to the biomass handling harbor yard, where it is unloaded. The pellets are then transported to the power plant in a semi-trailer truck.

Chipping at the plant (CHP): The scenario is similar to CRP but the delimbed stems are chipped in a stationary electric chipper.

Torrefaction plant in Helsinki (TPH): In this scenario, unlike previous scenarios, the torrefaction plant is assumed to be located in Helsinki, 20 km from the power plant. After the forest procurement, the logs are immediately transported on a truck-trailer to train loading site, where they are left to dry. The delimbed stems are then loaded onto the freight train and unloaded at the torrefaction plant, where the wood is crushed with a diesel-powered crusher. The torrefied pellets are then transported to the power plant in semi-trailer trucks.

2.4.3 Unit processes

Table 3 presents the various phases of the LCA (unit processes) and input data for the LCI calculations. The corresponding references are attributed accordingly.

Table 3. Unit processes and their description.

Unit processes	Description	Reference
Harvesting	Engine size 100 kW * Total weight 14t * Productivities • Energy wood 5.4 solid-m^3/h ¶ • Birch 10.4 solid-m^3/h * • Spruce, Pine 10.45 solid-m^3/h*	*[23] ¶ [24]
Forwarding	Engine size 110 kW * Total weight 11t * Productivities • Energy wood 6.8 solid-m3/h ¶ • Birch 12.3 solid-m^3/h * • Spruce, Pine 12.27 solid-m^3/h *	¶[24] *[25]
Trucks	EURO 6 Empty return considered Payloads capacity (utilization) • Full trailer-truck 40.6t (100%) • Semi-trailer 24.7t (80-85%)	[26]
Chipping/Crushing	Roadside energy wood chipper* • Drum chipper • Weight 19.2 t • Power 475 kW • Productivities ▪ Energy wood 30 solid-m^3/h ¶ High(diesel)-powered conventional roadside pulpwood chipper, emission factor • 9.38 kg CO_2/ton biomass (oven dry) § Stationary electric chipper ∞ • Electricity consumption 1.1 kWh/loose-m^3 of chips Crushing ¶ • GHG emissions 3.46 kg CO_2 eq/MWh	*[27] ¶[24] § [28] ∞ [29]
Loading/unloading	Logs (grab truck) • Loading 0.05 g CO2 per $MJ_{biomass}$ • Unloading 0.04 g CO2 per $MJ_{biomass}$ Chips and pellets (assumed to be same as chips) Loading/Unloading (wheel loaders) 0.03 g per $MJ_{biomass}$	[22]
Torrefaction	Energy consumption per kg (dry) • Electricity 0.128 kWh • Process heat 0.339 kWh	[30]
Train transport	• Payload capacity 1,452t • Volumetric capacity 60m^3/wagon • 24 wagon	[26]
Electricity mix	Electricity production mix (Finland) • Nuclear energy 33.26% • Hydropower 18.1% • Biomass 16.15% • Coal 15.07% • Natural gas 9.57% • Others 7.85%	[26]
Diesel at filling station	GHG emissions • 534g CO_2 per kg of diesel at filling station (EU-28 average)	[26]

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2.5 Sensitivity analysis

2.5.1 Moisture content

In this study, the moisture content of the raw biomass is kept constant at 30% in all scenarios. However, according to [31], the moisture content of delimbed stems depends on the duration of natural drying at the temporary storage facility and the weather conditions during the storage period. Thus, in order to address the uncertainty of moisture content in naturally dried stems, a sensitivity analysis is done assuming that the moisture content of the raw biomass after drying at temporary storage is 40%.

2.5.2 Heating value of pellets

The heating values of torrefied pellets are taken from Ranta et al. [18] and are constant in all scenarios. However, heating values of torrefied pellets depend on the production process parameters and the values can be higher than the values assumed [32]. In order to assess the impact of the heating value of the pellets, a sensitivity analysis is done assuming torrefied pellets with 10% higher heating values for each biomass type.

3. Results

3.1 LCIA

The total annual GHG emissions from the production of torrefied pellets for the different feedstock material and supply chain alternatives are shown in Figure 4. The results show that pellets produced in South Savo from energy wood crushed in a biomass terminal have the highest GHG emissions (23,909t/y), whereas pellets produced in South Savo from birch pulpwood after comminution in an electric chipper (CHP) have the lowest GHG emissions (15,741t/y). Moreover, torrefied pellets of energy wood were found to have significantly higher GHG emissions compared to pulpwood in all respective scenarios.

The GHG emission results of torrefied pellets of all feedstock types and supply chain alternatives with respect to the functional unit are presented in Figure 5. Of the four types of feedstock, the production chain of torrefied pellets of birch is found to emit the least amount of GHG gases in all five scenarios. In contrast, torrefied pellets made of energy wood have the highest GHG emissions. Furthermore, of the five scenarios studied, scenario CHP is found to have the lowest GHG emissions. Consequently, torrefied pellets of birch in scenario CHP, where the biomass is comminuted in an electric stationary chipper at the torrefaction plant located in South Savo, is found to have the lowest GHG emissions of 15.69 kg CO_2 eq. per MWh. In contrast, scenario CRT, where biomass is comminuted at the biomass terminal and torrefied in South Savo, has the highest GHG emissions. Thus, torrefied pellets made of energy wood produced in South Savo have the highest GHG emissions of 24.1 kg CO_2 eq. per MWh.

3.2 Emissions in life cycle phases

The contributions of the different phases in the supply chains to total GHG emissions for different types of feedstock are presented in Figure 6. Of the different life cycle phases, the torrefaction phase is found to be the largest contributor to total GHG emissions in all scenarios and for all feedstock types. In addition, forest procurement, comminution, and truck transportation are other major phases that contribute to total GHG emissions. In contrast, the comminution of biomass in a stationary electric chipper (assessed in scenario CHP of all type of feedstock) has ~3% GHG emissions compared to comminution in diesel-powered crushers (~18%). Even though the longer distance is covered, train transportation has a significantly lower share of emissions (~2%) than truck transportation (~10%–17%). The reason for the lower GHG emissions is that electricity-powered transport is significantly cleaner than transport with diesel-powered trucks.

As shown in Table 4, changing the supply chain alternative from roadside chipping to terminal chipping (from scenario RSC to scenario CRT) causes 4.7–17.1% additional GHG emissions depending on the feedstock material. Similarly, moving the torrefaction plant from South Savo to Helsinki (from scenario CRP to scenario TPH) will cause 5.5–6.5% additional GHG emissions. In contrast, chipping at the torrefaction plant yard with an electric stationary chipper instead of a diesel-powered crusher can reduce GHG emissions by 15.5–18.2%, depending on the raw material. As presented in Table 5, the results show that pulpwood of birch (13.7%-22.6%), spruce (8.8%-17.7) and pine (10.7%-19.8%) cause lower GHG emissions than energy wood. The size of the reduction depends on logistics alternatives.

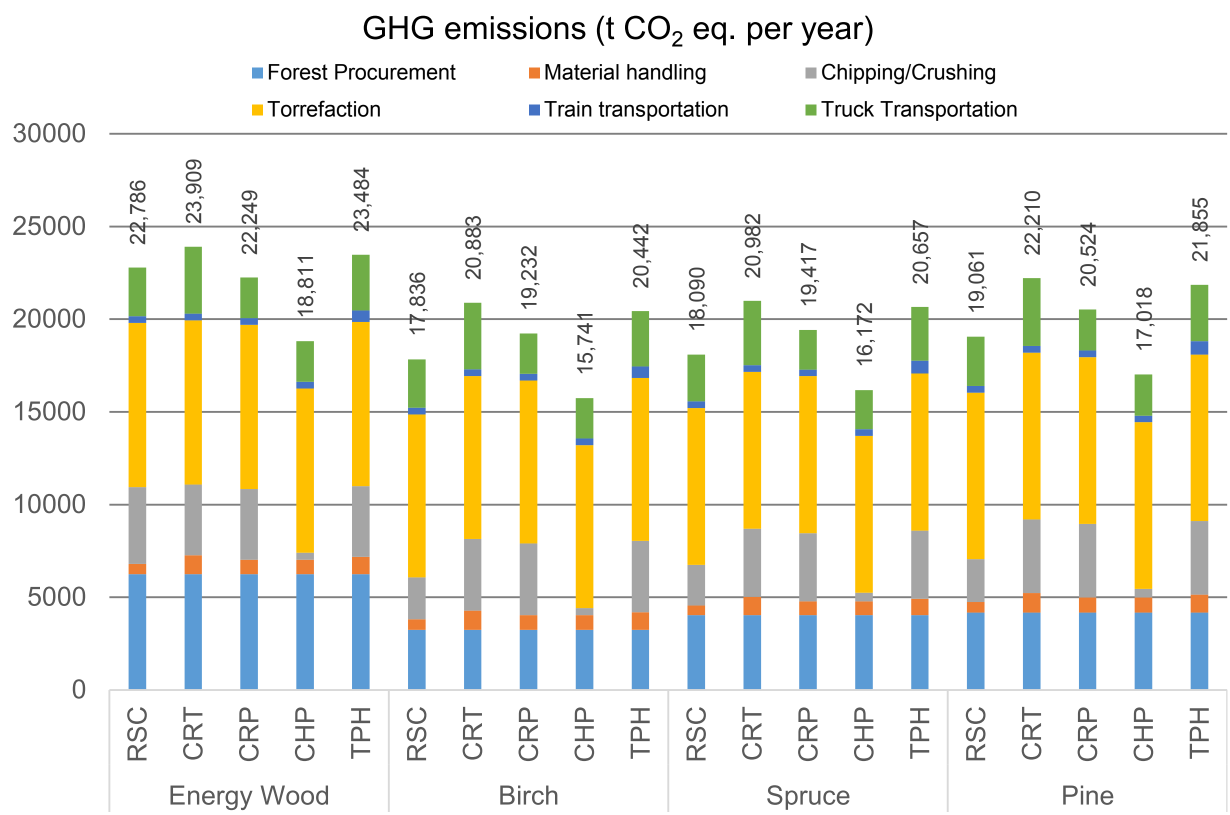

Figure 4. Total GHG emissions in a year from different feedstock scenarios and their supply chain alternatives.

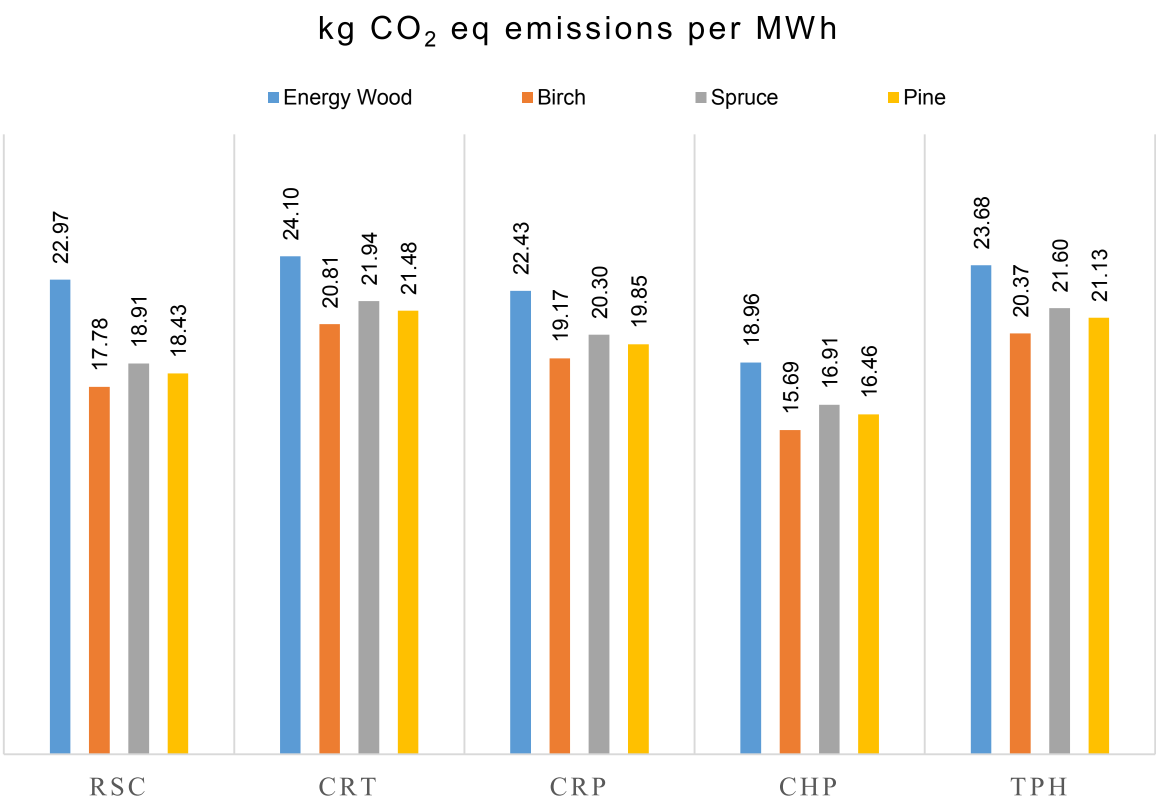

Figure 5. GHG emissions of different supply chain alternatives for each feedstock type.

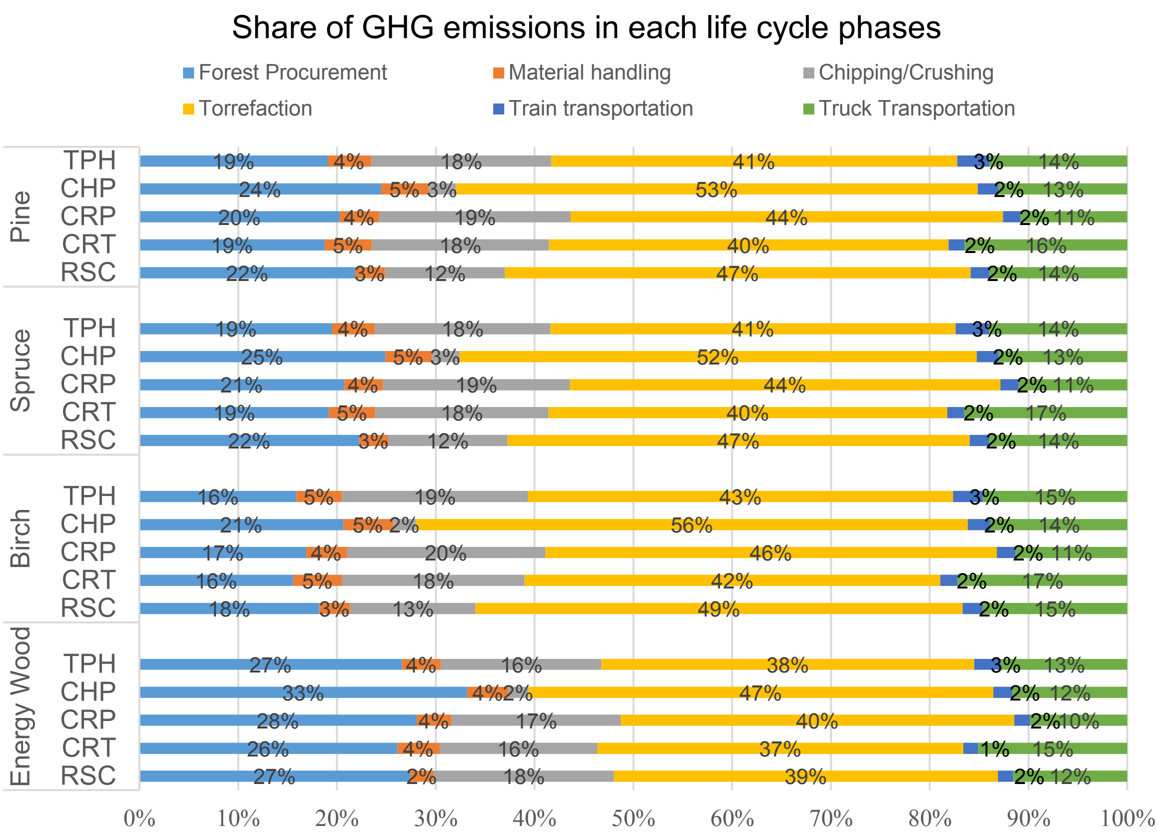

Figure 6. Share of GHG emission of different life cycle phases in each scenario for each feedstock type.

Table 4. Difference in GHG emissions in corresponding scenarios.

Scenarios	Energy Wood	Birch	Spruce	Pine
RSC→CRT	+4.7%	+17.1%	+16%	+16.5%
CRP→TPH	+5.5%	+6.3%	+6.4%	+6.5%
CRP→CHP	-15.5%	-18.2%	-16.7%	-17.1%

Table 5. GHG emissions of torrefied pellets of pulpwood compared to energy wood for each logistics alternative.

Logistics alternatives	Birch	Spruce	Pine
RSC	-22.6%	-17.7 %	-19.8 %
CRT	-13.7 %	-9.0 %	-10.9 %
CRP	-14.6 %	-9.5 %	-11.5 %
CHP	-17.3 %	-10.8 %	-13.2 %
TPH	-13.9 %	-8.8 %	-10.7 %

3.3 Sensitivity analysis

In this study, the moisture content of the dried biomass and the heating values of the pellets were kept constant. However, these two areas were highlighted in the sensitivity analysis, the results of which are presented in Figure 7. The upper and lower values of the error bars indicate sensitivity results of 10% higher moisture content in delimbed stems and 10% higher energy content in pellets, respectively. Based on the assessment, removal of biomass from forest roadside storage when the moisture content is 40% rather than 30% can cause up to 2% additional GHG emissions from transportation. However, it should be noted that emissions from storage and the effect of moisture on torrefaction are not studied in this assessment. On the other hand, 10% higher energy content in torrefied pellets causes <1% less emissions compared to the main study. However, it should be mentioned that energy yield is kept constant at 90%, as in the main study.

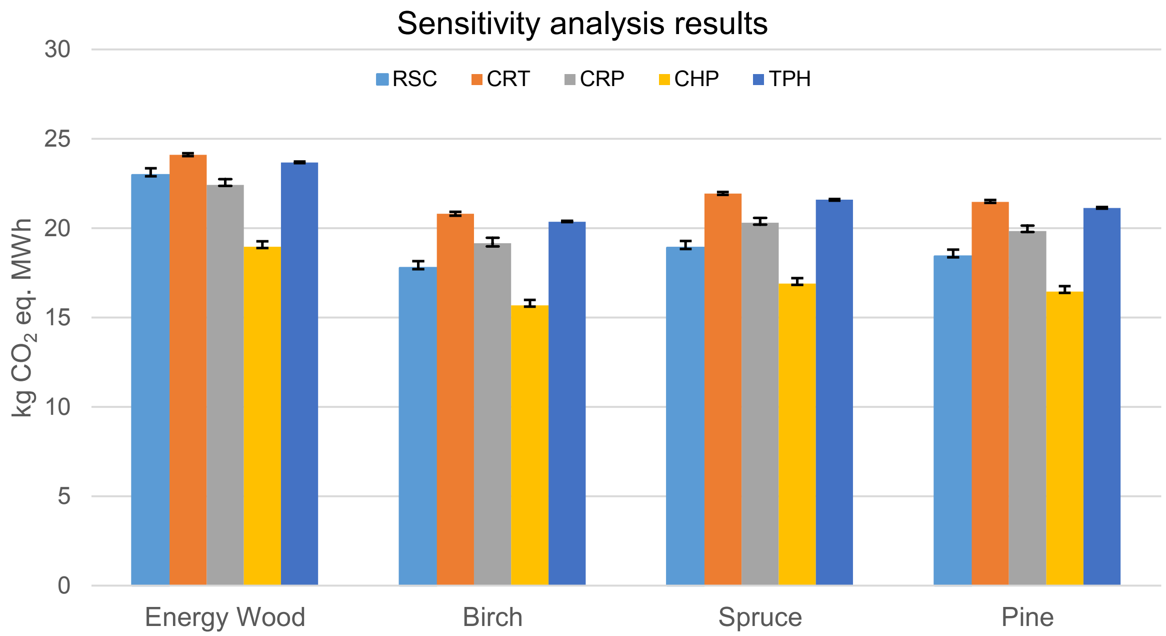

Figure 7. Sensitivity analysis results compared to the main results. The upper values of the error bars represent results from 10% additional moisture content in delimbed stems after natural drying, whereas lower values represent 10% higher energy yields in torrefied pellets.

4. Discussion

The results of this paper show that there is a real opportunity to lighten the environmental burden of bioenergy by adopting a suitable logistics alternative and using appropriate raw material for torrefaction. In particular, using an electric chipper instead of a diesel-powered crusher can help avert up to 18% of total emissions. A key factor is that the majority of the electricity mix in Finland consists of clean energy; a little over two-thirds of electricity is produced in the form of nuclear energy, hydropower, and bioenergy. However, in Finland, only about 11% of the energy biomass is chipped with electric chippers [33]. Thus, there is an opportunity to reduce the carbon footprint of comminution operation. Similarly, producing torrefied pellets from birch pulpwood instead of energy wood can help decrease GHG emissions by about 23% because of the higher productivity of the forest machinery and chipper with pulpwood than energy wood. According to the sensitivity analysis results, the location of the storage for natural drying, either at the forest roadside or in the plant yard, has no significant impact (~2%) on overall global warming potential of torrefied pellets. However, it is observable that the impact of higher moisture content is greater in the RSC, CRP and CHP scenarios, due to the biomass only being dried at the forest roadside before long-distance transportation.

The sensitivity analysis showed that the moisture content in the raw material is one of the important factors in GHG emissions of torrefied pellets. Transportation of biomass with 10% higher moisture contributed about 2% more GHG emissions from the overall supply chain. However, due to lack of inventory data, moisture content before comminution and torrefaction is assumed to be the same throughout the study which may not be the case in actual practice. Moreover, the natural drying process at forest roadside or biomass terminal is a crucial element for GHG emission reduction from torrefied pellets supply chain.

This is case-specific research dealing with a certain Finnish bioenergy scenario such as availability of forest biomass, transportation distance, and means of transportation. However, this research can also serve as a benchmark for other areas as more use of biomass and transportation distance is anticipated in the future. One of the drawbacks of case-specific studies, on the other hand, is that some of the key factors may drastically affect the results for one region, and the same factor may not be as effective in others. For example, in scenarios CRP and CHP where biomass is either crushed with a diesel-powered crusher or chipped with an electric chipper, the impact of the electricity mix was significant. However, the electricity mix may not have the same effect in any other region depending on the proportion of the source of electricity in those regions.

To our knowledge, no comparative LCA studies of torrefied pellets that investigate pulpwood and energy wood of different tree species as a raw material and supply chain alternatives have been presented. A study by Thrän et al. [30] examined GHG emissions of torrefied pellets made from straw, logging residues and short-rotation coppice (willow). In addition, the study compared GHG emissions for biomass originating from different countries such as Spain, Canada, USA, and Tanzania. It would be impractical to compare the results of this study with torrefied pellets of straw; however, results for logging residues and short-rotation coppice are somewhat comparable to this study. Thrän et al. [30] found that torrefied pellets of logging residues and short-rotation coppice from Spain generated GHG emissions of 39.9kg and 47.7kg CO_2 eq. per MWh of pellets, respectively. However, the results are very parameter-dependent because, as seen in this study, biomass supply alone contributes about 45% of total GHG emissions.

McNamee et al. [32] studied LCA of torrefied pellets of pine round wood produced in North America and shipped to the UK for final use. Their analysis indicated that GHG emissions varied from 27.9g CO_2 eq to 43g CO_2 eq per MJ of electricity produced depending on the torrefaction parameters (temperature and residence time) and utility fuel used during torrefaction (natural gas or wood chips). The study assumed 40% electric efficiency of the plant, thus, tentative comparable results would be 251 kg to 387 kg CO_2 eq per MWh of pellets. In cases where biomass is used as a utility fuel, transportation (including shipping) contributes over 80% of total GHG emissions.

Adams et al. [3] studied GHG emissions of torrefied pellets of Scots Pine (*Pinus sylvestris*). Their results showed GHG emissions varied from 17.5 g to 40.5 g per MJ of pellets depending on the energy demand for drying. The tentative comparable range of results would be 63 kg to 145 kg per MWh. However, in their study, 15% of the heat required was sourced from natural gas as utility fuel. In addition, the results included transportation of torrefied pellets from Norway to a power station in the UK.

Pergola et al. [34] studied the LCA of packaged traditional white pellets. According to their study, production of one ton of white pellets emitted 38 kg CO_2 eq. According to Alakangas et al. [20], one ton of white pellets equals 4.7-5 MWh of energy. With this assumption, the results would be 7.6-8 kg CO_2 eq per MWh of white pellets. It should be noted that wood chips are considered as a main fuel in the pelletization process as in our study. Similarly, Magelli et al. [35] studied the LCA of white pellets produced in Canada and imported to Sweden. It was found that production of one ton of white pellets from wood residues emitted 532 kg CO_2 eq., of which 422 kg was generated by ocean transportation. Thus, GHG emissions from forest procurement to production and delivery to the seaport is only about 110 kg CO_2 eq per ton, which is roughly 23 kg CO_2 per MWh pellets. It should be noted that land transportation in the study by Magelli et al. [35] included 763 km of train transportation.

Currently, it may be unrealistic to consider pulpwood as a feedstock for torrefied pellet production because of stiff competition from other industries such as the pulp and paper industry and biorefineries [36]. For instance, in the third quarter of 2018, the average price of delimbed stem (energy wood) was 23.3 EUR/solid-m^3 as delivery sales. On the other hand, the average price of birch pulpwood at the roadside was 32.8 EUR/solid-m^3 [14]. The significantly higher price of the raw material may prove to be an obstacle to pellet production for power plant usage. However, coal-fired power plants may look to use more biomass in energy production, since growing numbers of countries have pledged to phase out coal from the energy sector by 2030, including Finland, and other benefits of torrefied pellets such as being a potential replacement of fossil coal could play a role in wider adoption. According to Helen Oy [37], an energy firm owned by Helsinki city, utilizing biomass is the easiest way to replace coal and furthermore there is a lack of biofuel availability in the Helsinki area. In addition, as Helsinki is a coastal urban city with a less forested environment than commonly found in Finland, it is inevitable that biomass feedstock will need long-distance transportation, either from other parts of Finland or from neighboring countries such as Russia or the Baltic countries. Thus, biomass from areas such as South Savo could provide a timely solution for power industries in Helsinki. This study provides valuable information regarding the environmental performance of torrefied pellets originating several hundred kilometers inland from the power plant and transported using land transportation. However, biomass originating in Finland is not the only possible source and research is required on the environmental performance of biomass imported using marine transportation.

5. Conclusion

This study assessed GHG emissions associated with different supply chain alternatives and a range of raw biomass material for torrefied pellets. GaBi software tool was used for the LCA modeling and different databases and previous literature were used for the lifecycle inventory. The findings of this study were evaluated based on the CML (2001) 2016 version methodology and global warming potential (GWP) was chosen as a sole impact category. Finally, the results were interpreted as kg CO_2 eq. per MWh of pellets delivered to a power plant in Helsinki. The results show that GHG emissions are greatly impacted by the choice of supply chain and raw material. The torrefied pellets of energy wood were found to have significantly higher GHG emissions compared to pulpwood. On the other hand, torrefied pellets of birch (pulpwood) produced in South Savo contribute the lowest GHG emissions in respective supply chain method. Similarly, chipping at plant yard with an electric chipper contributes a lowest GHG burden among the supply chain alternatives. Thus, a significant amount of GHG emissions can be averted by choosing the right raw material for torrefaction. However, the high demand for pulpwood and consequent higher price as compared to energy wood is a major hindrance for pulpwood based pellets in Finland.

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Conflicts of interest
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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