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Time-Dependent Climate Impact and Energy Efficiency of Internationally Traded Non-torrefied and Torrefied Wood Pellets from Logging Residues

Charlotta Porsö [1] · Torun Hammar [1] · Daniel Nilsson [1] · Per-Anders Hansson [1]

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Abstract
Demand for wood pellets as a renewable alternative to fossil fuels has increased in the past decade. However, production and use of wood pellets involves several operations (biomass extraction, chipping, transport, drying, milling, pelleting, combustion) with negative impacts on e.g. the climate. In this study, the energy efficiency and climate impact of production and use of non-torrefied and torrefied wood pellets were analysed and compared. The wood pellets, produced from logging residues extracted from a boreal coniferous forest stand (Norway spruce (*Picea abies* (L.) H. Karst)) in northern Sweden, were assumed to be exported and finally used in a power plant. Time-dependent life cycle assessment, expressing the climate impact as global temperature change over time, was used to include annual greenhouse gas fluxes of both fossil and biogenic origin. The results showed that carbon stock changes due to extraction of logging residues contributed most of the warming effect on global temperature. Due to greater demand for raw material, a higher warming impact per gigajoule fuel was obtained for torrefied wood pellets than for non-torrefied wood pellets. However, torrefied wood pellets demonstrated a lower climate impact (per GJ electricity) when advantages such as higher electrical energy efficiency and higher co-firing rate were included. A general conclusion from this study is that replacing coal with non-torrefied or torrefied wood pellets made from logging residues can mitigate climate change. The energy output of these systems was about sevenfold the primary energy input.

Keywords Life cycle assessment · LCA · Global warming · Time-dependent climate impact · Biogenic carbon · Torrefied wood pellets

Introduction

With climate change recognised as a global threat, reductions in emissions of anthropogenic greenhouse gases (GHGs) are crucial [1]. Replacing fossil fuels with biomass is considered a viable approach, and this has increased the demand for biomass for energy conversion [2]. Transforming biomass to pellets provides improved characteristics, such as higher energy density, lower moisture content and a more homogeneous shape [3], making the material easier to transport, store and use. The global wood pellet market has grown sharply in recent decades and further growth is expected. Wood pellets are traded internationally, with large trade flows from North America and Russia to Europe, which is currently the main market for wood pellets. This is partly a consequence of the European Union's target to reduce GHG emissions and increase the share of renewable energy sources [3]. Using wood pellets for electricity production in new dedicated bioenergy plants or for co-firing in existing fossil fuel-fired plants has been shown to be a relatively economically and technically straightforward solution to mitigate GHG emissions [2, 4, 5].

In addition to non-torrefied wood pellets, interest in pellets made from torrefied biomass (torrefied wood pellets) is increasing [6, 7]. In the production of torrefied wood pellets, a torrefaction step, in which biomass is exposed to temperatures between 220 and 300 °C in a low-oxygen atmosphere, is added before densification of the biomass [8]. The torrefied biomass typically contains about 90% of the initial energy content, but only 70% of the initial mass [9–11]. Consequently, torrefied wood pellets are more similar to coal in terms of handling, transport and milling [6, 7]. Compared with non-torrefied wood pellets, they have higher energy

✉ Charlotta Porsö
charlotta.porso@slu.se

1 Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, SE-750 07 Uppsala, Sweden

density, are less moisture sensitive and require less energy for grinding [7, 8]. In existing coal-fired power plants, co-firing rates of up to 10–15% for non-torrefied wood pellets are possible without major modifications. However, with torrefied wood pellets, the co-firing rate can be up to 50% and they can thereby replace more coal [6, 7, 11–13]. Besides woody biomass, other biomass feedstock is suitable for torrefaction (e.g. herbaceous biomass) [10, 14, 15]. Great improvements have been made in the torrefaction technology during the past decade and the main challenge today is to move from demonstration to industrial scale [15]. However, with the inclusion of an extra process and increased raw material demand, the production costs will most likely increase.

Increasing the use of biomass to replace fossil fuels is a central component in many climate change mitigation strategies [16]. It is important to have knowledge about the climate effects when new energy systems are being developed. As a major contributor to GHG emissions, coal generates about 40% of the world's electricity [17]. In existing coal-fired power plants, both non-torrefied and torrefied wood pellets are seen as a potential replacement for coal.

Life cycle assessment (LCA) is a standardised method (ISO 14040/44) that assesses the potential environmental impact throughout the whole life cycle of a product or process. The method is often used to evaluate the climate effects of bioenergy systems [18–20], with global warming potential (GWP) being the most commonly used metric to describe the climate impact. GWP is defined as the integrated radiative forcing (RF) due to a pulse emission relative to the integrated RF for a reference gas (most commonly carbon dioxide (CO_2)) over a defined time horizon. Radiative forcing ($W\ m^{-2}$) describes the energy balance on Earth due to altered GHG concentrations, with a positive RF reflecting a warming climate response and a negative RF a cooling climate response [21].

Climate benefits of using non-torrefied or torrefied wood pellets instead of fossil alternatives have been shown in several studies [4, 22–26]. Most LCAs of bioenergy systems include only GHG emissions released during the production chain, including harvest, upgrading and transport of the biomass. However, these systems may also be connected to land use changes causing altered biogenic carbon stocks in both soil and living biomass. Furthermore, the general assumption that bioenergy is carbon-neutral (i.e. assuming that the same amount of CO_2 as released during combustion is sequestered during regrowth of new plants) has been questioned for disregarding the time lag between emission and uptake of biogenic CO_2 [27, 28]. The importance of including these effects in climate impact assessments of bioenergy systems has been repeatedly emphasised [29–31].

In LCA, all emissions from the system are usually summed up into a single pulse, irrespective of when they occur. With this approach, net changes in biogenic carbon stocks during the study period can be captured in the climate impact assessment, but not the temporary fluxes. In order to include these temporary fluxes, both the timing and magnitude of the GHG fluxes need to be considered in the climate impact assessment. Several approaches have been suggested to handle these temporal effects of GHG fluxes connected to bioenergy systems, e.g. expressing climate impact as radiative forcing or as temperature change [19].

Traditionally, sawdust and shavings have been the main raw materials used for wood pellet production [32]. However, in many Western and Central European countries, these residues from the sawmilling industry are already utilised to a large extent. Their availability is also dependent on the shifting demand for timber products. This has increased the interest in alternative raw materials, such as bark, wood from thinnings, forest residues and even prime log wood [32]. Sweden has large forest resources [33] and potential to increase the use of forest residues which would otherwise be left in the forest after final felling or thinning [34]. Forest residues are already used for heat and power production, but pelleting the biomass produces a more energy-dense and homogeneous product, which could open up new market possibilities.

The aim of this study was to analyse and compare the energy efficiency and climate impact of production and use of non-torrefied and torrefied wood pellets. The wood pellets, produced from logging residues extracted from a boreal coniferous forest stand (Norway spruce (*Picea abies* (L.) H. Karst)) in northern Sweden, were assumed to be exported and finally used in a power plant. In order to include annual GHG fluxes of both fossil and biogenic origin, a time-dependent LCA, expressing the climate impact as global temperature change over time, was performed.

Method

System Description

The production system included supply of raw material, upgrading, transport to the end-user and final use of the non-torrefied and torrefied wood pellets in a power plant (Fig. 1). In a base scenario, a transport distance of 600 km by train, from the pellet production plant to a harbour in Central Sweden, followed by a transport distance of 3000 km by ship, was assumed. These distances represent export to the UK or the Benelux countries. The wood pellet systems were also compared with a coal-based reference scenario.

For raw material supply, a boreal coniferous forest stand (Norway spruce) in Västerbotten in northern Sweden (64° N) was assumed for extraction of logging residues, with a rotation interval of 120 years. The analysis included extraction of logging residues, allocating emissions occurring prior to final felling to timber production. Ash was assumed to be spread

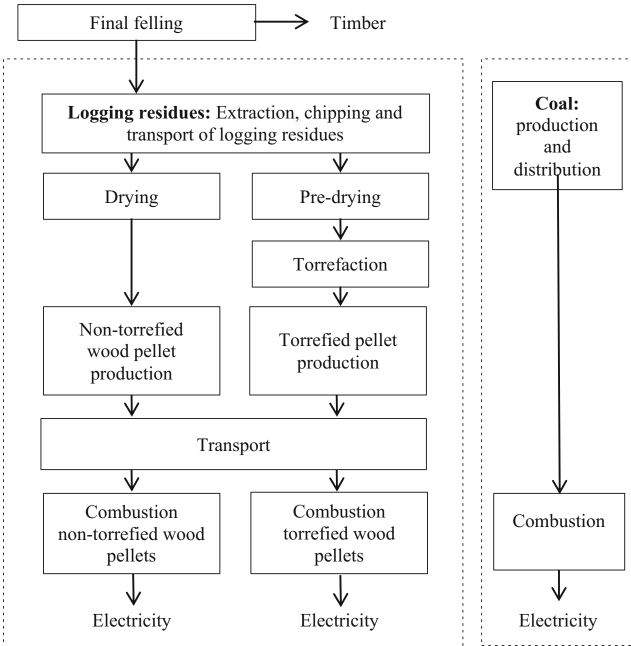

Fig. 1 Overview of the production system for non-torrefied and torrefied wood pellet systems based on logging residues, compared with a coal-based reference scenario

in the stand according to Swedish recommendations to avoid soil depletion [35].

A wood pellet production chain comprising drying, fine milling, pelleting and finally cooling was assumed. For production of torrefied wood pellets, a torrefaction step was added before milling of the biomass. During torrefaction, about 30% of the initial biomass is converted to torrefaction gases (mainly water, organics and lipids) and non-condensable gases (mainly carbon monoxide (CO) and CO_2) [7]. These gases can be recirculated and combusted to partly cover the heat requirement within the process, with current technology covering at least 60% of the heat requirement according to Batidzirai et al. [23]. Even for relatively dry raw materials, the main components of the torrefaction gas are incombustible water and CO_2 [11]. To increase the combustion properties, the raw material is often pre-dried to a moisture content of about 20% before torrefaction [23, 32]. Compared with untreated biomass, torrefaction results in a 50–85% reduction in the electricity requirement for milling, depending on the degree of torrefaction applied [6, 10, 11]. Moreover, depending on the degree of torrefaction required, binders may be needed in the pelleting process [7]. Under optimal conditions, the electricity requirement for densification may be similar to that for non-torrefied wood pelleting, but values up to threefold higher have also been reported [6].

Mass and Energy Efficiency

To assess the overall energy efficiency of a system, the energy ratio (E_r), describing the primary energy input per unit output energy, is a frequently used indicator [36]. Here, E_r was calculated by dividing the energy in the non-torrefied or torrefied wood pellets produced (E_{out}) by the primary energy input to the system (E_{in}), based on lower heating value (LHV) of dry biomass adjusted for the specific moisture content:

$$E_r = \frac{E_{out}}{E_{in}} \tag{1}$$

Part of the incoming raw material was assumed to be used within the non-torrefied and torrefied wood pellet production process, to cover the heat requirement for drying and torrefaction. To assess the mass and thermal energy efficiency of non-torrefied and torrefied wood pellet production, the mass ratio (M_r) and thermal energy ratio (E_{THr}) of the processes [7] were calculated as follows:

$$M_r = \frac{M_{out}}{M_{in}} \tag{2}$$

$$E_{TH_r} = \frac{M_{out} \times \mathrm{LHV}_{out}}{M_{in} \times \mathrm{LHV}_{in}} \tag{3}$$

where M_{out} is the biomass output in the form of non-torrefied or torrefied wood pellets and M_{in} is the biomass input including both the densified biomass and the biomass used for drying and in the torrefaction process, based on dry weight. The energy in the non-torrefied or torrefied wood pellets produced, LHV_{out}, is equivalent to E_{out}, while LHV_{in} is equivalent to the energy in the unrefined biomass.

Climate Impact

First, GWP was calculated for the different systems using a time horizon of 100 years. The functional unit in the GWP calculations was 1 GJ fuel (produced in year 1). The GWP was expressed in CO_2 equivalents (CO_2-eq.) per functional unit, using characterisation factors of 28 and 265 kg CO_2-eq. kg^{-1} for CH_4 and N_2O, respectively [21]. Biogenic CO_2 fluxes were not included in the GWP calculations.

The climate impact was also expressed as the global mean surface temperature change, referred to as ΔT_S in this study, at a specific point in time, following the time-dependent LCA methodology described in the study by Ericsson et al. [37]. Besides the RF, this method also considers the inertia of Earth's processes, which delays climate effects. To calculate ΔT_S, a time-dependent life cycle inventory is required, which makes it possible to include annual net biogenic CO_2 fluxes between atmosphere and biogenic carbon stocks in biomass and soil, as well as GHG emissions from the production system. Annual fluxes of the three major GHG gases (CO_2, methane (CH_4) and nitrous oxide (N_2O)) were quantified in a time-dynamic life cycle inventory including GHG emissions from harvest, upgrading and transport and biogenic CO_2 emissions. Biogenic carbon fluxes were defined as the yearly difference between harvesting forest residues (combustion) and leaving the residues in the forest (decomposition).

A time step of 1 year was used for calculation of ΔT_S and a temperature response function was applied. This function, referred to as the absolute global temperature change potential (AGTP) [38], represents the global temperature change due to RF. The atmospheric GHG concentrations were estimated based on the atmospheric perturbation lifetime of the gases, using simple exponential decay for CH_4 and N_2O [38]. To model the more complicated decomposition of CO_2, the Bern carbon cycle model was used [39, 40]. The indirect effect of CH_4 oxidation to CO_2 was included by adding the oxidised fraction in the following year [38]. Baseline atmospheric GHG concentrations (CO_2 390 ppm, CH_4 1803 ppb, N_2O 324 ppb) reported by IPCC and representing mean values for the year 2011 were used [41].

The forest management system was simulated using the Heureka Forestry Decision Support System (Heureka), and the forest carbon balance was modelled with the Q model [42]. The Heureka system is a software developed for forest planning analysis [43] and can be used for projection of forest growth when modelling live biomass stocks. The Q model can be used to simulate carbon stock changes in Heureka [44]. The Q model describes the decomposition over time for different litter fractions of a certain litter quality and requires data on the annual input of litter and annual weather.

The temperature change, ΔT_S, for non-torrefied and torrefied wood pellets was expressed per gigajoule fuel (including emissions from large-scale combustion) and per gigajoule electricity (including the end-use efficiency). A stand view perspective was applied, meaning that the impact of a single harvest was studied.

Data Collection and Assumptions

Supply of Raw Material

Performance data for the raw material supply operations, including extraction, chipping and transport of logging residues to the pelleting plant, were obtained from the study by Hammar et al. [29]. An extraction level of 70% of the available biomass was assumed, resulting in a harvest level of 33.5 Mg dry matter (DM) per hectare. After final felling, the logging residues were assumed to be forwarded to the roadside for storage for a period of 8 months before chipping by a truck-mounted chipper. The chipped raw material was then assumed to be transported by truck to the pelleting plant. Based on the average transport distance of forest fuels in northern Sweden, the length of the round trip between the forest stand and pelleting plant was set to 145 km [29]. The truck was assumed to have a load weight of 34 Mg.

Dry matter losses during storage were set to 1% per month and chipping losses to 3.6% [45]. A moisture content of 45% (on a wet weight basis) at chipping was assumed and a LHV on a dry weight basis of 19.2 MJ per kg DM for forest residues [45, 46]. Fuel consumption for all activities associated with raw material supply (forwarding, roadside chipping and transport of logging residues) was assumed to be the same as reported by Hammar et al. [29]. Emission factors for diesel fuel were 77.8 g CO_2 MJ^{-1}, 0.034 g CH_4 MJ^{-1} and 0.003 g N_2O MJ^{-1} [47] and the primary energy factor was 1.09 [48].

Upgrading

For non-torrefied wood pellet production, part of the incoming raw material was assumed to cover the heat requirement for drying the raw material from 45 to 10% moisture content (wet basis). For torrefied wood pellet production, the heat requirement in the torrefaction process and for pre-drying the raw material to a moisture content of 20% was assumed to be covered by combustion of the torrefaction gases released and by direct combustion of part of the incoming raw material. Assumed electricity and biomass use for non-torrefied and torrefied wood pellet production in this study are shown in Table 1. In addition, 6.3 MJ diesel per GJ non-torrefied or torrefied wood pellets was assumed to be used for raw material handling at the pelleting plant according to Uasuf and Becker [49]. Emission factors for electricity, assuming Nordic electricity mix, were 19.3 g CO_2 MJ^{-1}, 0.162 g CH_4 MJ^{-1} and 0.0023 g N_2O MJ^{-1} [50], and the primary energy factor was 1.5 [51]. The carbon stored in biomass used for drying the raw material was assumed to be released as CO_2 to the atmosphere on combustion. For CH_4 and N_2O, emission factors were 0.011 g MJ^{-1} and 0.006 g MJ^{-1}, respectively [52]. The DM losses at the pelleting plant (for both non-torrefied and torrefied wood pellets) were set to 3% for handling and storage of the raw material and 1% in the pelleting process, according to the work by Sikkema et al. [26].

Transport

A transport distance of 600 km by rail and 3000 km by ship was assumed for the wood pellets, which represents export to the UK or the Benelux countries. For handling and transport by rail, DM losses for non-torrefied and torrefied wood pellets were set to 1%, while for ocean transport, additional 2% DM losses were added, based on the study by Sikkema et al. [26]. Cargo capacity and energy use of the transport options are described in Table 2. Emission factors and primary energy factor for heavy fuel oil were the same as reported by Gode et al. [54]. No return trips for rail and ship were included in the calculations.

Table 1 Electricity and biomass use for non-torrefied and torrefied wood pellet production, based on a lower heating value (LHV) of 19 MJ kg^{-1} dry matter for non-torrefied wood pellets [29] and of 21 MJ kg^{-1} dry matter for torrefied wood pellets [7, 15]

	Electricity (MJ GJ^{-1} fuel)		Biomass (MJ GJ^{-1} fuel)	
	Non-torrefied wood pellets	Torrefied wood pellets	Non-torrefied wood pellets	Torrefied wood pellets
Drying and torrefaction[a]	6.6	15.0	139	286
Milling[b]	10.3	1.6		
Pelleting[c]	10.0	16.0		
Cooling and other equipment[d]	6.8	6.8		

[a] Electricity use estimated from Thek and Obernberger [53], biomass use based on a heat requirement of 3600 MJ Mg^{-1} evaporated water (including heat losses) [53]. For torrefied wood pellets, integrated drying and torrefaction was assumed, with a biomass demand based on a thermal efficiency of 91% for a torrefaction temperature of 270 °C for 30 min [15]

[b] Estimated from [23]

[c] Estimated from Koppejan et al. [6]. For torrefied wood pellets, the middle of the range 45–150 kWh Mg^{-1} was assumed

[d] Estimated from [49]

Energy Conversion

Combustion of the fuels was assumed to occur within a few months of delivery to the energy conversion plant, releasing the carbon stored in the biomass as CO_2 to the atmosphere (including also CO_2 emissions from raw material used within the wood pellet production process). Emission factors for non-CO_2 emissions in large-scale combustion of non-torrefied wood pellets were 0.01 g CH_4 MJ^{-1} and 0.006 g N_2O MJ^{-1} [50]. The same emission factors were used for combustion of torrefied wood pellets. Emission factors for production and distribution [56] and combustion [52] of coal result in total emissions of 100 g CO_2, 0.04 g CH_4 and 0.01 g N_2O per MJ fuel.

The electrical efficiency of using non-torrefied wood pellets in a dedicated biomass power plant was assumed to be 35% for non-torrefied wood pellets and was set to 45% for coal, based on the study by Giuntoli et al. [56]. With the properties of torrefied wood pellets being more similar to those of coal, the efficiency for torrefied wood pellets was assumed to lie between that of coal and non-torrefied wood pellets (40%).

Forest Carbon Balance

Data on forest soil carbon balance and biomass harvest were obtained from a previous study [29] in which biogenic carbon stock changes were estimated when using logging residues in different Swedish climate zones for energy conversion. In that study, biomass stock changes were simulated using the Heureka forestry decision support system where the Q model is used for simulating decomposition [28]. The Heureka system is based on an empirical relationship of forest growth. Information on the forest management regime was retrieved from the forest planning tool INGVAR, and average values for site productivity and understory cover were calculated based on the Swedish Forest Soil Inventory and the Swedish National Forest Inventory [57, 58]. In this study, a forest stand located in northern Sweden (64° N) with a rotation interval of 120 years and with one thinning at year 65 was studied. The productivity (maximum tree height at age 100 year) was 20 m and the understory was blueberry and mosses.

Table 2 Cargo capacity and energy use for transport by rail and ship; maximum cargo capacity was assumed based on weight [55]

Transport	Energy	Cargo capacity (Mg)	Energy use (MJ km^{-1})
Rail	Electricity	1000	587
Ship	Heavy fuel oil	4000	647

Analysis of Alternative Scenarios and Changed Calculation Assumptions

With the higher energy density of torrefied wood pellets, more efficient transport is possible than with that of non-torrefied wood pellets. Different transport alternatives and distances were analysed to assess the effect on the total climate impact of the different pellet systems (Table 3) compared with the base scenario (S1). Export to destinations farther away was investigated (S2) assuming an increased transport distance by

Table 3 Transport distance (km) by different modes for transport scenarios S1–S3

Scenario	Train	Ship
S1 (base scenario)	600	3000
S2	600	25,000
S3	1200	0

ship (25,000 km), which represents export to Asia where the consumption of pellets more than doubled in 2014 [59]. In scenario S3, use in southern Sweden or nearby countries was assumed (1200 km by rail).

Torrefied wood pellet production is a relatively new industrial process compared with production of non-torrefied wood pellets. Therefore, the sensitivity of some of the assumptions made for the production process for torrefied wood pellets was studied:

- A change in emission factors of ± 20% for non-CO_2 emissions for large-scale combustion of torrefied wood pellets (these values were set to 0.01 g CH_4 MJ^{-1} pellets and 0.006 g N_2O MJ^{-1} pellets in the base scenario).
- A change in thermal energy efficiency (E_{THr}) of ± 5%-units (this value was set to 91% in the base scenario).

Furthermore, a sensitivity analysis was performed in which the fuel use in field operations and electricity use for pellet production was varied (± 20%). For torrefied pellets, systems in which the use of electricity for pellet production was 7 and 25 MJ per GJ pellets, respectively, were also investigated (this value was set to 16 MJ per GJ pellets in the base scenario).

In addition, the total temperature response per gigajoule electricity for co-firing wood pellets with coal was assessed, including emissions originating from both wood pellets and coal. Different co-firing rates were assumed: 5, 10 and 15% for non-torrefied wood pellets and 40, 50 and 60% for torrefied wood pellets. Based on findings by Zhang et al. [5], co-firing was assumed to result in 0.5% lower efficiency for every 10% non-torrefied wood pellets compared with using 100% coal. For torrefied wood pellets, a smaller reduction in efficiency can be expected [23], and therefore, a reduction of half that used for pellets was assumed. Electricity consumption for pulverisation of the fuel mix (coal and wood pellets), which is common in direct co-firing with coal, was not included in this study.

Results

Life Cycle Inventory of the Base Scenario

Mass and Energy Efficiency

The primary energy input and energy ratio were approximately the same for non-torrefied and torrefied wood pellets (Table 4). Higher primary energy requirement for upgrading and slightly higher energy requirement for supply of raw material for torrefied wood pellets compared with non-torrefied pellets were found. However, this was partly compensated for by more energy-efficient transport.

Table 4 Primary energy input per gigajoule fuel and the energy ratio for non-torrefied and torrefied wood pellets, not including end-use efficiency

	Non-torrefied wood pellets	Torrefied wood pellets
Energy input (MJ GJ^{-1} fuel)	148	151
Energy ratio (E_r) (MJ MJ^{-1})	6.8	6.7

When upgrading the biomass into non-torrefied or torrefied wood pellets, part of the raw material was assumed to be used to cover the heat requirement within the process. For non-torrefied wood pellet production, the thermal efficiency was calculated to be 96% and for torrefied wood pellet production, it was 91%. The mass efficiency for non-torrefied and torrefied wood pellet production was calculated to be 87 and 74%, respectively.

Greenhouse Gases

The production system (including non-CO_2 emissions from large-scale combustion but not biogenic CO_2 emissions) for non-torrefied and torrefied wood pellets contributed similar levels of CO_2 emissions per gigajoule fuel (Table 5). However, the CH_4 and N_2O emissions were somewhat higher (in a percentage perspective) for torrefied wood pellets compared with non-torrefied wood pellets.

All emissions associated with the production systems were assumed to be emitted in year 1, while biogenic net CO_2 emissions (ΔCO_2) were taken as the difference in CO_2 emissions between combustion of the logging residues in year 1 and leaving the residues in the forest to decompose over time, as shown in Fig. 2. The positive ΔCO_2 in year 1 mainly represents CO_2 emissions from combustion, while the negative ΔCO_2 during the rest of the time frame represents the decomposition of the logging residues over time.

Life Cycle Impact Assessment of the Base Scenario

Global Warming Potential

The GWP for the non-torrefied and torrefied wood pellet systems studied, not including biogenic CO_2 emissions, was

Table 5 Total greenhouse gas emissions (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) from production and use (including non-CO_2 emissions from large-scale combustion, but not biogenic CO_2 emissions) of 1 GJ non-torrefied and torrefied wood pellets

GHG	Non-torrefied wood pellets	Torrefied wood pellets
CO_2 (kg GJ^{-1} fuel)	6.0	5.9
CH_4 (kg GJ^{-1} fuel)	0.02	0.03
N_2O (kg GJ^{-1} fuel)	0.007	0.008

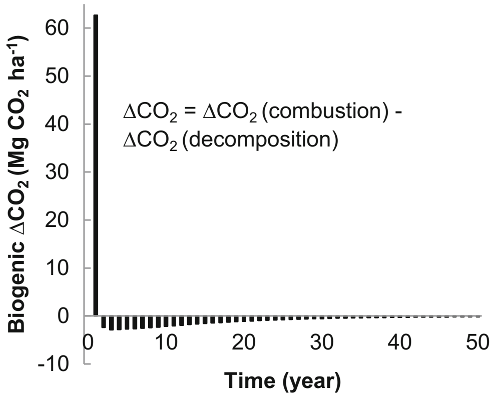

Fig. 2 Differences in biogenic carbon dioxide (CO_2) emissions (Mg CO_2 ha^{-1}) over time, referred to as ΔCO_2, between direct combustion of logging residues in year 1 and leaving the residues in the forest to decompose over time

calculated to be 8.5 and 8.8 kg CO_2-eq. GJ^{-1}, respectively. In comparison, coal resulted in a much higher GWP, 114 kg CO_2-eq. GJ^{-1} fuel.

Temperature Change

The climate impact assessment showed that, per gigajoule fuel, both non-torrefied and torrefied wood pellets contributed to lower global mean surface temperature change (ΔT_S) during the whole study period compared with coal (Fig. 3). Non-torrefied wood pellets had a slightly lower ΔT_S value than torrefied wood pellets. The difference in ΔT_S between the non-torrefied and torrefied wood pellets peaked after 10 years and then decreased over time. The highest global temperature effect for all fuels was obtained about 10–15 years after the emission impulse due to combustion in year 1. This delay is due to the inertia of the Earth's climate processes. For both non-torrefied and torrefied wood pellets, the ΔT_S curves declined faster over time compared with coal, partly because of the net negative CO_2 emissions included for logging residues, as shown in Fig. 2. The forest stand studied had a rotation period of 120 years. However, the greatest global temperature changes took place during the first 50 years of the study (Fig. 3), and therefore, the remainder of this results section focuses on that period.

Net emissions of biogenic CO_2 accounted for by far the largest part of the global temperature effect for both non-torrefied and torrefied wood pellets (Fig. 4). They were also found to be the main cause of the higher ΔT_S for torrefied wood pellets compared with non-torrefied wood pellets. The higher raw material demand for production of torrefied wood pellets resulted in greater net emissions of biogenic CO_2, as these are fixed per hectare. Comparing only the differences in climate impact of the production systems, torrefied wood pellets had a higher global temperature impact in raw material supply and upgrading, while the global temperature impact for transport to the end-user was lower from torrefied wood pellets than from non-torrefied wood pellets (Fig. 5).

Higher electrical efficiency was assumed for torrefied wood pellets compared with non-torrefied wood pellets, which can be expected since it has characteristics more similar to coal. On including the energy conversion efficiency, this resulted in a lower ΔT_S being obtained per gigajoule electricity produced for the torrefied wood pellets (Fig. 6).

Analysis of Alternative Scenarios and Changed Calculation Assumptions

The results showed a small difference in GWP between non-torrefied and torrefied wood pellets for all transport scenarios investigated. In contrast to the shorter transport scenarios (S1 and S3), a slightly lower GWP value was obtained for torrefied wood pellets in the longest transport scenario studied (S2) compared with non-torrefied wood pellets (Table 6). On the other hand, for all transport scenarios, the total ΔT_S was found to be

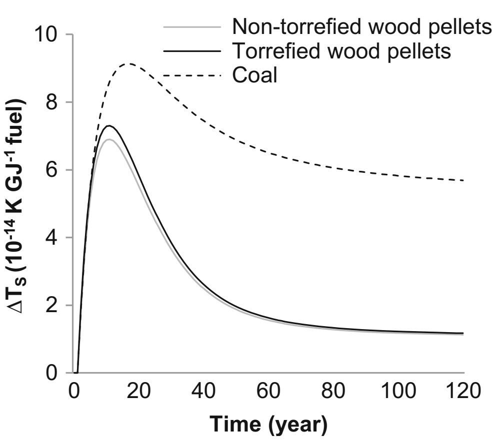

Fig. 3 Global mean surface temperature change (ΔT_S) over time for 1 GJ non-torrefied and torrefied wood pellets produced from logging residues combusted at a power plant compared with 1 GJ coal (produced and used in a power plant in year 1) over one rotation period (120 years)

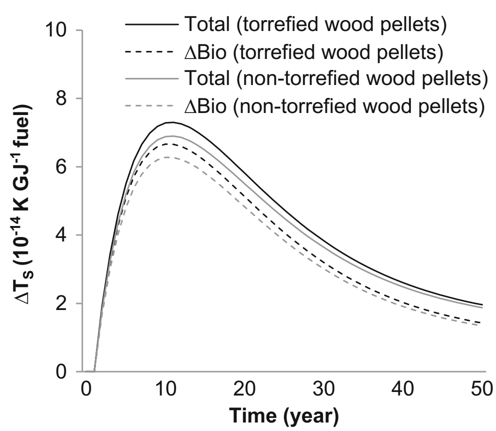

Fig. 4 Global mean surface temperature change (ΔT_S) over time for 1 GJ non-torrefied and torrefied wood pellets produced from logging residues and used in a power plant, and temperature change for only biogenic carbon stock changes (ΔBio)

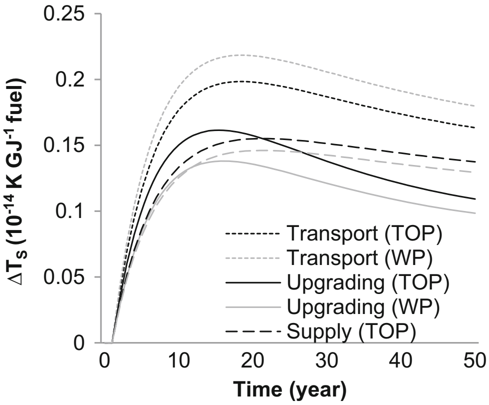

Fig. 5 Global mean surface temperature change (ΔT_S) over time for the production system for 1 GJ non-torrefied wood pellets (WP) or 1 GJ torrefied wood pellets (TOP), divided into supply of raw material, upgrading and transport to end-user

lower for non-torrefied wood pellets than for torrefied wood pellets. This is explained by the dominant effect of biogenic CO_2 emissions on the results, which is not included in the GWP values. Nevertheless, the long transport distance in scenario S2 resulted in higher ΔT_S and significantly higher GWP values for both non-torrefied and torrefied wood pellets compared with scenarios S1 and S3 (Table 6 and Fig. 7).

The same emission factors for combustion at a large-scale power plant were assumed for both non-torrefied and torrefied wood pellets in this study. In the sensitivity analyses, changing the emission factors for CH_4 and N_2O by 20% for torrefied wood pellets was shown to have little impact on the total ΔT_S. In contrast, a change in thermal energy efficiency of 5%-units for the torrefaction process had a larger impact on the total ΔT_S (Fig. 8). The thermal energy efficiency affected the degree of torrefaction and thereby also the raw material demand in the process, which had a large impact on ΔT_S from biogenic CO_2 emissions per gigajoule torrefied wood pellets.

A sensitivity analysis of the use of fuels for field operations and of the use of electricity for pellet production showed that

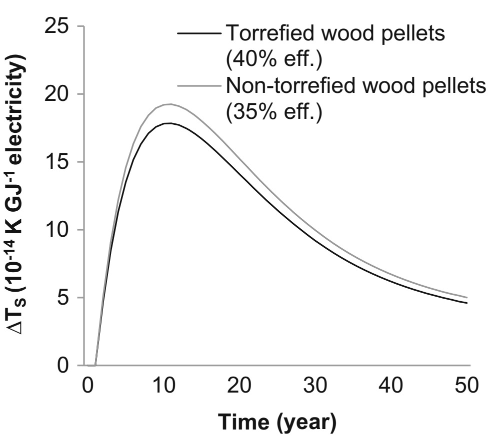

Fig. 6 Global mean surface temperature change (ΔT_S) over time for 1 GJ electricity produced in year 1 from non-torrefied and torrefied wood pellets produced from logging residues used in a power plant

Table 6 Global warming potential (GWP) for production and use (including non-CO_2 emissions from large-scale combustion, but not biogenic CO_2 emissions) of 1 GJ non-torrefied and torrefied wood pellets delivered to a power plant for no transport and for transport scenarios S1–S3

Transport scenario	GWP (kg CO_2-eq. GJ^{-1})	
	Non-torrefied wood pellets	Torrefied wood pellets
No transport	5.6	6.2
S1 (600 km rail, 3000 ship)	8.5	8.8
S2 (600 km rail, 25,000 ship)	26.5	24.6
S3 (1200 km rail)	6.5	6.9

these factors had a small impact on the total global mean surface temperature (Table 7). It was also noted that the difference between non-torrefied and torrefied pellets was negligible. Little impact on ΔT_S was also found for a larger change in electricity demand (7 and 25 MJ GJ^{-1} pellets, instead of 16 MJ GJ^{-1}) within the production of torrefied wood pellets.

The ΔT_S from co-firing wood pellets with coal (including GHG fluxes from both pellets and coal) was substantially lower for torrefied wood pellets than for non-torrefied wood pellets. This was due to the expected higher co-firing rates for torrefied wood pellets (studied rates 40, 50 and 60%) than for non-torrefied wood pellets (studied rates 5, 10 and 15%) and thus more coal being replaced in the former alternative (Fig. 9).

Discussion

In this assessment of the energy efficiency and climate impact of production and use of non-torrefied and torrefied wood pellets made from logging resides, by far, the largest impact

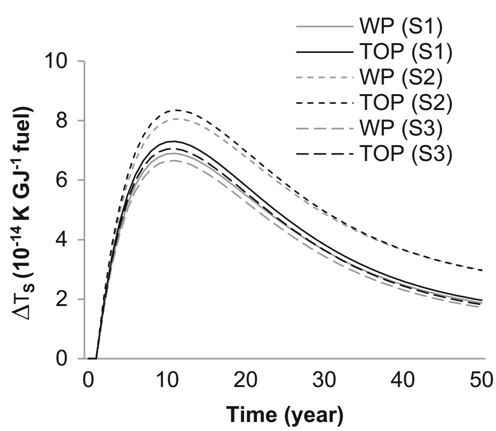

Fig. 7 Global mean surface temperature change (ΔT_S) over time for 1 GJ non-torrefied wood pellets (WP) and torrefied wood pellets (TOP) produced from logging residues and transported and used in a power plant for the base transport scenario S1 (600 km rail, 3000 km ship) and the transport scenarios S2 (600 km rail, 25,000 km ship) and S3 (1200 km rail)

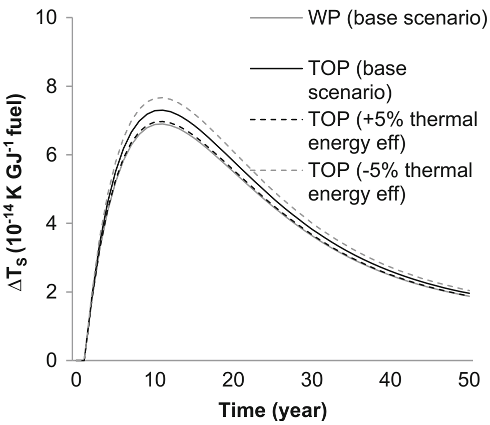

Fig. 8 Global mean surface temperature change (ΔT_S) for 1 GJ fuel produced in year 1 of non-torrefied wood pellets (WP) and torrefied wood pellets (TOP) produced from logging residues and used in a power plant for the base scenario and with a change in assumed thermal energy efficiency of 5%-units (from 91% to 86 or 96%)

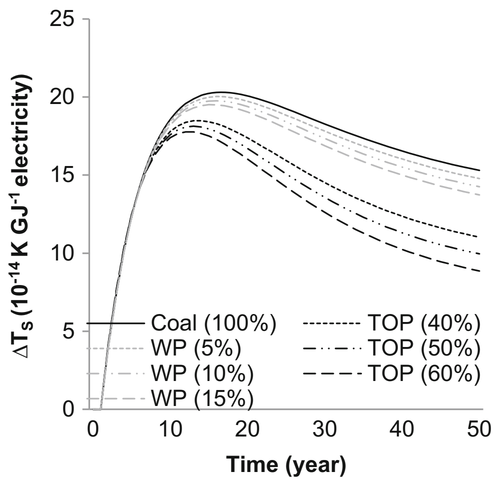

Fig. 9 Global mean surface temperature change (ΔT_S) over time for 1 GJ electricity generated in year 1 for different scenarios for co-firing non-torrefied wood pellets (WP) (5, 10 or 15%) or torrefied wood pellets (TOP) (40, 50 or 60%) produced from logging residues with coal (including emissions from both the wood pellets and coal) compared with using 100% coal

on global temperature was found to be caused by biogenic CO_2 emissions (Fig. 4). These were calculated as the net biogenic CO_2 release between harvest and use of logging residues (in year 1) compared with on-site decomposition over time of the biomass. This indicates that choice and origin of the raw material and efficient use of the biomass are important factors when assessing the climate impact of wood pellet systems. It also confirms the importance of biogenic carbon fluxes in climate impact assessments of bioenergy systems, as discussed in several other studies (see [31, 37, 60]). Harvesting forest residues for energy releases the CO_2 earlier in time (compared with the slower process of decomposition), which has a warming climate impact. In contrast, biomass grown directly for wood pellet production, such as willow and poplar established on former agricultural land, can have a cooling effect on mean global temperature, as shown by Porso and Hansson [30]. This is due to biogenic carbon sequestration in soil and biomass. In such cases, previous land use and its initial carbon stock are crucial factors, as they determine whether the system is going to be a net carbon sink or emitter [30, 31].

Table 7 Change (%) in global mean surface temperature (ΔT_S per GJ pellets produced) in a time perspective of 50, 100 and 120 years, as a result of changes in the use of fuels and electricity for non-torrefied and torrefied wood pellets

		Year 50	Year 100	Year 120
Non-torrefied wood pellets				
Fuel use in field operations	+ 20%	+ 1.4	+ 2.0	+ 2.0
	− 20%	− 1.4	− 2.0	− 2.0
Electricity use for pellet production	+ 20%	+ 0.5	+ 0.7	+ 0.7
	− 20%	− 0.5	− 0.7	− 0.7
Torrefied wood pellets				
Fuel use in field operations	+ 20%	+ 1.4	+ 2.0	+ 2.1
	− 20%	− 1.4	− 2.0	− 2.1
Electricity use for pellet production	+ 20%	+ 0.6	+ 0.7	+ 0.8
	− 20%	− 0.6	− 0.7	− 0.8

In order to produce a fuel more suitable for storage and transport, a torrefaction step could be added in the pellet production chain. However, a larger share of the incoming raw material was shown to be required in the production process for torrefied wood pellets compared with non-torrefied pellet production. One of the main benefits of producing torrefied wood pellets is energy-efficient transport, but with net biogenic CO_2 emissions accounting for most of the global mean surface temperature change (ΔT_S), efficient use of the raw material is more important in a climate perspective. This explains why torrefied wood pellets had higher ΔT_S values than non-torrefied wood pellets per gigajoule fuel in this study (Figs. 4 and 7).

On the other hand, when benefits in the end-use phase of the torrefied wood pellets were included, such as potentially higher electrical conversion efficiency and higher co-firing rates, a lower ΔT_S value for torrefied wood pellets per gigajoule electricity was obtained compared with non-torrefied wood pellets (Fig. 6). However, in the long term, building new dedicated power plants for biomass combustion or enabling high co-firing rates may reduce the benefits of using torrefied wood pellets compared with non-torrefied wood pellets, as discussed by Koppejan et al. [6].

Factors such as thermal efficiency (Fig. 8) and the degree of torrefaction affect the performance of the torrefied wood pellet production process. Thermal efficiency is an important indicator of the technical performance of a process and is determined by thermal losses, moisture content and heating value of the raw material used. In the long-term perspective, Batidzirai et al. [7] point out that the thermal efficiency is likely to increase due to expected technical improvements in the torrefaction process, as well as more optimised use of torrefaction gas. Improved torrefaction technology may also result in wider use of torrefaction gas, replacing petroleum-based products. This could potentially result in both economic and climate benefits.

As mentioned, the largest part of the global temperature change was found to be caused by biogenic CO_2 emissions. By assessing the climate impact using GWP with a fixed time horizon, these emissions would not be considered. Expressing the climate impact over time as global temperature change, as done in this study, or as instantaneous or cumulative radiative forcing over time [37, 61] enables inclusion of these temporal biogenic fluxes. All these studies report increased climate benefits over time for use of forest residues compared with a fossil alternative, as the difference in carbon stocks between extraction of the residues and leaving them to decompose in forest decreases over time. By including the temperature response, the inertia of the Earth is also considered, resulting in a delayed temperature response after radiative forcing. While additional uncertainties are introduced when presenting the results as temperature change rather than radiative forcing, temperature change values may be easier for policymakers to interpret.

However, using GWP and assuming biomass to be carbon-neutral (not including biogenic CO_2 emissions) is the most common approach used to assess the climate impact of different non-torrefied and torrefied wood pellet production chains in earlier studies [23–25, 30]. In the present study, the GWP value was approximated to 7–26 kg CO_2-eq. per GJ non-torrefied wood pellets and 7–25 kg CO_2-eq. per GJ torrefied wood pellets for the different transport scenarios (Table 6). The GWP value for wood pellets used in Sweden is reported to range between 2 and 25 kg CO_2-eq. per GJ non-torrefied wood pellets, including both national and imported pellets [24]. Roder et al. [25] reported a GWP value for non-torrefied wood pellets from forest residues produced in the south-east USA and exported for use in the UK, of approximately 15 kg CO_2-eq. per GJ pellets. Agar et al. [22] compared the climate impact of non-torrefied and torrefied wood pellets from logging residues in Finland used for co-firing in Spain and found small differences between these two types of pellets, which is in line with findings in the present study (recalculated to 12–13 CO_2-eq. per GJ fuel for non-torrefied and torrefied wood pellets). However, as also pointed out by Ehrig and Behrendt [4, 24] and Hansson et al. [4, 24], the design of the supply chain determines the climate impact and energy efficiency of a system. Different assumptions regarding e.g. raw material used, transport alternatives and electricity origin mean that the results of different studies of pellet production chains are not directly comparable. Factors with a large influence on the results include GHG emissions due to electricity mix, transport and emissions from drying the raw material depending on fuel used and moisture content [24, 25]. There are also great uncertainties in CH_4 emissions during storage of raw materials, as discussed by Roder et al. [25].

Concerns regarding potential negative effects when removing additional forest biomass have been raised, especially regarding the risk of nutrient removal and its implications for future forest productivity and the risk of biodiversity loss [62–64]. A recent study by de Jong et al. [65], which examined the environmental sustainability of energy for forest residues, found that the highest risk of biodiversity loss is when deciduous forest residues are harvested. Furthermore, it is difficult to estimate the level to which the harvest should be limited, although the risk of species extinction increases when more than 50% of tops and branches are harvested at landscape level (at final felling).

A review by Egnell [66] found that harvesting tops and branches under Nordic conditions may have a moderate negative impact on growth in Norway spruce stands. This risk was increased when residues were harvested at thinnings. To avoid nutrient removal and potential negative effects on site productivity and acidification, in the present study, harvest was limited to the final felling; all needles were fallen to the ground before the material was chipped and ash was assumed to be recycled to the forest stand. Ash recycling could also be complemented by N fertiliser [65]. No long-term effects on carbon stocks were considered in this study. A review by Lippke et al. [67] concluded that carbon accumulation in forest soil depends on moisture content in the soil, carbon-nitrogen dynamics and climate, and not necessarily on the amount of dead biomass in the form of forest residues left at the forest site. However, it is important to increase knowledge of these long-term effects on soil carbon stocks and the effects on future forest productivity.

In conclusion, the present analysis revealed that:

- Replacing coal with non-torrefied or torrefied wood pellets made from logging residues could mitigate climate change.
- Torrefied wood pellets are better from a climate perspective (per GJ electricity), due to an assumed higher electrical efficiency and a higher co-firing rate compared with non-torrefied wood pellets.
- Biogenic CO_2 emissions are the greatest contributor to the global mean surface temperature change in non-torrefied and torrefied wood pellet systems.
- For both short and long transport distances, total ΔT_S is lower for non-torrefied wood pellets than for torrefied wood pellets (per GJ pellet fuel). This is explained by the dominant role of biogenic CO_2 emissions for the outcome.
- The energy output of these systems is about sevenfold the primary energy input.

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References

1. IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA
2. Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Goss Eng A, Lucht W, Mapako M, Masera Cerutti O, McIntyre T, Minowa T, Pingoud K (2011) Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
3. Lamers P, Junginger M, Hamelinck C, Faaij A (2012) Developments in international solid biofuel trade—an analysis of volumes, policies, and market factors. Renew Sustain Energy Rev 16(5):3176–3199. https://doi.org/10.1016/j.rser.2012.02.027
4. Ehrig R, Behrendt F (2013) Co-firing of imported wood pellets—an option to efficiently save CO2 emissions in Europe? Energy Policy 59:283–300. https://doi.org/10.1016/j.enpol.2013.03.060
5. Zhang YM, Mckechnie J, Cormier D, Lyng R, Mabee W, Ogino A, Maclean HL (2010) Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. Environ Sci Technol 44(1):538–544. https://doi.org/10.1021/es902555a
6. Koppejan J, Sokhansanj S, Melin S, Madrali S (2012) IEA Bioenergy Task 32 report. Final report. Status overview of torrefaction technologies. Enschede, The Netherlands
7. Batidzirai B, Mignot APR, Schakel WB, Junginger HM, Faaij APC (2013) Biomass torrefaction technology: techno-economic status and future prospects. Energy 62:196–214. https://doi.org/10.1016/j.energy.2013.09.035
8. Agar D, Wihersaari M (2012) Bio-coal, torrefied lignocellulosic resources—key properties for its use in co-firing with fossil coal—their status. Biomass Bioenergy 44:107–111. https://doi.org/10.1016/j.biombioe.2012.05.004
9. van der Stelt MJC, Gerhauser H, Kiel JHA, Ptasinski KJ (2011) Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenergy 35(9):3748–3762. https://doi.org/10.1016/j.biombioe.2011.06.023
10. Bergman PCA (2005) Combined torrefaction and pelletisation—the TOP process. Energy research Centre of the Netherlands (ECN), Petten, The Netherlands
11. Tumuluru JS, Sokhansanj S, Hess AR, Wright CT, Boardman RD (2011) A review on biomass torrefaction process and product properties for energy applications. Ind Biotechnol 7(5):384–401. https://doi.org/10.1089/IND.2011.0014
12. Agbor E, Zhang XL, Kumar A (2014) A review of biomass co-firing in North America. Renew Sustain Energy Rev 40:930–943. https://doi.org/10.1016/j.rser.2014.07.195
13. Nunes LJR, Matias JCO, Catalao JPS (2014) A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renew Sustain Energy Rev 40:153–160. https://doi.org/10.1016/j.rser.2014.07.181
14. Batidzirai B, Valk M, Wicke B, Junginger M, Daioglou V, Euler W, Faaij A (2016) Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: illustrated for South Africa. Biomass Bioenergy 92:106–129. https://doi.org/10.1016/j.biombioe.2016.06.010
15. Thrän D, Witt J, Schaubach K, Kiel J, Carbo M, Maier J, Ndibe C, Koppejan J, Alakangas E, Majer S (2016) Moving torrefaction towards market introduction—technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass Bioenergy 89:184–200. https://doi.org/10.1016/j.biombioe.2016.03.004
16. Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A (2015) Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. Global Change Biology Bioenergy 7(4):618–634. https://doi.org/10.1111/gcbb.12162
17. World Coal Associoation (2016). http://www.worldcoal.org/resources/coal-statistics/
18. Agostini A, Giuntoli J, Boulamanti A (2013) Carbon accounting of forest bioenergy. Conclusions and recommendations from a criticial literature review. Report EUR 25354 EN. Publications Office of the European Union, Luxembourg
19. Matthews R, Sokka L, Soimakallio S, Mortimer N, Rix J, Schelhaas M-J, Jenkins T, Hogan G, Mackie E, Morris A, Randle T (2014) Review of literatur on biogenic carbon and lifecycle assessment of forest bioenergy. Final Task 1 report, DG ENER project, 'Carbon impacts of biomass consumed in the EU'. Forest Research: Farnham
20. Bergman R, Gu H, Page-Dumroese D, Anderson N (2017) Life cycle analysis of biochar. In: Biochar: A regional supply chain approach in view of climate change mitigation. Cambridge University Press., Cambridge, United Kingdom
21. Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt JS, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H (2013) Anthropogenic and Natural Radiative Forcing Supplementary Material. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
22. Agar D, Gil J, Sanchez D, Echeverria I, Wihersaari M (2015) Torrefied versus conventional pellet production—a comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria. Appl Energy 138:621–630. https://doi.org/10.1016/j.apenergy.2014.08.017
23. Batidzirai B, van der Hilst F, Meerman H, Junginger HM, André PC, Faaij APC (2013) Optimization potential of biomass supply chains with torrefaction technology. Biofuels Bioprod Biorefin 8(2):253–282. https://doi.org/10.1002/bbb.1458
24. Hansson J, Martinsson F, Gustavsson M (2015) Greenhouse gas performance of heat and electricity from wood pellet value chains—based on pellets for the Swedish market. Biofuels Bioproducts Biorefining-Biofpr 9(4):378–396. https://doi.org/10.1002/bbb.1538
25. Roder M, Whittaker C, Thornley P (2015) How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. Biomass Bioenergy 79:50–63. https://doi.org/10.1016/j.biombioe.2015.03.030
26. Sikkema R, Junginger M, Pichler W, Hayes S, Faaij APC (2011) The international logistics of wood pellets for heating and power production in Europe: costs, energy-input and greenhouse gas

balances of pellet consumption in Italy, Sweden and the Netherlands (vol 5, pg 226, 2011). Biofuels Bioproducts Biorefining-Biofpr 5 (2):226–226. doi:https://doi.org/10.1002/bbb.285
27. Cherubini F, Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. Global Change Biology Bioenergy 3(5):413–426. https://doi.org/10.1111/j.1757-1707.2011.01102.x
28. Brandao M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Jorgensen SV, Hauschild MZ, Pennington DW, Chomkhamsri K (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int J Life Cycle Assess 18(1):230–240. https://doi.org/10.1007/s11367-012-0451-6
29. Hammar T, Ortiz C, Stendahl J, Ahlgren S, Hansson P-A (2015) Time-dynamic effects on the global temperature when harvesting logging residues for bioenergy. BioEnergy Res 8(4):1912–1924. https://doi.org/10.1007/s12155-015-9649-3
30. Porso C, Hansson PA (2014) Time-dependent climate impact of heat production from Swedish willow and poplar pellets—in a life cycle perspective. Biomass Bioenergy 70:287–301. https://doi.org/10.1016/j.biombioe.2014.09.004
31. Zanchi G, Pena N, Bird N (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. Global Change Biology Bioenergy 4(6):761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x
32. Obernberger I, Thek G (2010) The pellet handbook—the production and thermal utilisation of biomass pellets. Earthscan, London, UK, Washington DC, USA
33. Swedish Energy Agency (2014) Energy in Sweden 2013. Eskilstuna, Sweden
34. de Jong J, Akselsson C, Berglund H, Egnell G, Gerhardt K, Lönnberg L, Olsson B, von Steding H (2014) Consequences of an increased extraction of forest biofuel in Sweden - a synthesis from the biofuel research programme 2007–2011. Summary of synthesis report. IEA Bioenergy Task 43. Report 2014:01
35. Swedish Forest Agency (2008) Rekommendationer vid uttag av avverkningsrester och askåterföring (Recommendations for extraction of logging residues and ash recycling) Skogsstyrelsens förlag, Jönköping, Sweden
36. Djomo SN, El Kasmioui O, Ceulemans R (2011) Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. Global Change Biology Bioenergy 3(3):181–197. https://doi.org/10.1111/j.1757-1707.2010.01073.x
37. Ericsson N, Porsö C, Ahlgren S, Nordberg Å, Sundberg C, Hansson P-A (2013) Time-dependent climate impact of a bioenergy system—methodology development and application to Swedish conditions. GCB Bioenergy 5(5):580–590. https://doi.org/10.1111/gcbb.12031
38. Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt JS, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H (2013) Anthropogenic and Natural Radiative Forcing Supplementary Material. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, USA
39. Joos F, Prentice IC, Sitch S, Meyer R, Hooss G, Plattner GK, Gerber S, Hasselmann K (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Glob Biogeochem Cycles 15(4):891–907. https://doi.org/10.1029/2000GB001375
40. Joos F, Roth R, Fuglestvedt JS, Peters GP, Enting IG, von Bloh W, Brovkin V, Burke EJ, Eby M, Edwards NR, Friedrich T, Frolicher TL, Halloran PR, Holden PB, Jones C, Kleinen T, Mackenzie FT, Matsumoto K, Meinshausen M, Plattner GK, Reisinger A, Segschneider J, Shaffer G, Steinacher M, Strassmann K, Tanaka K, Timmermann A, Weaver AJ (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos Chem Phys 13(5):2793–2825. https://doi.org/10.5194/acp-13-2793-2013
41. Hartmann DL, Klein Tank AMG, Rusticucci M, Alexander LV, Brönnimann S, Charabi Y, Dentener FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorne PW, Wild M, Zhai PM (2013) Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
42. Wikstrom P, Edenius L, Elfving B, Eriksson LO, Lamas T, Sonesson J, Ohman K, Wallerman J, Waller C, Klinteback F (2011) The Heureka forestry decision support system: an overview. Mathematical Computational Forestry Natural Resources Sci 3(2): 87–94
43. Wikström P, Edenius L, Elfving B, Eriksson OL, Lämås T, Sonesson J, Öhman K, Wallerman J, Waller C, Klintebäck F (2011) The Heureka forestry decision support system: an overview. Mathematical Computational Forestry Natural-Resource Sci 3(2): 87–94
44. Rolff C, Agren GI (1999) Predicting effects of different harvesting intensities with a model of nitrogen limited forest growth. Ecological Modelling 118(2–3):193–211. https://doi.org/10.1016/S0304-3800(99)00043-5
45. Lindholm EL, Berg S, Hansson PA (2010) Energy efficiency and the environmental impact of harvesting stumps and logging residues. Eur J For Res 129(6):1223–1235. https://doi.org/10.1007/s10342-010-0412-1
46. Strömberg B, Herstad Svärd S (2012) Bränslehandboken 2012 (The fuel handbook 2012). VÄRMEFORSK (Thermal Engineering Research Institute), Stockholm, Sweden
47. Öman A, Hallberg L, Rydberg T (2011) LCI för petroleumprodukter som används i Sverige. Report B1965. Swedish Envrironmental Institute. Stockholm, Sweden
48. Uppenberg S, Almemark M, Brandel M, Lindfors L-G, Marcus H-O, Stripple H, Wachmeister A, Zetterber L (2001) Miljöfaktabok för bränsle, del 2. bakgrundsinformation och teknisk bilaga. Swedish Environmental Research Institute, Stockholm, Sweden
49. Uasuf A, Becker G (2011) Wood pellets production costs and energy consumption under different framework conditions in Northeast Argentina. Biomass Bioenergy 35(3):1357–1366. https://doi.org/10.1016/j.biombioe.2010.12.029
50. Hagberg L, Särnholm E, Gode J, Ekvall T, Rydberg T (2009) LCA calculations on Swedish wood pellets production chains—according to the Renewable Energy Directive. Swedish Environmental Reserach Institute, Stockholm, Sweden
51. SOU (Statens offentliga utredningar) (2008) Ett energieffektivare Sverige SOU 2008:25. Swedish Government, Stockholm, Sweden
52. Paulrud S, Fridell E, Stripple H, Gustavsson T (2010) Uppdatering av klimatrelaterade emissionsfaktorer (Updated climate related emission factors). SMED 92 2010. Swedish Meteorological and Hydrological Institute (SMHI). Norrköping, Sweden
53. Thek G, Obernberger I (2004) Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenergy 27(6):671–693. https://doi.org/10.1016/j.biombioe.2003.07.007
54. Gode J, Martinsson F, Hagberg L, Öman A, Höglund J, Palm D (2011) Miljöfaktaboken 2011. Uppskattade emissionsfaktorer för bränslen, el, värme och transporter (Miljöfaktaboken 2011. Estimated emission factors for fuels, electricity, heat and transport in Sweden). Stockholm, Sweden

55. Hamelinck CN, Suurs RAA, Faaij APC (2005) International bioenergy transport costs and energy balance. Biomass Bioenergy 29(2):114–134. https://doi.org/10.1016/j.biombioe.2005.04.002
56. Giuntoli J, Agostini A, Edwards R, Marelli L (2014) Solid and gaseous bioenergy pathways: input values and GHG emissions. JRC Science and policy reports, European Commission
57. SLU (2014) Swedish Forest Soil Inventory. Swedish University of Agricultural Science. www.slu.se/en/collaborative-centres-and-projects/swedish-forest-soil-inventory/. Accessed 2014-06-02. 2014
58. SLU (2014) Swedish National Forest Inventory. Swedish University of Agricultural Science. www.slu.se/en/collaborative-centres-and-projects/swedish-national-forest-inventory/publications/. Accessed 2014–06-02. 2014
59. FAO (2015) 2014 Global Forest Products Facts and Figures. Food and Agriculture Organization of the United Nation, Rome, Italy
60. Repo A, Tuomi M, Liski J (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. Global Change Biology Bioenergy 3(2):107–115. https://doi.org/10.1111/j.1757-1707.2010.01065.x
61. Zetterberg L, Chen DL (2015) The time aspect of bioenergy - climate impacts of solid biofuels due to carbon dynamics. Global Change Biology Bioenergy 7(4):785–796. https://doi.org/10.1111/gcbb.12174
62. Thiffault E, Hannam KD, Paré D, Titus BD, Hazlett PW, Maynard DG, Brais S (2011) Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—a review. Environ Reviews 19(NA):278–309. https://doi.org/10.1139/a11-009
63. Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth—a meta-analysis. For Ecol Manag 348:124–141. https://doi.org/10.1016/j.foreco.2015.03.042
64. Bouget C, Lassauce A, Jonsell M (2012) Effects of fuelwood harvesting on biodiversity—a review focused on the situation in Europe1This article is one of a selection of papers from the International Symposium on Dynamics and Ecological Services of Deadwood in Forest Ecosystems. Can J For Res 42(8):1421–1432. https://doi.org/10.1139/x2012-078
65. de Jong J, Akselsson C, Egnell G, Löfgren S, Olsson BA (2017) Realizing the energy potential of forest biomass in Sweden—how much is environmentally sustainable? For Ecol Manag 383:3–16. https://doi.org/10.1016/j.foreco.2016.06.028
66. Egnell G (2017) A review of Nordic trials studying effects of biomass harvest intensity on subsequent forest production. For Ecol Manag 383:27–36. https://doi.org/10.1016/j.foreco.2016.09.019
67. Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management 2(3):303–333. https://doi.org/10.4155/cmt.11.24