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How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues

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ABSTRACT

Climate change and energy policies often encourage bioenergy as a sustainable greenhouse gas (GHG) reduction option. Recent research has raised concerns about the climate change impacts of bioenergy as heterogeneous pathways of producing and converting biomass, indirect impacts, uncertainties within the bioenergy supply chains and evaluation methods generate large variation in emission profiles. This research examines the combustion of wood pellets from forest residues to generate electricity and considers uncertainties related to GHG emissions arising at different points within the supply chain. Different supply chain pathways were investigated by using life cycle assessment (LCA) to analyse the emissions and sensitivity analysis was used to identify the most significant factors influencing the overall GHG balance. The calculations showed in the best case results in GHG reductions of 83% compared to coal-fired electricity generation. When parameters such as different drying fuels, storage emission, dry matter losses and feedstock market changes were included the bioenergy emission profiles showed strong variation with up to 73% higher GHG emissions compared to coal. The impact of methane emissions during storage has shown to be particularly significant regarding uncertainty and increases in emissions. Investigation and management of losses and emissions during storage is therefore key to ensuring significant GHG reductions from biomass.

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1. Introduction

To reach climate change targets the total greenhouse gas (GHG) emissions of the EU and the UK are required to reduce

by 20% [1] and 37% [2] respectively by 2020 compared to the 1990 level. Existing European and UK policies consider bioenergy as a valid GHG reduction option in reaching these targets [3–5]. By 2020 about 10% of the EU's primary energy requirements could be supplied by biomass [6]. It is therefore

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imperative that bioenergy systems deliver real emission reductions [5,7,8]. Recent research has presented different outcomes regarding the benefits and climate change impacts of bioenergy, due to the broad variability in feedstocks, different application and conversion methods, uncertainties in supply chain processes, variability in models and methods of evaluation and system assumptions [7].

Bioenergy from forest residues is often considered as carbon neutral and emissions from production stages of the main product are often ignored in policy-related calculations as the feedstock is considered a by-product [5,9–12]. Forest and sawmill residues are claimed to have a large global availability and under certain conditions can achieve large GHG emissions savings [13–15]. They are commonly processed as pellets to deliver benefits of low moisture content, high energy density, low storage requirements, relatively clean and easy handling and manageability across various scales. Over the last 5–10 years the global pellet market has grown steadily and is projected to continue its growth [14,16]. Due to the increasing demand within the EU, imports of pellets from North America have increased rapidly [14,17]. This has been mainly driven by policies promoting bioenergy as an option to significantly decrease GHG emissions and maintain energy security. However, recent research has questioned the emission savings actually achieved. When land use, carbon stock changes or temporal aspects are taken into account lower levels of GHG savings are sometimes reported [11,12,15,18–23], while more traditional life cycle assessments (LCA) of wood pellets find savings of 60–90% compared to fossil fuel systems [13,15,24–29].

The work presented here examines the significance of key sources of GHG uncertainty in wood pellet supply chains from forest and sawmill residues. The research is specific to large-scale electricity generation in the UK; however will be relevant to other consumers of wood pellets sourcing from the South-East USA (SE U.S.). The analysis has been done through life cycle assessment (LCA) to identify supply chain emissions and sensitivity analysis was used to assess the impact of uncertainty on the final GHG emission results. The aim was to evaluate emissions and impacts of imported wood pellets and to identify critical steps where improved characterisation will support management of the biomass supply chains to maximize the emission reduction potential and avoid unintentional outcomes from energy and climate change policies.

2. Methods

2.1. Life cycle assessment

2.1.1. Goal

The goal of this study was to investigate emission uncertainties of selected forest residue supply chains to evaluate possible impacts and identify supply chain steps that require close attention to ensure real GHG reductions. For this purpose, an attributional LCA was appropriate, with a comprehensive supply chain scope that includes all steps from forest establishment through to the generation of electricity. The fossil fuel based reference source was coal-fired electricity generation, since this reflects current UK trends to convert

coal-fired power plants to high levels of biomass pellet co-firing and large-scale, dedicated biomass firing. The analysis followed the principles of LCA according to ISO Standard 14040:2006 and 14044:2006 [30,31].

2.1.2. Scope

2.1.2.1. Supply chain description and functional unit. The supply chains were selected and defined according to existing pathways of large-scale electricity production in the UK from biomass. The functional unit (FU) of the LCA was 1 kWh of generated electricity in the UK. The supply chains were agreed with industrial stakeholders and academic research partners. The term forest residue covers several different products and parts of trees in forest and timber production, including sawmill residues [13,15,32]. Several of these materials can be used to produce wood pellets. Currently sawdust (sawmill residues) is the main raw material for producing wood pellets [14]. However, residues like tree branches, tree tops, bark and early thinnings are increasingly used [13,32]. Hence, the supply chain emissions of wood pellets can differ with variations in raw material, management practices, processing steps and logistics (transport and storage). Since it was the aim of this work to explore the significance of uncertainties at different stages to the overall GHG balance, two different supply chains were chosen which are common pathways for the production of industrial wood pellets:

1. **Forest residues** composed of: 80% thinnings and 20% forest residues (branches, tops and bark)
2. **Sawmill residues** composed of: 91% sawdust, 9% sawmill residues (shavings, bark, chips)

Combinations of both feedstock types maybe used commercially which were found to give results lying between the above cases and so only these 2 are presented. The proportions were selected according to existing literature and stakeholder information [13,15].

2.1.2.2. System boundaries. The pellets are produced from forest and sawmill residues in the South-East USA (SE U.S.), which is one of the major forest production locations in North America and a main supply region of industrial wood pellets for the UK market [13,15,22,26,33].

The forest considered is a mixed loblolly pine (*Pinus taeda*) and shortleaf pine (*Pinus echinata*) stand, which makes up about 25% of the forest area and 59% of the net volume of growing stock in SE U.S. [34,35]. The forests are under private corporate management focussing on long-term supply of high quality timber in accordance with sustainability and policy regulations [13,20,36].

The forest is established by land preparation and planting of new seedlings [34,35,37] with a growing period of 45 years, yield class 9 and then harvested by clear cut [19,35]. While yield and rotation can be significant parameters when evaluating carbon stocks, carbon debt and payback time [15,19–22,36,38,39], they did not significantly affect the parameters explored in this assessment as described in Section 3 and so variants of these have been neglected in the analysis. It is assumed that forest management follows a medium-intensive cultivation [22], which includes fertiliser and

herbicide application at site establishment and during early growing stages [22,38,40]. The forest stand is thinned moderately in 5–10 year cycles starting at year 25 [35,41]. At the end of the rotation trees are harvested in a whole-tree logging system [42,43]. It is assumed that a minimum of 35% of the residues are left in the forest to maintain the nutrient and soil carbon balance [15,20,32,36,44]. Trees are cut to length and left for seasoning at the landing site.

Forest residues scope of system – The forest is established and managed as described above. The “forest residues” (including thinnings) are collected at the landing site and left for a period of 10–12 weeks for natural drying [42]. The moisture content decreases from about 50% to 30% (wet basis) during this period [42]. The forest residues are then chipped at the landing site [32,42,43] and transported by truck to the pellet mill.

Sawmill residues scope of system – The forest is established and managed as described above. The “sawmill residues” are derived from logs transported by truck to the sawmill where the wood is processed. The sawmill residues are collected and stored after sawing and transported to the nearby pellet mill. The moisture content of the sawmill residues is considered at 30% (wet basis) [42].

At the pellet mill the chipped “forest residues” and “sawmill residues” are processed according to common pelleting processes [14,22,36,45]. The pellets are then transported by rail to a SE U.S. port and shipped by a bulk vessel to an east coast port of the UK where the pellets are transported by rail to a power plant and combusted in a dedicated 670 MW biomass boiler to generate electricity. Fig. 1 illustrates the supply chain steps and the system boundaries.

2.1.2.3. Impact assessment methodology. To evaluate the GHG emissions of electricity generation from forest and sawmill residue-derived wood pellets a cradle-to-grave LCA was conducted. The impact category global warming potential (GWP) was the focus of this study as the aim of the research was to analyse GHG emission uncertainties, as described in Sections 2.1.1 and 2.2. The final unit of measurement was g CO₂ equivalent (eq) kWh⁻¹. For the LCA analysis a spreadsheet model in MS Excel was used. It was combined with the LCA software SimaPro 8.0.1 using the Ecoinvent database (2009) and the CML 2001 baseline method, version 2.04 for mid-point assessment [46]. The results focus on GHG emissions, accounting for carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄) expressed as CO₂eq with a 100-year time horizon [47]. From this point forward the term ‘emissions’ will refer to emissions of greenhouse gases. Direct emissions from soil were calculated according to Ecoinvent and IPPC guidelines [46,47] considering nitrous oxide emissions as intermediate product from denitrification through soil microorganisms, as well as indirect N₂O emissions from leakage and volatilisation. Parameters with concern of variability were analysed and discussed in the sensitivity analysis.

The LCA methodology suggests to avoid allocation processes but to extend the system boundaries to included additional functions of co-products [30]. In comparison to this other GHG accounting methodology like RED states that upstream stages of ‘cultivation’ are not allocated to residues [5]. With this it could be assumed that the upstream forest production stages (establishment etc.) should not be include in

the system boundaries of the LCA study [5]. However, since the objective of this work was to examine the significance of different supply chain steps, production was included and price allocation was chosen as an appropriate method and was applied at relevant supply chain stages. This will be discussed further in Sections 2.2.4 and 4.4.

2.1.2.4. Data requirements and quality. Selected peer-reviewed literature, government, industrial and manufacturer reports were used during the data inventory phase to estimate inputs, energy requirements and emissions of supply chain parameters and processes. Emission factors for the energy and fuel used in supply chain processes were derived from Defra [48]. To define a realistic supply chain structure, information and data were sourced from industrial stakeholders with expertise on existing large-scale electricity generation from biomass in the UK. The data was obtained through personal communications and through industrial records according to reporting and auditing regulations in the UK and in scope with ISO Standard 14040:2006 and 14044:2006 [30,31]. The inventory data was also cross-checked with existing literature.

2.2. Sensitivity analysis

The main objective of this research was to identify emission uncertainties of the chosen supply chains. Following evaluation of the GHG emissions by LCA, key parameters were varied to establish the extent to which the supply chains can deliver real GHG reductions, to identify the most potentially significant supply chain parameters from a GHG balance perspective, and which superficially similar supply chains might actually deliver significantly different GHG outcomes if process or economic conditions change.

The base case LCA was calculated and variations tested corresponding to different feasible supply chain management options. In this paper the consequences of varying the following steps are examined in detail for the two supply chains in Fig. 1:

- Pelleting – change of drying fuel – A supply chain management decision where the GHG consequences need to be evaluated are the trade-off between maximizing electricity generation and system efficiency by channelling all residues through the main supply chain or minimizing external fossil fuel inputs by substituting biomass as an auxiliary drying fuel.
- Sawing and Pelleting – There is relatively little detailed measurement or evaluation of GHG emissions during feedstock storage and so investigating the potential impact of these emissions is important
- Chipping, Transport and Sawing – The impact of dry matter losses during the processing and handling were assessed.
- Price changes for the feedstock material – The economic allocation methods are appropriate for the analysis of a multiple product system with highly divergent values and markets. Effectively the GHG burdens are placed proportionately with the product that most drives the demand for the overall production system. This makes regulatory

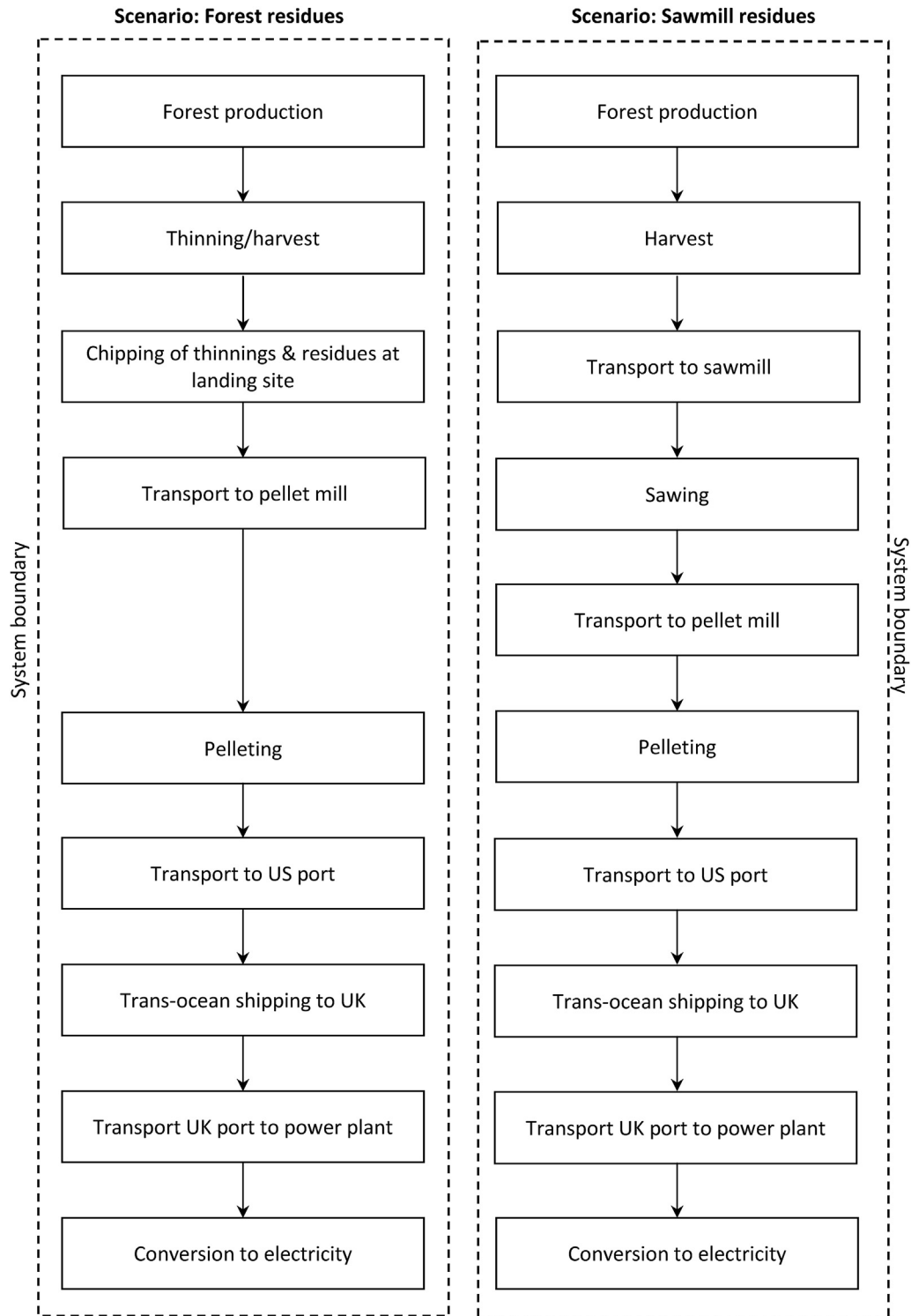


Fig. 1 – Supply chain and system boundary for forest and sawmill residues.

sense because if policy stimulated demand, this would be reflected in a less attractive GHG balance. However, it also means that the reported GHG emissions for the bioenergy system would change without there actually being any physical increase in the net GHG emissions of the overall system. It is therefore worth evaluating the extent to which this “theoretical” increase affects the results presented.

2.2.1. *Drying of feedstock during pelleting*

It is common practice that the heat for drying during pelleting is generated from biomass based fuel (sawdust or bark). This option was applied in the baseline options for both, the forest and sawmill residue model. However, drying with fossil fuel based sources is also practiced, therefore variations were explored and diesel as drying fuel is here presented as alternative option.

2.2.2. Storage duration of feedstock in form of wood chips and sawdust

At present little is known about the extent of methane (CH₄) emissions from wood stockpiles [49]. Wihersaari [50] theorised that CH₄ emissions resulted from wood chip storage, and since then a number of studies have investigated this, with conflicting results. For example, samples from gas probes embedded in a pine woodchip stack in Ferrero et al. [51], showed that CO₂ was the only GHG present in appreciable concentration, whereas Pier and Kelly [52]; detected CH₄ concentrations of 4–63% across probe samples from a sawdust pile, with CH₄ contributing 20% of the gas emitted from the stack. Another study by He et al. [53], examined small-scale (2.5 kg) samples of forest residues and detected CH₄ concentrations of 0.15% in the headspace, which was small, but was emitted constantly for up to 25 days. The results of these studies suggest that there remains some uncertainty over the emissions of CH₄ from wood chip piles. Therefore this is examined here as part of a sensitivity analysis to assess the relative impact of these emissions.

Wihersaari [54] estimated a CH₄ emission factor of 24 g d⁻¹ m⁻³ from wood chips when stored outside to allow natural ventilation [54]. The CH₄ release during the feedstock storage was included in the emission accounting and considered as lost carbon in the supply chain with an impact on the biogenic carbon balance and loss of material. For the sensitivity analysis CH₄ emissions were considered at the stage of storing wood chips from forest and sawdust from sawmill residues at the pellet mill. Additionally CH₄ emissions were included at the sawmill stage as it was assumed that sawmill residues are not directly transported to the pellet mill. While the default maximum storage period at the sawmill was assumed to be 1 month, the duration of material storage at the pellet mill was calculated for 1–4 months. Nitrous oxide emissions from storage have not been considered as they are likely to occur be negligible [54].

2.2.3. Dry matter losses in the supply chain

Dry matter losses in the supply chain depend on several factors like technologies, handling and storage practices [25,55–57]. According to previous research, total dry matter losses along the supply chain vary widely from 7% [22] up to 20% [24], therefore there is a high degree of uncertainty in the literature [55–58]. For the baseline supply chains, total losses of 9.5–10.5% were assumed, depending on the supply chain option. Default losses at different supply chain stages are shown in Table 1. Sensitivity analysis was then conducted with increased dry matter losses during the stage of storage of wood chips and sawdust (default: 1%, increase: 3%) [55–59], handling (default: 1%, increase: 3%) [25,60] and chipping (default: 2%, increase: 10%) and sawing (default: 2%, increase: 5%) [25,61]. With this total supply chain losses increased to 20.5–21.5% for both supply chains.

2.2.4. Price allocation with changing market

Over the last 5–10 years the global pellet market has grown steadily and is projected to continue its growth. Due to the increasing demand in the EU, imports of pellets from North America into the EU have increased rapidly [14,17]. As demand increases, and therefore the volume of pellet production, a

change in the energy market is possible. Currently the raw material for pellets is treated as a waste product of the wood processing sector, but current and projected market developments may stimulate changes in forest management [7]. If the residues become a “product”, the allocation of the emission profile of the supply chain should be adjusted in accordance with their economic value.

The price allocation was based on price and allocation provided by Aebiom [13] with the following price values in USD per tonne for the different forest products: lumber and timber blocks for \$564, wood chips for \$72, sawdust and shavings for \$37, bark for \$8, pulpwood for \$7.25 and fuelwood for \$5.40. Fuelwood prices were considered for the forest residue supply chain and sawdust and chip prices for the sawmill residue supply chain allocated according to feedstock mix.

According to recent market dynamics the price for wood pellet feedstocks, due to raw material shortage has increased by about 40% [13,14,16,62]. This was investigated by varying the price by 10% and 40% for the different pellet feedstocks, while the prices for other forest products remained unchanged. While this does not necessarily reflect the full potential impact of a significant price shift (since an increased raw material demand could potentially influence the actual harvesting activities and a snapshot per FU is unable to capture the full complexity of the problem), it is also true that, with less extreme price changes, increased GHG emissions can be a function only of the allocation process and not necessarily represent real additional emissions from the forestry system.

2.2.5. Uncertainty analysis

To analyse uncertainty within the different supply chains and regarding the above describe parameters drying, storage, price changes, dry matter losses and overall variations additionally a sensitivity analysis was conducted. The uncertainty range was associated with minimum and maximum value for each parameter within the supply chain option. The results were expressed as mean value and standard deviation.

3. Inventory

Inventory data were collected for all relevant processes within the system boundaries and adjusted to the functional unit. The data is presented in Table 1. The above ground forest yield was estimated with 427.5 m³ ha⁻¹ at wet basis after a 45-year rotation [35,63]. This includes 133 m³ ha⁻¹ of thinnings [41]. The share of the different tree parts is as followed: 78% roundwood, 10% bark, 8% branches, 4% foliage [64]. The fractions of sawmill products is considered with 46% lumber and trim blocks, 15% sawdust and shavings, 30% wood chips and 9% bark [13].

According to the type and capacity of the power generating combustion unit 0.537 kg wood pellets were required to generate 1 kWh of electricity. The actual amount of biomass required to produce the pellets was calculated via a bottom-up approach that considered the flow of biomass through the supply chain including moisture content changes, and dry matter and carbon losses. The calorific value of the produced wood pellets at a moisture content of 10% (wet basis) was

Table 1 – Life cycle inventory for forest and sawmill residues (mass for wood given as oven dry).

Forest residues scenario		Sawmill residues scenario	
Process/activity	Value	Process/activity	Value
Forest		Forest	
Rotation	45 years	Rotation	45 years
Yield (final harvest and thinning)	427.5 m ³ ha ⁻¹	Yield	427.5 m ³ ha ⁻¹
Moisture content of green wood ^g	50%	Moisture content of green wood ^g	50%
Fuel use (excl. transport)		Fuel use (excl. transport)	
Forest site		Forest site	
Site establishment (diesel) ^a	1.42 l t ⁻¹	Site establishment (diesel) ^a	1.42 l t ⁻¹
Fertiliser application (aviation spirit) ^a	0.17 l t ⁻¹	Fertiliser application (aviation spirit) ^a	0.17 l t ⁻¹
Herbicide application (diesel) ^b	0.27 l t ⁻¹	Herbicide application (diesel) ^b	0.27 l t ⁻¹
Harvester (diesel) ^a	5.76 l t ⁻¹	Feller buncher (diesel) ^d	1.78 l t ⁻¹
Forwarder (diesel) ^a	4.07 l t ⁻¹	Skidder (diesel) ^d	1.99 l t ⁻¹
Drum chipper (diesel) ^b	1.85 l t ⁻¹	Delimber (diesel) ^d	1.61 l t ⁻¹
		Loader (diesel) ^d	1.42 l t ⁻¹
Sawmill		Sawmill	
	–	All sawing processes (electricity) ^g	45.8 kWh t ⁻¹
Pellet mill		Pellet mill	
Drying with biomass (per tonne of pellets) ⁱ	0.18 t t ⁻¹	Drying with biomass (per tonne of pellets) ⁱ	0.18 t t ⁻¹
Drying with diesel (per tonne of pellets) ^j	2880 MJ t ⁻¹	Drying with diesel (per tonne of pellets) ^j	2880 MJ t ⁻¹
Pelleting processes per tonne of pellets (electricity) ^{k,l,m}	152.41 kWh t ⁻¹	Pelleting processes per tonne of pellets (electricity) ^{k,l,m}	152.41 kWh t ⁻¹
Inputs forest management		Inputs forest management	
DAP as nitrogen ^a	0.72 kg t ⁻¹	DAP as nitrogen ^a	0.72 kg t ⁻¹
Urea as nitrogen ^a	1.88 kg t ⁻¹	Urea as nitrogen ^a	1.88 kg t ⁻¹
Glyphosate (active ingredient) ^c	0.028 kg t ⁻¹	Glyphosate (active ingredient) ^c	0.028 kg t ⁻¹
Losses		Losses	
Losses at landing site ^r	0.5%	Losses at landing site ^r	0.5%
Losses during chipping ^t	2%	Losses during sawing ^t	2%
Losses transport forest – pellet mill ^s	1%	Losses transport forest – sawmill ^s	0.5%
		Losses transport sawmill – pellet mill ^s	1%
Losses during pelleting ^{s,u}	2%	Losses during pelleting ^{s,u}	2%
Losses transport pellet mill – US port ^s	1%	Losses transport pellet mill – US port ^s	1%
Losses trans-ocean shipping ^s	2%	Losses trans-ocean shipping ^s	2%
Transport		Transport	
Forest to pellet mill		Forest to sawmill to pellet mill	
Transport mode	HGV	Transport mode	HGV
Distance one way ^e	80 km	Distance forest-sawmill one way ^g	40 km
		Distance sawmill-pellet mill one way ^e	25 km
Fuel use (diesel) ^f	0.41 l km ⁻¹	Fuel use (diesel) ^f	0.41 l km ⁻¹
Pellet mill to US port		Pellet mill to US port	
Transport mode	Rail	Transport mode	Rail
Distance one way ^h	150 km	Distance one way ^h	150 km
Distance in tkm	0.085 tkm	Distance in tkm	0.085 tkm
Fuel use (fuel oil) ^f	8.36 g tkm ⁻¹	Fuel use (fuel oil) ^f	8.36 g tkm ⁻¹
Trans-ocean shipping US to UK		Trans-ocean shipping US to UK	
Transport mode	Vessel	Transport mode	Vessel
Distance one way ⁿ	9032 km	Distance one way ⁿ	9032 km
Fuel use (diesel) ⁿ	2.51 l km ⁻¹	Fuel use (diesel) ⁿ	2.51 l km ⁻¹
UK port to power plant		UK port to power plant	
Transport mode	Rail	Transport mode	Rail
Distance one way ^o	174 km	Distance one way ^o	174 km
Distance in tkm	0.096 tkm	Distance in tkm	0.096 tkm
Fuel use (fuel oil) ^f	8.36 g tkm ⁻¹	Fuel use (fuel oil) ^f	8.36 g tkm ⁻¹
Power generation		Power generation	
Calorific value pellets ^g	16.5 MJ kg ⁻¹	Calorific value pellets ^g	16.5 MJ kg ⁻¹
Boiler capacity ^p	670 MW	Boiler capacity ^p	670 MW
Load factor ^p	80%	Load factor ^p	80%
Plant efficiency ^p	40%	Plant efficiency ^p	40%

a [38].

b [69].

c [70].

d [71].

e [42].

f [67].

g [46].
 h [26].
 i [36].
 j [72].
 k [22].
 l [73].
 m [74].
 n [75].
 o [76].
 p [66].
 r [77].
 s [60].
 t [25].
 u [29].

16.5 MJ kg⁻¹ [65]. The combustion system was based on a direct-injection modified coal boiler, as similar to those currently operating in the UK. The capacity of the combustion unit was 670 MW with a load factor of 80% and an efficiency of 40% [66].

Emission factors for the energy and fuel used in supply chain processes were derived from Defra, and Ecoinvent [48,67]. Electricity used in the USA and UK was based on the electricity mix of each country with a CO₂eq mass of 729 g kWh⁻¹ and 446 g kWh⁻¹ respectively [48]. All transport (road, ocean, rail) was included with an empty return journey. Emission factors, fuel consumption and vehicle characteristics were taken from Defra, VTT and Edwards [48,67,68].

4. Results

4.1. GHG emission from baseline scenarios

The emission result from the baseline scenarios forest residues supply chain and sawmill residues supply are illustrated in Fig. 2 with the emissions represented as a CO₂eq mass of g kWh⁻¹ of generated electricity.

It was estimated that 0.537 kg of wood pellets are required to produce 1 kWh of electricity. In the forest residue system the dry biomass required at forest stand level was 0.610 kg kWh⁻¹ and 3.1 kg kWh⁻¹ in the sawmill residue case. The biomass requirement in the sawmill residue case was significantly higher as a tree has to be grown as a whole considering all the parts which are related to sawdust, such as the saw log. The proportion of the different sawmill products (lumber, timber, chips, sawdust, shavings and bark) were considered to identify the share of each product and then price allocation was applied to evaluate the GHG emissions.

The total base case GHG emissions for generating electricity from forest residue and sawmill residue pellets have a CO₂eq mass of 132 g kWh⁻¹ and 140 g kWh⁻¹ respectively. In both cases the supply chain stages releasing the largest amount of emissions were transport (39% for forest and 36% for sawmill residues), followed by processing activities (31% and 29% respectively). The conversion process of generating electricity (calculated with BEAT2 [78]) caused 18% of the total emissions of forest residues and 17% for sawmill residues, while the wood production created 12% and about 18% of forest and sawmill residues respectively. The figures for wood production include direct emissions from soil, which are

relatively low (less than 1%) for forest residues, but as high as 5% for sawmill residues. The life cycle emissions released by burning coal as reference system were considered to have a CO₂eq mass of 752 g kWh⁻¹ [76] which means that the two baseline cases achieve emission savings of 83% for forest and 82% for sawmill residues.

4.1.1. Drying fuel options during the pelleting process

It is common for pellet mills to use heat from burning biomass for drying feedstock prior to pelleting. This study did examine other options involving the use of fossil fuels as part of a sensitivity analysis. Electricity, natural gas and diesel were considered, but for simplicity in the following sections only diesel will be further discussed showing the most contrasting option to drying with biomass.

Shifting from biomass to a fossil fuel for drying not only increases the life cycle GHG emissions, but also changes the proportion of the different supply chain processes. The emissions from the different drying options are shown in Fig. 2. When drying with diesel, the emissions for the forest residue scenario increased to a CO₂eq mass of 271 g kWh⁻¹, corresponding to an increase of emissions of over 100% compared to using biomass as drying fuel. For the sawmill residues drying with diesel increased the emission intensity in terms of CO₂eq mass to 279 g kWh⁻¹; again a 100% increase of emissions.

When drying with diesel the emission savings compared with the reference scenario (coal) were 64.8% for the forest residue and 63.8% for the sawmill residue supply chain, which is about 18% less emission savings compared to using biomass as drying fuel.

4.2. Methane emissions during the storage of wood chips and sawdust

It was assumed that sawmill residues are stored for a maximum 1 month at the sawmill but that the duration of storage at the pellet mill can be longer. Therefore, the variation of 1–4 months storage in monthly steps was analysed.

According to the CH₄ emission factors theorised by Wihersaari [50,54] the CH₄ emissions during storage have a large impact on the overall supply chain emissions: a period of 1 month storage at the pellet mill increased the GHG emissions of the forest residue baseline scenario by about 140% from a CO₂eq mass of 132 g kWh⁻¹ to 317 g kWh⁻¹, with the CH₄ emissions making up 58% of the total supply chain

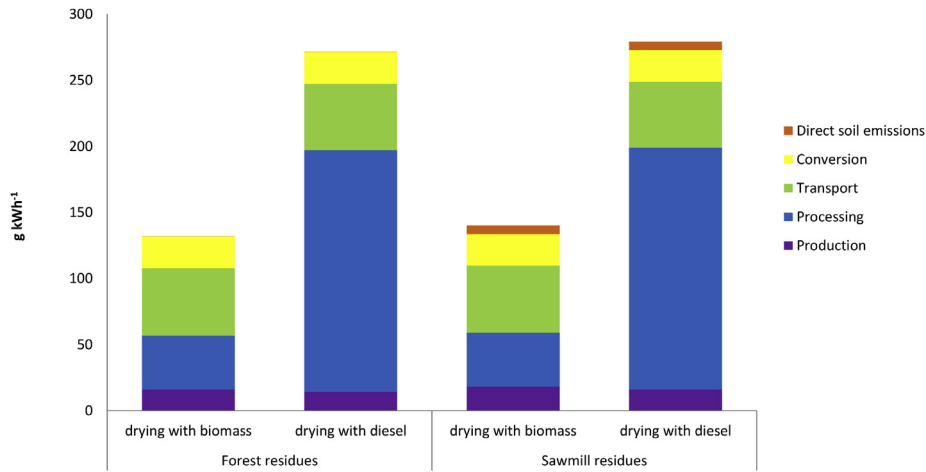


Fig. 2 – GHG intensity of drying options as CO₂eq mass.

emissions. This reduces the GHG emission savings from 83% to 59%. In this case the CH₄ emissions dominate the sources of GHG emissions (see Fig. 3). Assuming the CH₄ are continuous, after 2 months of storage, the total supply chain emissions increased to a CO₂eq mass of 489 g kWh⁻¹, 3 months to 670 g kWh⁻¹ and 862 g kWh⁻¹ after 4 months, exceeding the emissions of the coal-based electricity reference system. This sharp increase of emissions is even more significant if diesel is used for drying, since the emission savings are already reduced by about 18% compared to drying with biomass. In this case after only 3 months storage, the emission intensity (CO₂eq mass of 812 g kWh⁻¹) exceeded that of the coal reference system.

Storage-derived CH₄ emissions were more pronounced in the sawmill residue scenario. This is due to assumptions made in the analysis. It is assumed that forest residues are chipped before imminent transport to the pellet mill, however the model assumes that sawmill residues have an additional storage stage prior to arriving at the pellet mill. The longer storage period resulted in higher CH₄ emissions from the

storage phase [54]. When sawmill residues were dried with biomass, the supply chain emission intensity increases to a CO₂eq mass of 495 g kWh⁻¹ after 1 month, 674 g kWh⁻¹ after 2 months and 859 g kWh⁻¹ after 3 months, latest exceeding the GHG emissions from the coal baseline. When diesel was used for drying the total bioenergy supply chain emission intensity exceeded those of coal by 7% already after 2 months of storage (CO₂eq mass of 822 g kWh⁻¹).

The total emissions, including CH₄ in the given life cycle stages and savings compared to coal are illustrated in Fig. 3.

4.3. GHG emissions from dry matter losses

Dry matter losses were included in the calculations as described in Section 2.2.3 and results are illustrated in Fig. 4. Applying increased losses to the baseline scenarios as well as drying with diesel led to 2.4–3.3% higher GHG emissions compared to the default losses. Dry matter losses in the forest residue scenarios are considered higher than in the sawmill residues scenarios because the supply chain is more prone to

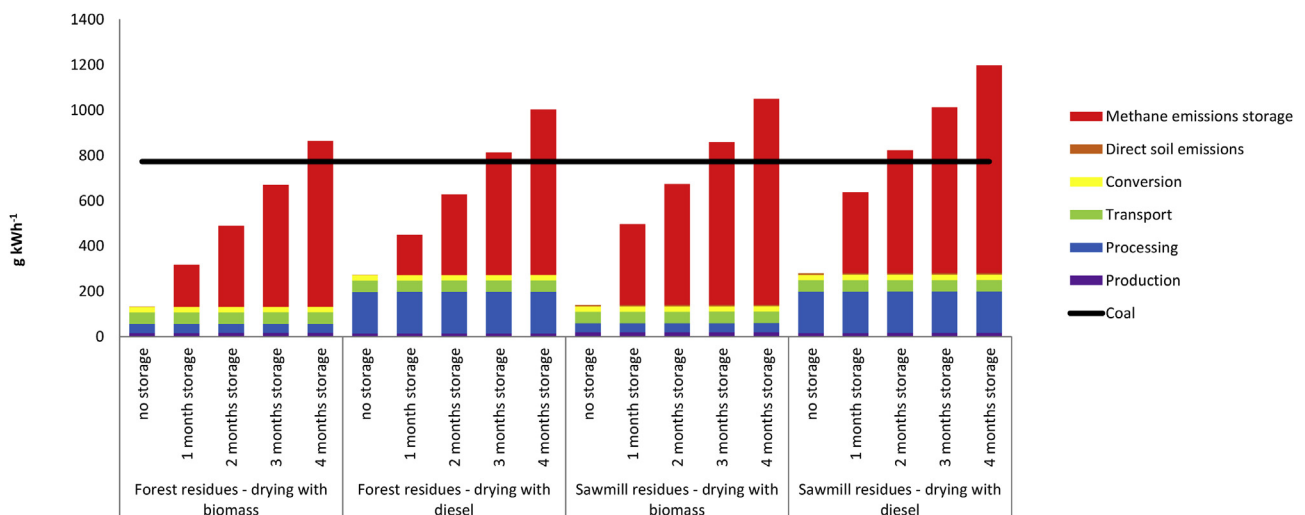


Fig. 3 – GHG intensity from storing wood chips and sawdust for 1–4 months as CO₂eq mass.

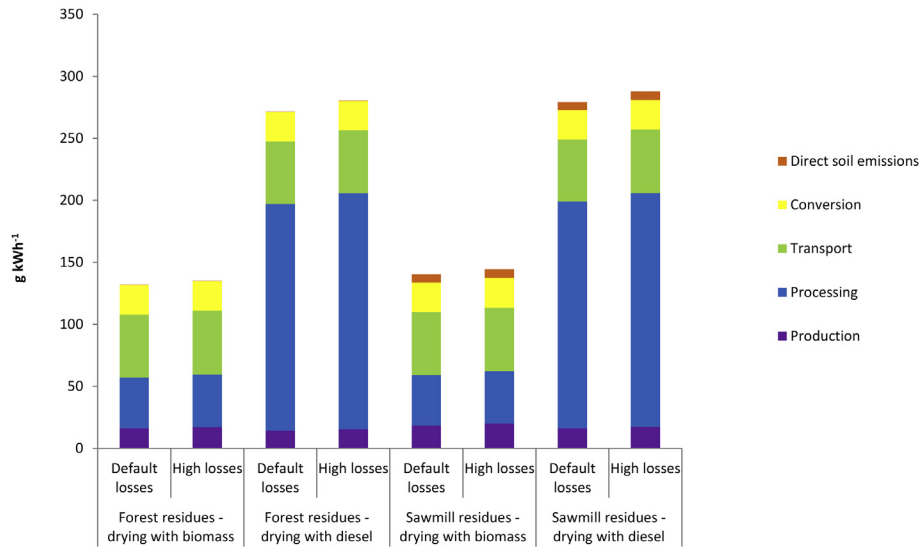


Fig. 4 – GHG intensity of different supply chain options associated with dry matter losses as CO₂eq mass.

losses during chipping at the landing site than during sawing processes. Combining high losses with the different storage options of 1–4 months, emissions increased by a range of 2–4.7% after 1 month storage, in case of 2 months storage by 6–8%. With 3 months storage emissions increased by 7–11% and in month 4 by 11–13% (see Fig. 6).

4.4. Emissions associated with changing bioenergy markets

Pellet and feedstock prices are elastic and in recent years price increases of up to 40% took place [13,14,16,62]. Therefore, price increases of 10% and 40% were included in the sensitivity analysis. Prices for forest and sawmill residues are relatively low compared to the main timber product. Sawdust and shavings are receiving prices less than 7% compared to timber. Fuelwood is even lower with about 1%. The most valuable product of the different residues are wood chips which receive about 12% of the original timber price [13]. With a 10% price increase, emissions of the forest residues baseline option increased marginally by 0.02%. If residues become more valuable, drying with fossil fuel might become more attractive. In the diesel drying option total life cycle emissions rose 0.77% with a 10% price increase and 0.79% with a 40% price increase.

The sawmill residue supply chain showed more pronounced emission increases as more biomass is involved in the system. Additionally the price for sawmill residues is about 10 times higher than for forest residues. For drying with biomass and a 10% price increase, total supply chain emissions rose by 1.81%. At a 40% price increase, total emissions increased by 5.90%. Drying with diesel, total emissions increased by 1.40% with a 10% price increase. With a 40% price increase total emissions rose by 3.41%. The trends are similar in all cases when storage emissions (CH₄) were included.

A bioenergy market change that increased the price of residues could influence the choice of drying fuel. If this leads to a switch from drying with biomass to drying with fossil

fuels, total supply chain emissions would increase by 101–107% for forest and sawmill residues comparing the baselines with the option of drying with diesel and adding price increases (see Fig. 5). Additionally, if the raw material becomes more valuable, production stage emissions will be much more sensitive to price fluctuations.

4.5. Emission uncertainties in life cycle emissions

Fig. 6 shows the range of emission profiles related to varying production pathways for wood pellets from forest and sawmill residues that were investigated in this study. While some supply chain options show a high GHG emission saving potential, such as the two baseline scenarios, others led to even higher emissions than coal. The lowest supply chain emissions were calculated for the baseline scenarios forest residues and sawmill residues both drying with biomass. Comparing these to the coal-based reference 83% and 82% GHG emission savings were achieved. Including dry matter losses and price changes to the calculations had only a marginal impact on the emission profile while varying drying fuel from biomass to diesel changed emission saving from 83% to 65% for forest residues and from 82% to 64% for sawmill residues. From Fig. 6 it can be seen that when considering storage emissions emission savings compared to the coal reference drop significantly. Combining the CH₄ emissions with the other considered options drying fuel, dry matter losses and price changes led to the bioenergy supply chain emission exceeding the coal reference by 73% for the case of sawmill residues, drying with diesel, high losses and a 40% price increase stored the pellet feedstocks for 4 months.

Based on the large range of emission profiles, uncertainty analysis was conducted and results are summarised in Fig. 7 a–e. The graphs express the uncertainty for each supply chain as a mean value and standard deviation. Uncertainty in the presented cases is highest regarding methane emissions occurring during storage, while price changes and losses have a very low standard deviation. Fig. 7e shows the emission mean

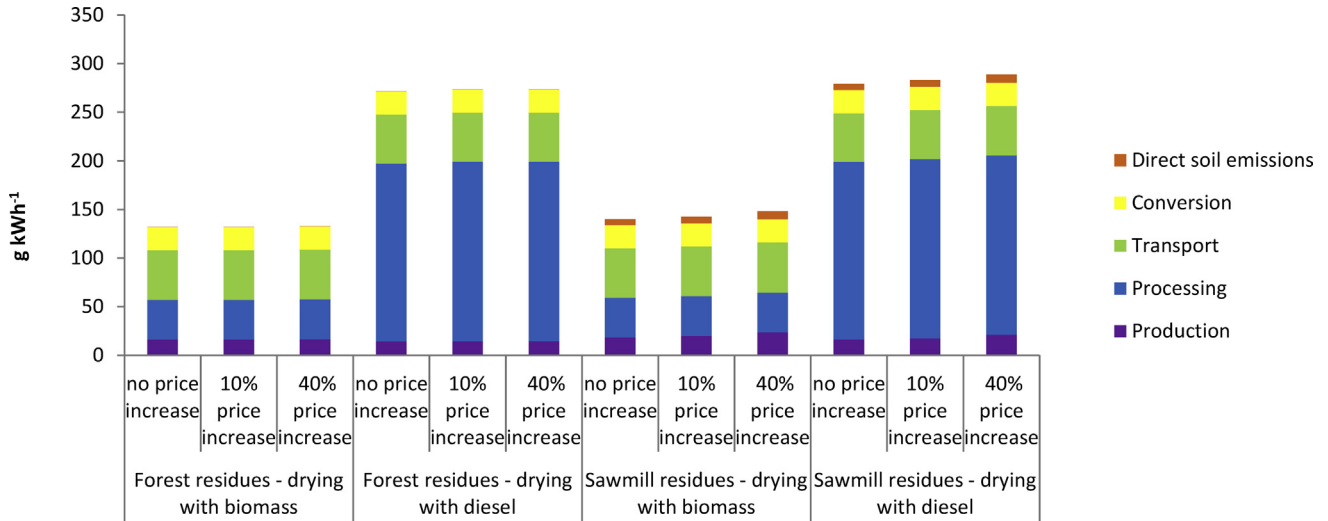


Fig. 5 – GHG intensity associated with price changes and higher demand for biomass.

and standard deviation of all examined options for the forest and sawmill residue supply chains. With a mean of a CO₂eq mass of 615 g kWh⁻¹ and a relative standard deviation of 45.2% for forest residues and a CO₂eq mass of 731 g kWh⁻¹ and a relative standard deviation of 46.6% sawmill residues, emission savings compared to coal are much less pronounced and highly uncertain compared to what the baseline options suggested.

5. Discussion

Methane emissions during storage of wood, based on theoretical data, are a very significant driver in the calculations above and yet are poorly documented for different supply chains and storage conditions. It is therefore important to thoroughly evaluate the scope for controlling methane emissions during storage to confirm the applicability of the above.

Therefore what can be done to ensure real GHG savings and what needs to be done at certain supply chain stages to avoid emissions?

Using biomass for drying gives greater GHG emission savings and should be encouraged. The here presented research also demonstrates that GHG emissions from forest and sawmill residue supply chains can be rather high with high grades of uncertainty if the feedstock is stored in certain forms. Wihersaari's [54] research showed that methane emissions from biomass are mainly of concern when the material is stored as chips which allows micro bacterial activities in the pile. This might be avoided if residues are stored in a form less prone to decomposition e.g. unprocessed, as whole trees, logs or brash bales so the stack is less likely to host anaerobic conditions, as pellets, torried or enclosed so that CH₄ emissions are captured and can be used for other purposes.

Changing dry matter losses had a relatively small impact on the total supply chain emissions with very low uncertainty, although they are important from an economic and sustainability perspective as this has an impact on the amount of feedstock required and energy associated with the pellet supply chain. Dry matter losses at early supply chain stages,

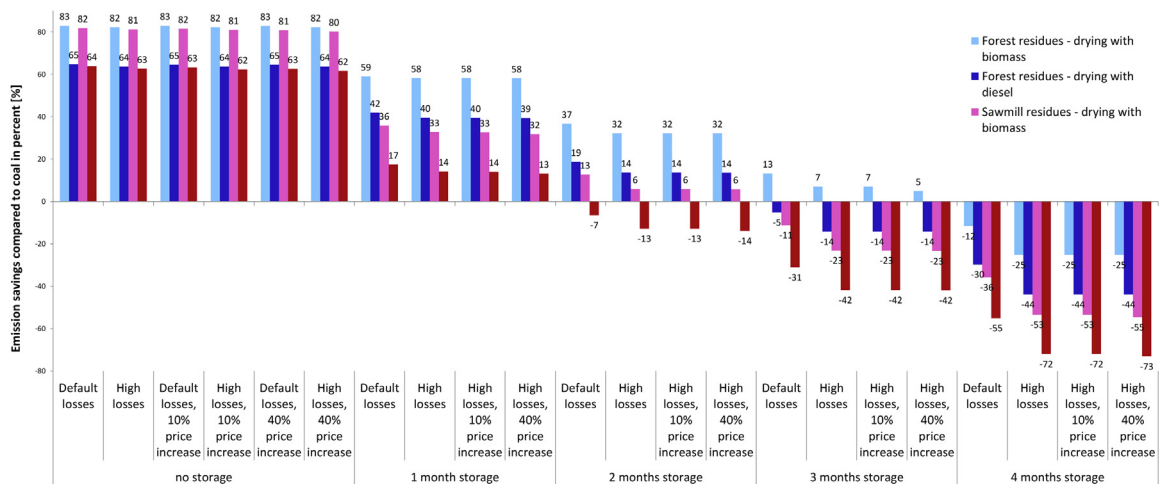


Fig. 6 – Emission savings compared to coal.

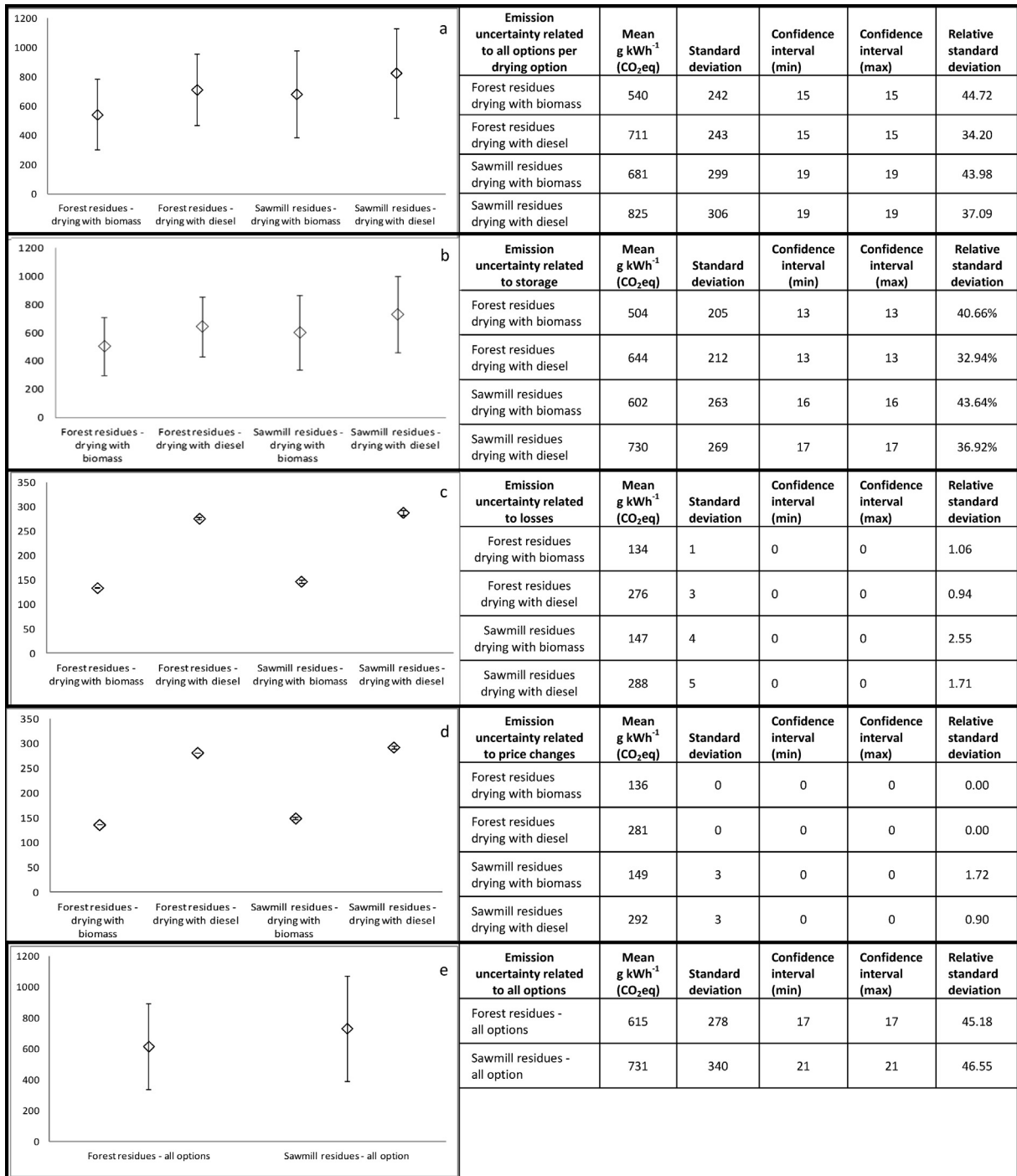


Fig. 7 – Uncertainties of supply chain options.

e.g. during storage or chipping can be relatively high [61], but might not be considered as a loss in an economic or sustainable sense if the biomass stays in the forest, possibly contributing to soil fertility. Nonetheless, storing biomass in unprocessed form may also help to reduce dry matter losses from the storage phase. Previous research [56,57,59,77] showed that storing and handling forest residues as long as possible unprocessed, reduces not just dry matter losses compared to wood chips but also avoids reduction in energy

content of the biomass. Eriksson showed for example that a bundle system saves GHG emissions compared to a wood chip system [77]. This would also address the issues of CH₄ storage emissions. In the sawmill supply chain some storage and form of material may be unavoidable, therefore it is recommended that further research is performed to assess the potential methane emission and dry matter losses from sawdust piles. These options should be evaluated at scales and conditions that are representative to current practice.

Emission changes from price increases and uncertainty related to these are relatively small. A change in the bioenergy market with rapidly increasing demand is likely [13,14,16,62], forest and sawmill residues could become a “product” and forest management focus might change with possibly higher emissions related to the bioenergy products. Nonetheless, price developments for residues are highly uncertain [15] and have to be seen and understood in relation to prices for other wood uses. Currently many experts find it unlikely that forests are solely grown to produce bioenergy [6,13,15,19,22], but such a shift would certainly reframe the issue of emission reductions.

6. Conclusion

GHG emissions from bioenergy supply chains are critical to their sustainability and GHG mitigation potential. The results presented here show a large variation in emissions from electricity generated from forest and sawmill residues ranging from a CO₂eq mass of 132–1330 g kWh⁻¹. While the lower values can achieve emissions reductions of over 80% compared to coal, the higher emissions exceed the fossil fuel option by more than 70%. It must be noted that these results are based on the assumptions made in the study (described in Sections 2.2.2 and 4.2).

This research can only present a snapshot of supply chain emissions, sensitivities and related uncertainties of electricity generated from forest residue wood pellets, but the above presented results show that there can be significant uncertainty associated with GHG emissions from forest residue bioenergy. In particular emissions associated with drying and storage are subject to high variability and this needs to be taken into account in GHG assessments and supply chain management. While the LCA produced a set of robust numbers indicating emissions of specific supply chain options, the uncertainty analysis showed that emission savings compared to coal are much less pronounced and highly uncertain compared to what for example the baseline supply chain options suggested. This is an outcome that should be taken into account when considering the emission saving potential of forest residue supply chains.

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