

Carbon factor for wood fuels for the Supplier Obligation Final report

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Executive summary

Defra asked AEA to estimate the CO₂ equivalent factor of wood pellets and chips, in kg CO₂ eq/MWh, including emissions from transport and processing of the wood, and emissions associated with combustion. AEA were also asked to estimate the NO_x and black carbon emissions associated with transport, processing and combustion, and consider whether these indirect greenhouse gases could be included in the overall CO₂ equivalent factor. In order to do this, a modified version of the Biomass Environmental Assessment Tool (BEAT₂) was used.

Emissions were estimated from the production of heat by the combustion of wood chips and pellets from a range of sources. These included:

- Forestry residues: unused timber (e.g. branchwood) from conventional forestry operations.
- Short rotation coppice: an energy crop (typically willow) in the UK which is grown and harvested every few years.
- 'Clean' wood waste: wood waste from sawmills, or wood waste (if untreated) from furniture production.

The results showed that GHG emissions were generally greater for wood pellets rather than chips, though there were large variations between different sources. In summary, emissions were lowest for wood processing wastes and forest residues from the UK and highest for SRC and imported wood from Canada and the Baltic. For wood pellets, there was little difference in emissions between bulk drying (forcing air through the pellets) and batch drying with diesel (some heating of the chips), though where batch drying occurred using wood fuel an emissions reduction was seen. Due to the variability in the emissions it makes it difficult to recommend a carbon factor for use in the supplier obligation. Therefore three options were presented that may go some way to addressing this variability.

The results for NO_x emissions showed the impact of long distance transportation, with the highest emissions coming from wood from the Baltic States and Canada especially, for both chips and pellets. For wood fuel sourced in the UK, the combustion phase represented a significant proportion of the total emissions. As this figure is the same across all feedstocks there was little variation in total emissions between either pellets or chips or between different sources from within the UK.

The situation was similar for PM₁₀ emissions, with the combustion phase representing a larger proportion of total emissions. Consequently, there was less variation between chips and pellets and between different sources, even for wood fuel sourced from Canada and the Baltic States.

A brief review of the role of NO_x and PM₁₀ as GHGs was also conducted. It found that the relationship between these emissions and climate change is complicated and that there is no accepted global warming potential for these pollutants. Therefore it was concluded that it does not seem appropriate to convert the estimates of NO_x and PM₁₀ emissions to kg CO₂ eq and to include them in the total carbon factor for wood fuels.

Finally a comparison between emissions across the lifecycle of fossil and wood fuels was made. It was found that GHG emissions from the production of natural gas and light fuel oil are of the same order of magnitude as those associated with the production of wood chips. For pellets emissions are substantially greater than for fossil fuels. It could therefore be argued that only including these emissions for wood fuels is underestimating the GHG savings which are achieved.

In the case NO_x emissions from fuel production for chips, it was found that they are of a similar order of magnitude as light fuel oil, unless they are transported long distances, in which case they are substantially higher due to NO_x emissions from shipping. NO_x emissions for pelleted fuels are higher than for fossil fuels, again particularly so if they are transported long distances by ship. PM₁₀ emissions follow a similar pattern. Combustion related NO_x emissions are similar for wood, oil and gas, but PM₁₀ emissions are three to four times higher than emissions from oil combustion.

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1 Introduction

The Carbon Emissions Reduction Target (CERT) came into effect on 1st April 2008, replacing the Energy Efficiency Commitment (EEC). It is an obligation on energy suppliers to achieve targets for promoting reductions in carbon emissions in the household sector. One form of technology the obligation will support is biomass boilers both for individual dwellings and blocks of flats. These boilers will burn either wood chips or pellets.

Under CERT, a factor of 0.0249 kg CO₂ /kWh was assumed for wood. Using this carbon factor means that biomass boilers are, at least on paper, highly cost effective measures for energy suppliers to subsidise. However, the true greenhouse gas (GHG) factor for biomass may be higher, because of the CO₂ (and other greenhouse gases) emitted in the processing and transport of biomass.

Defra therefore asked AEA to estimate the CO₂ equivalent factor of wood pellets and chips, in kg CO₂ eq/MWh, including emissions from transport and processing of the wood, and emissions associated with combustion. AEA were also asked to estimate the NO_x and black carbon emissions associated with transport, processing and combustion, and consider whether these indirect greenhouse gases could be included in the overall CO₂ equivalent factor.

2 Methodology

2.1 Wood Fuels

There are several potential sources of wood fuel, including:

- Forestry residues: unused timber (e.g. branchwood) from conventional forestry operations.
- Short rotation coppice: an energy crop (typically willow) in the UK which is grown and harvested every few years.
- 'Clean' wood waste: wood waste from sawmills, or wood waste (if untreated) from furniture production.

Forestry residues and clean wood waste may be sourced from the UK or imported from overseas, typically from countries with a large forestry industry.

Wood fuels used in boilers may be in either the form of chips, or pellets. The latter are often preferred, particularly for smaller boilers, because of the advantages they offer e.g. they are easier to handle and store, and boiler feeding can be automated. In order to process chips into pellets, they must first be dried, so that they can then be milled and formed into pellets. Various processes may be used for drying pre – pelletisation. For this study we considered bulk drying, where the chips are dried by forcing air through them, and batch drying, where there is also some heating of the chips to aid drying. For batch drying we looked at two options – one where heat for drying is provided by oil, and one where a portion of the wood fuel is burnt to provide the heat for drying.

The wood fuel sources and drying methods we have considered in the study are summarised in Table 2.1. For imported fuels, we considered imports from the Baltic States and Canada.

Table 2.1 Sources of wood fuels and the method of drying.

Fuel Type	Source	Drying methods
Chips	Forest residues (UK and imported)	Natural drying
	Wood processing waste (UK and imported)	
	Short rotation coppice	
Pellets	Forest residues (UK and imported)	Bulk Drying (forced ventilation); Batch drying (using diesel as a fuel) Batch drying (using wood as a fuel)
	Wood processing waste (UK and imported)	
	Short rotation coppice	

For combustion related emissions, we considered three typical types of boiler size

- Domestic <50kW
- Community 500kW
- Commercial 2MW

2.2 GHG Emissions

The Biomass Environmental Assessment Tool (BEAT₂) was used to estimate the emissions of the direct greenhouse gases (GHGs), CO₂, CH₄ and N₂O from production, process and transport of the above fuels¹. This tool has been developed by AEA and North Energy Associates for Defra (and the Environment Agency), and allows the assessment of the environmental impacts of a variety of bioenergy technologies in a consistent way. The tool calculates the emissions of the direct greenhouse gases, CO₂, CH₄ and N₂O over the whole life cycle of a biomass energy scheme, from cultivation of the energy crop, through processing and transport of the fuel, to combustion of the fuel at a power station or boiler, and disposal of ashes. Emissions from the production of machinery, the combustion/generation plant, and major inputs such as agrochemicals are also included.

¹ BEAT₂ can be downloaded from the Biomass Energy Centre website
http://www.biomassenergycentre.org.uk/portal/page?_pageid=74,153193&_dad=portal&_schema=PORTAL

For the purposes of this analysis we used data from BEAT on greenhouse gas emissions up to the point of delivery of the wood fuel to the boiler. We generally used the default data in BEAT which represents typical practice for biomass production and processing. We have assumed a transport distance of 90km by road (round trip) for delivery of fuel to boilers, and additional transport by road to a port and onwards by ship for imported fuels. Data on GHG emissions from combustion of wood in boilers are the average of measurements AEA has recently conducted on boilers in Scotland.

Table 2.2 GHG emissions from combustion of wood fuels in boilers (g/GJ)

Pollutant	Fuel type	Domestic <50 kW	Community 500 kW	Commercial (2MW)
CH ₄	Chips	5	5	0.5
	Pellets	10	5	0.5
N ₂ O	Chips	5	5	5
	Pellets	5	5	5

Emissions of CH₄ and N₂O were converted to kg CO₂ eq using the global warming potentials from the IPCC's second assessment report i.e. a GWP for CH₄ of 21 and for N₂O of 310. While the IPCC's 4th assessment report contains revised values for these GWPs, the values from the second assessment report are used in reporting the UK's GHG inventory and will be used to determine its compliance under the Kyoto protocol.

2.3 NO_x and black carbon emissions

As discussed earlier, DEFRA also wished to explore the contribution that emissions of the indirect greenhouse gases, NO_x and black carbon emissions, associated with the production and transport of wood fuels might make to the overall carbon factor for wood fuels. The methodology used to estimate NO_x and black carbon emissions is described below, and the attribution of a GWP for these gases to allow conversion of emissions to CO₂ eq is discussed in Section 2.4.

Emissions of NO_x and black carbon are not included in BEAT₂, however the methodology used for estimating GHG emissions in the tool, combining information on the activities and materials involved in particular steps (e.g. diesel used in cultivation operations, steel used in agricultural machinery and fencing) with emissions factors for that activity (e.g. CO₂ from diesel use, CO₂ from steel production) can easily be extended to NO_x and black carbon by including the appropriate emissions factors for these pollutants. Within the scope of this project it was not possible to enter emissions factors for all of the individual processes in BEAT; and we therefore concentrated on those activities which were the main source of GHG emissions, as these are likely to be the main sources of NO_x and black carbon. They included:

- Diesel used in the cultivation, harvesting, transport and drying processes.
- Petrol used in the cultivation process.
- Electricity and heating oil used in the drying process.
- The manufacture of steel used in the cultivation process (e.g. in manufacture of agricultural equipment and fencing).

There is no 'black carbon' emissions inventory, so PM₁₀ emissions factors were used as this was considered the most relevant emission factor for the sources considered i.e. for diesel combustion most PM₁₀ would be black carbon.

Table 2.3 below shows the emission factors that were used, and their sources.

Table 2.3 NO_x and PM₁₀ emission factors

	NO _x emissions	PM ₁₀ emissions	Unit	Source
Agricultural machinery	6.03 x 10 ⁻⁴	5.88 x 10 ⁻⁴	kg/MJ diesel	Adapted from the NAEI
Chainsaws	3.00 x 10 ⁻⁵	6.37 x 10 ⁻⁷	kg/MJ petrol	Adapted from the NAEI
Shipping	1.70 x 10 ⁻³	6.47 x 10 ⁻⁵	kg/MJ diesel	UK ship emissions inventory, Entec 2008
Lorries	7.57 x 10 ⁻⁴	1.83 x 10 ⁻⁵	kg/MJ diesel	Adapted from the NAEI
Electricity	3.14 x 10 ⁻⁴	9.13 x 10 ⁻⁶	kg/MJ electricity	Adapted from the NAEI

Heating oil in boiler	4.44×10^{-5}	4.45×10^{-6}	kg/MJ oil	Adapted from the NAEI
Mild steel	4.38×10^{-3}	5.15×10^{-3}	kg/kg steel	Ecoinvent life cycle database
Steel wire	4.83×10^{-3}	5.40×10^{-3}	kg/kg steel	Ecoinvent life cycle database

NO_x and PM₁₀ emissions can vary by a factor of 10 between the best and worst performing equipment. We have used the values shown in Table 2.4 as representative of best practice in current equipment. While no data is available to allow differentiation between the source of the wood chips, NO_x (and possibly N₂O) emissions will depend on the fuel nitrogen content, so might vary with fuel source. At the domestic scale, the emissions factors are relevant for boilers only, and not open fires or wood burning stoves.

Table 2.4 NO_x and PM₁₀ emissions from combustion of wood fuels in boilers (g/GJ)

Pollutant	Fuel type	Domestic <50 kW	Community 500 kW	Commercial (2MW)
NO _x	Chips	60	60	60
	Pellets	60	60	60
PM ₁₀	Chips	20	20	50
	Pellets	15	15	30

2.4 The role of NO_x and PM₁₀ as GHGs

The relationship between air quality and climate change, including the role of the air quality pollutants NO_x and black carbon aerosols in climate change was considered in depth by the Air Quality Expert Group (AQEG) in 2007 (AQEG, 2007).

AQEG concluded that the role of air quality pollutants in climate change is complicated, with some emissions having both positive and negative radiative forcing effects. This is the case for both NO_x and PM₁₀. NO_x is a precursor to O₃ which is responsible for the third largest single component of radiative forcing on climate. At the same time, emissions of NO_x act to increase the rate of CH₄ destruction, therefore decreasing its concentration in the atmosphere. Integrated over time, the positive radiative forcing (warming) effect of NO_x via O₃ production, and the negative (cooling) effect through a decrease in CH₄ lifetime are approximately equal, but with a high degree of uncertainty in both. For ground based sources, the climatic effect of NO_x maybe slightly negative whereas they may be slightly positive for aviation emissions.

The situation is similar for PM₁₀ emissions, which in itself covers a range of pollutants which include the aerosol components of sulphate, black carbon, organic carbon and mineral dust. The impact of sulphate aerosol has been extensively studied and modelled and has been shown to increase the amount of incoming solar radiation reflected back out into space, therefore having a negative radiative forcing. However, the situation for black and organic carbon is more complicated as they can have both positive and negative radiative forcings.

Over a dark surface such as ocean or forest the forcing can be negative, while over a bright surface such as desert or snow or above cloud the forcing is positive (e.g. Haywood and Shine, 1995; Chylek and Wong, 1995). The radiative forcing of black carbon is also sensitive to its vertical distribution in the atmosphere relative to the top and bottom cloud layers. This is because at different heights, black carbon can influence the number of cloud condensation nuclei and therefore cloud droplets. Due to the varying factors affecting the influence of black carbon on climate, there appears to be little consensus regarding its overall effect. Hansen *et al.* (2002) and Jacobson (2002) suggest that black carbon is a more potent GHG than CO₂ and Jacobson (2002) suggests that the control of black carbon and organic matter is possibly the most effective method of slowing global warming. However Feichter *et al.* (2003), Penner (2003), and Chock *et al.* (2003) question these findings. They suggest that the atmospheric model used by Jacobson (2002) had not undergone the necessary rigorous testing; that the integration time for inferring temperature response from the model is too short, so that the efficacy could not be adequately determined; and that the timescale for the temperature reduction is too short, owing to the misrepresentation of the thermal lag of the ocean. Furthermore, a study by Roberts and Jones (2004) using a more rigorously validated global model actually suggests that the black carbon is a less potent GHG than CO₂. To further complicate the picture, any positive radiative forcing

associated with black carbon is likely to be fully or partially offset by the negative forcing associated with organic carbon from the same sources.

Given the complex nature of the relationship between emissions of NO_x and PM_{10} and climate change, the uncertainties involved in estimating their contribution to global warming, and the lack of an accepted GWP for emissions of these pollutants, it does not seem appropriate, particularly for a regulatory scheme such as the Supplier obligation to convert the estimates of NO_x and PM_{10} emissions to $\text{kg CO}_2 \text{ eq}$ and to include them in the total carbon factor for wood fuels.

3 Results

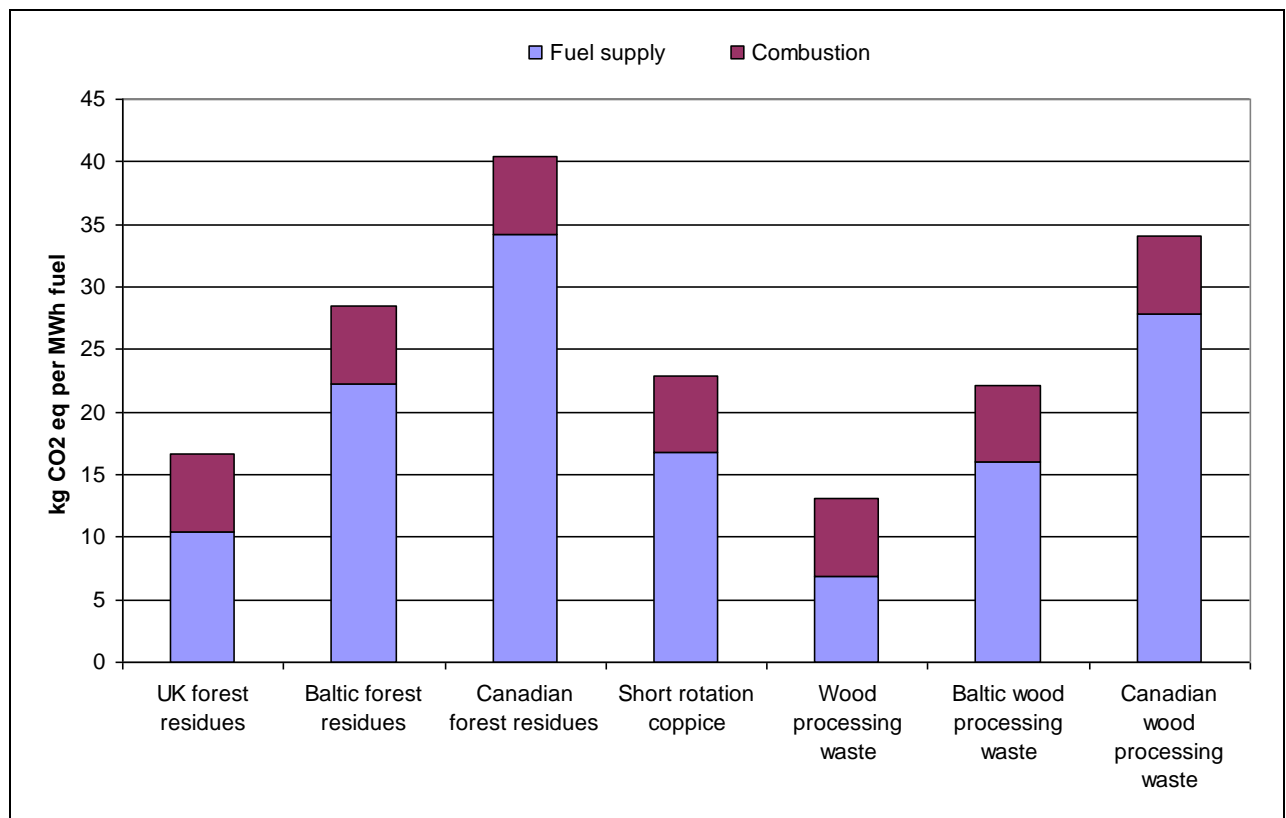
3.1 GHG emissions

The estimates of GHG emissions for chips and pellets are shown in Figure 3.1 for wood chips and Figure 3.2 for wood pellets. They are based on combustion in community scale size boilers (about 500 kW); as combustion related emissions are similar for the three boiler sizes considered. Data is presented in tabular form in Appendix 5.1.

3.1.1 Wood chips

The source of the wood chips has a significant influence, with emissions associated with Canadian forest residues (at 40 kg CO₂/MWh) being two to three times greater than emissions associated with forest residues or wood processing waste from the UK (at 13 and 17 kg CO₂/MWh). This is due to the much larger distances the chips have to be transported, and the same effect, but to a lesser extent, can be seen in the emissions associated with wood chips from the Baltic region. In summary, the impact of transporting forestry residues or wood processing waste to the UK adds about 10 kg CO₂/MWh for transport from the Baltic region and just over 20 kg CO₂/MWh if transported from Canada.

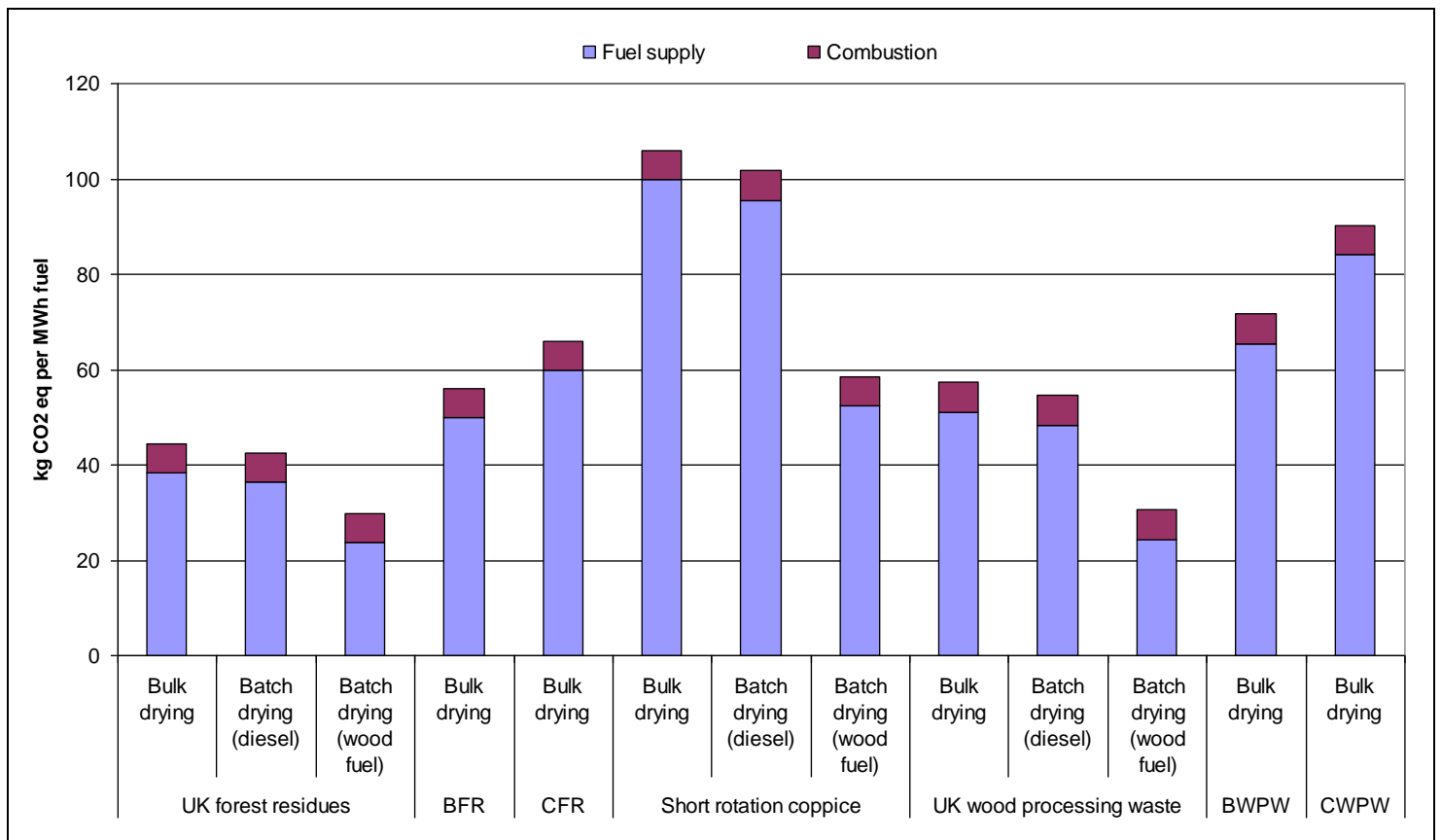
Figure 3.1 GHG emissions from combustion of wood chips



3.1.2 Wood pellets

The carbon factor for pellets is higher than for chips due to the additional energy consumption involved in drying, milling and pelletising, and ranges from 30 to 106 kg CO₂/MWh depending on the type of wood used to produce the pellets, its source, and method for drying the wood pre-pelletisation. The highest emissions are associated with the processing of short rotation coppice. This is mainly due to the high moisture content of the wood and therefore the energy requirements in the drying process. Once again, the impact of transporting wood from abroad can be seen with higher emissions from the Baltic and Canadian sources, especially for wood processing waste.

Figure 3.2 GHG emissions from combustion of wood pellets.



Note BRF = Baltic Forest Residues, CFR = Canadian Forest Residues, BWPW = Baltic Wood Processing Waste, CWPW = Canadian Wood Processing Waste.

3.1.3 Impact of IPCC Global Warming Potentials

All the data provided in Figure 3.1 and Figure 3.2 is based on Global Warming Potentials (GWP) supplied in the IPCC’s Second Assessment Report (SAR). This is because it is mandatory to use these GWPs for reporting purposes under the United Nations Framework Convention on Climate Change (UNFCCC). However, these GWPs have been updated in both the Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). Consequently, the total GHG emissions are affected by which GWPs are used. Total emissions, using GWPs from all three reports is presented in Table 5.4 for wood chips Table 5.5 for wood pellets. Overall the impact of using the revised GWPs is minor, changing the estimate of total GHG emissions in CO2 eq by 1% or less.

3.1.4 A carbon factor for use in the supplier obligation

The analysis shows that the carbon factor associated with wood fuels, particularly pelletised wood fuels can vary significantly depending on the source of the wood, distance it is transported, and for pellets, the method used to dry the wood chips prior to pelletisation.

For any boiler installation which falls under the Supplier Obligation, it is unlikely that the energy supplier would be able to guarantee the wood fuel source which would be used to supply the boiler over the next ten to twenty years. The use of individual factors relating to specific feedstocks, e.g. wood chips from SRC or pellets from UK forest residues therefore does not seem practicable.

Three options remain:

- To adopt a precautionary approach and use the highest of the values estimated above on the basis that this will ensure that savings are not overestimated. For chips this would give a value of 40.4 kg CO₂eq/MWh and for pellets a value of 106.1 kg CO₂eq/MWh.
- To take an average of the values estimated above. However, there are several disadvantages with this; firstly, due to the ranges in the values, there is large scope to over or underestimate actual emissions, depending on what feedstock is used. Secondly, the analysis presented above does not cover all possible sources of wood fuel in the UK. Therefore any average value is likely to be relatively arbitrary and again this presents scope to either over or underestimate actual emissions.
- To take a view of the likely mix of sources of wood chips and pellets in the medium term and calculate a weighted average from the carbon factors listed above. This could be based on an estimation of current and future resource estimates. However, as the market matures, the quantities of wood fuel traded internationally are likely to increase. Therefore, there would still be a degree of subjectivity in any figure calculated using this methodology.

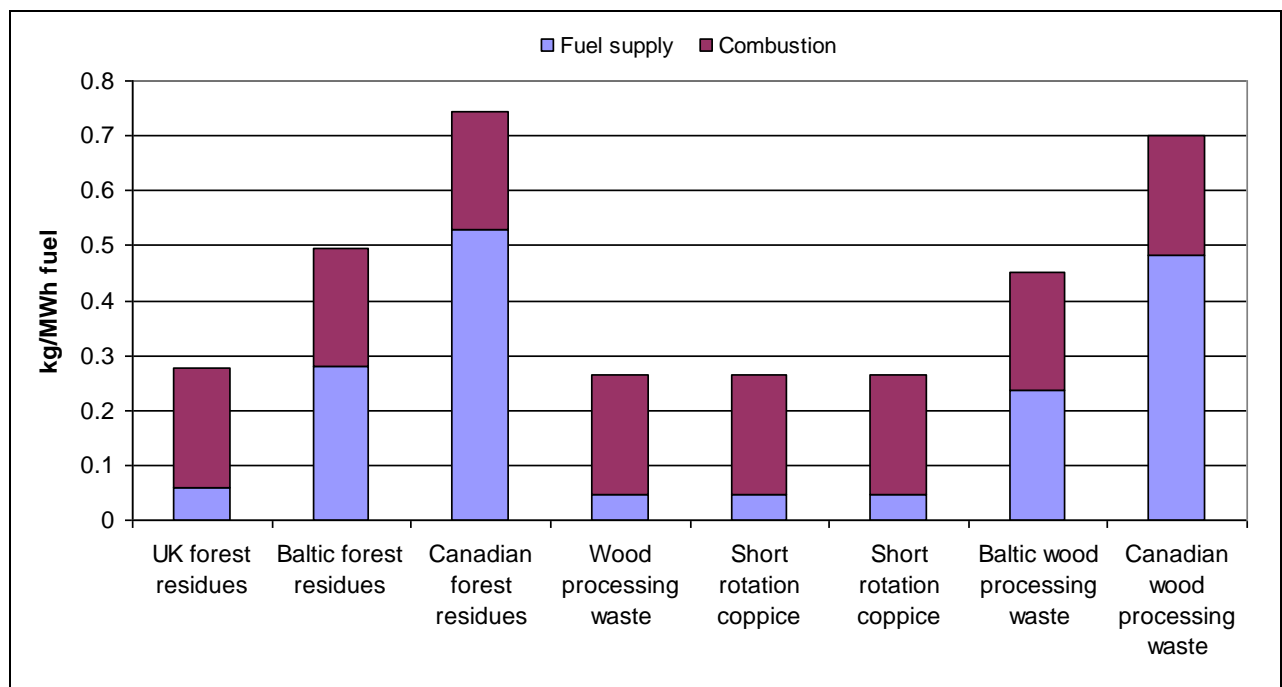
3.2 NO_x Emissions

The estimates of NO_x emissions for chips and pellets are shown in Figure 3.3 for wood chips and Figure 3.4 for wood pellets. Again they are based on combustion in community scale size boilers. Data is presented in tabular form in Appendix 5.3.

3.2.1 Wood chips

As was the case with GHGs, wood chips from the Baltic region and Canada have the highest NO_x emissions. This is largely due to emissions associated with the combustion of diesel fuel used during transportation. For chips sourced in the UK, emissions in the fuel supply process are relatively small and the majority are produced during combustion.

Figure 3.3 NO_x emissions from combustion of wood chips

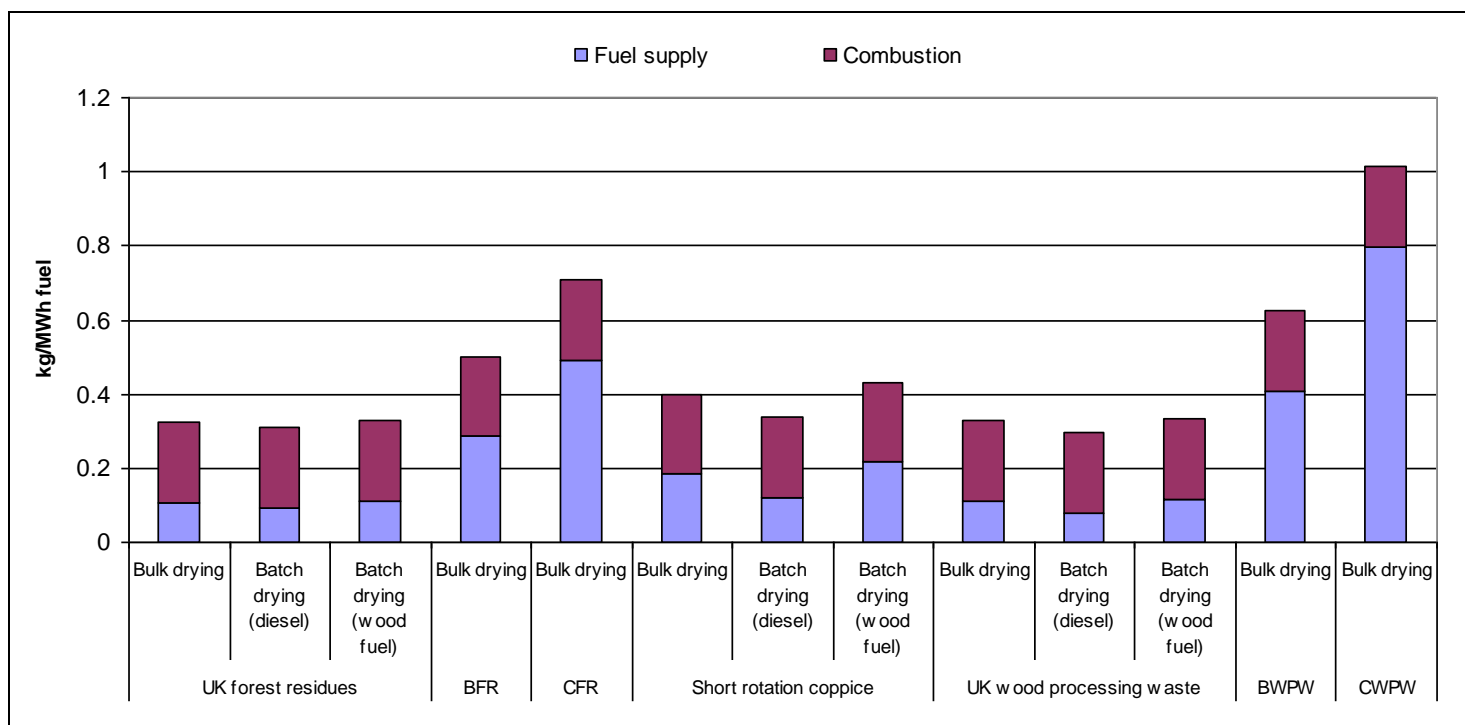


3.2.2 Pellets

Once again, wood pellets sourced from the Baltic region and Canada has the highest emissions, and the majority of these are associated with the fuel supply process. On average, transport from Canada adds about 0.5 kg NO_x/MWh and transport from the Baltic region adds about 0.2 kg NO_x/MWh. For

pellets sourced in the UK, the range in values is relative small (0.13 kg NO_x/MWh) and the majority of emissions are associated with combustion.

Figure 3.4 NO_x emissions from combustion of wood pellets.



Note BRF = Baltic Forest Residues, CFR = Canadian Forest Residues, BWPW = Baltic Wood Processing Waste, CWPW = Canadian Wood Processing Waste.

3.3 PM₁₀ Emissions

The estimates of PM₁₀ emissions for chips and pellets are shown in Figure 3.5 for wood chips and Figure 3.6 for wood pellets. Again they are based on combustion in community scale size boilers. Data is presented in tabular form in Appendix 5.4.

3.3.1 Wood chips

Unlike NO_x and GHG emissions, the range in PM₁₀ emissions from wood chips from different sources is relatively small at only 0.02 kg PM₁₀/MWh. This is caused by the large majority of emissions coming from the combustion process. Therefore, the impact of sourcing the chips from different geographic locations is minimised.

3.3.2 Pellets

Again, the range in PM₁₀ emissions from wood pellets from different sources is generally smaller than for NO_x and GHG emissions, though slightly larger than for PM₁₀ emissions from wood chips. In the majority of cases, emissions from the fuel supply process are minimal except in the case of SRC dried using wood fuel and wood processed waste from Canada. In these two cases, the fuel supply process is responsible for between 35-40% of total emissions.

Figure 3.5 PM₁₀ emissions from combustion of wood chips

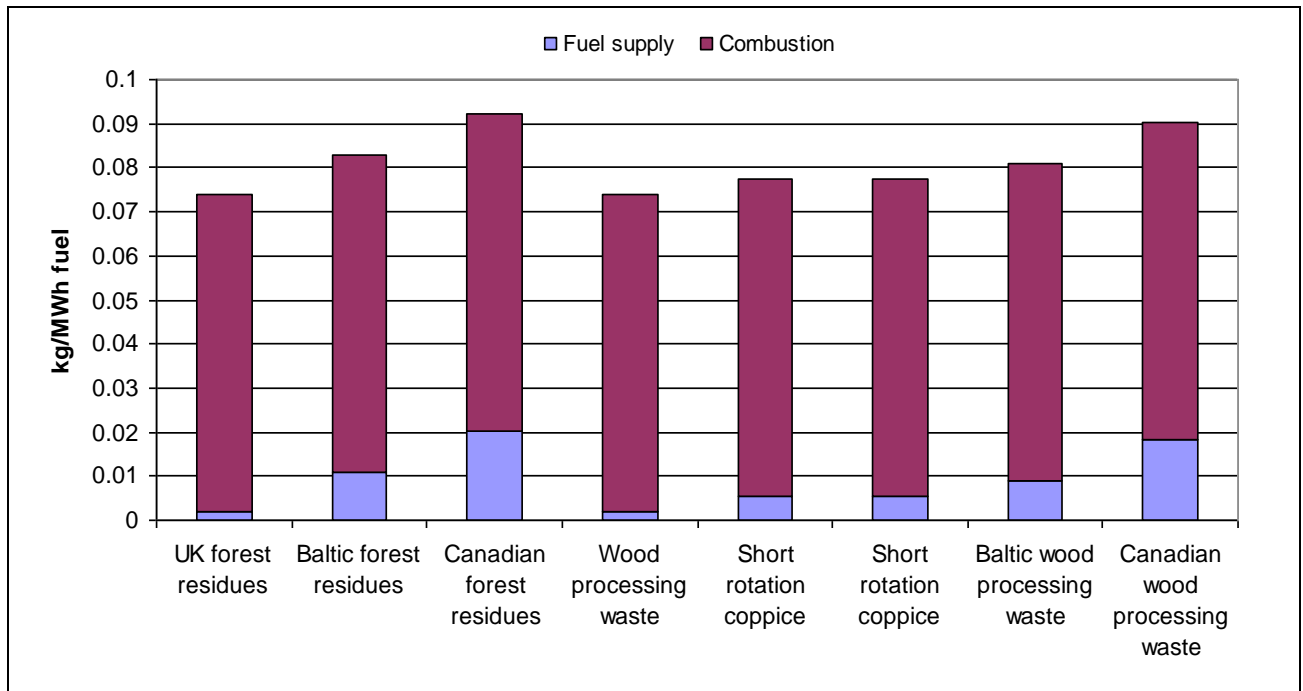
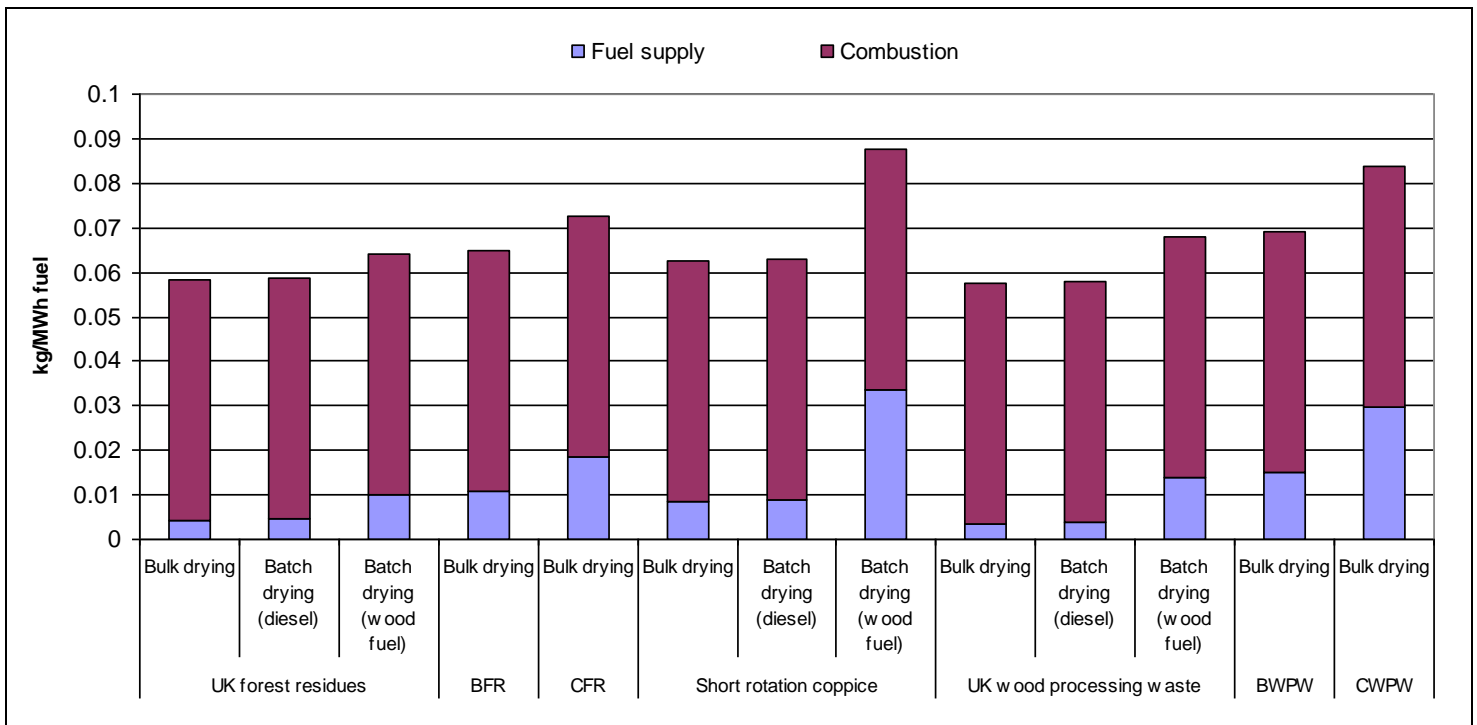


Figure 3.6 PM₁₀ emissions from combustion of wood pellets.



Note BRF = Baltic Forest Residues, CFR = Canadian Forest Residues, BWPW = Baltic Wood Processing Waste, CWPW = Canadian Wood Processing Waste

3.4 Comparison with fossil fuels

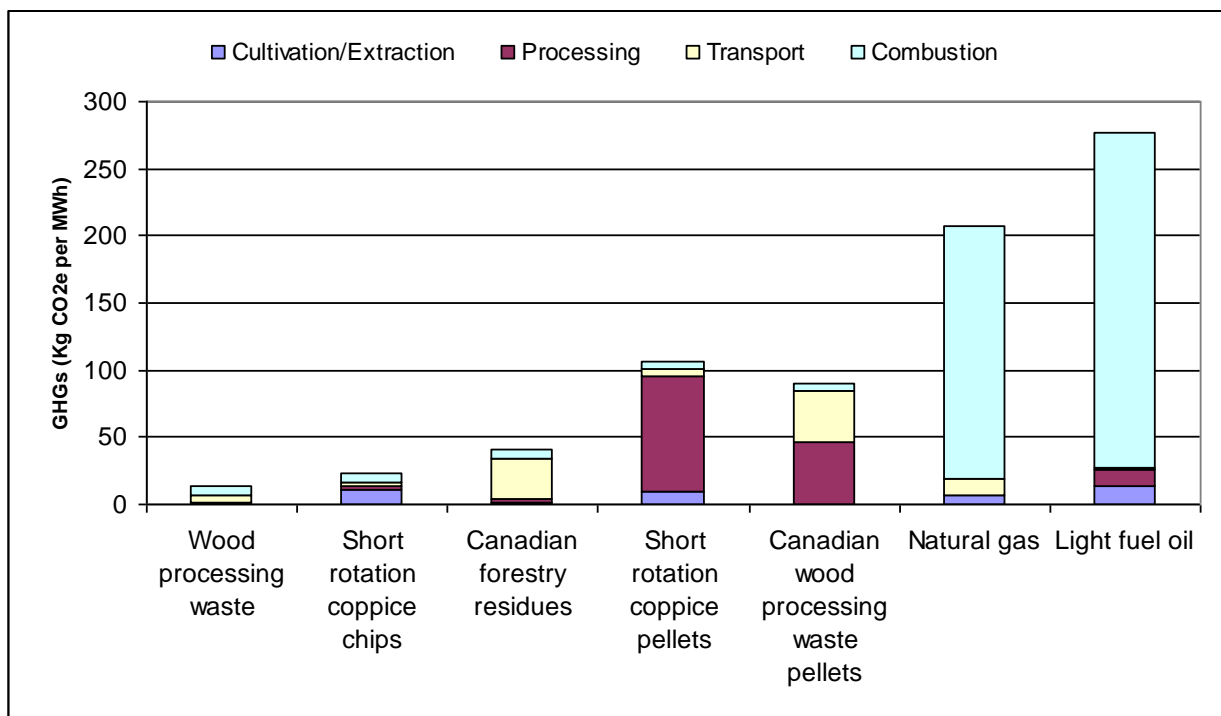
3.4.1 GHG Emissions

Including the GHG emissions from processing and transport of wood fuels, and/or the combustion related emissions in a carbon factor for wood fuels, would mean that they are treated differently from fossil fuels in the Supplier Obligation. For fossil fuels, only the direct CO₂ emissions from combustion are included.

Figure 3.7 shows the emissions associated with the production and combustion of fossil fuels as well as for a selection of the wood fuels examined in this study. The emissions associated with fossil fuel production are those associated with energy used in extraction, processing and distribution of the fossil fuel, and any fugitive emissions. The figure shows that the GHG emissions from production of natural gas and light fuel oil are of the same order of magnitude as those associated with the production of wood chips. For pellets emissions are substantially greater than for fossil fuels. It could therefore be argued that only including these emissions for wood fuels is underestimating the GHG savings which are achieved.

Combustion related emissions of CH₄ and N₂O are low for fossil fuels, particularly compared to their CO₂ emissions. N₂O emissions are significantly higher for wood fuels, and should perhaps be included in the carbon factor.

Figure 3.7 GHG emissions from production and combustion of fossil and wood fuels



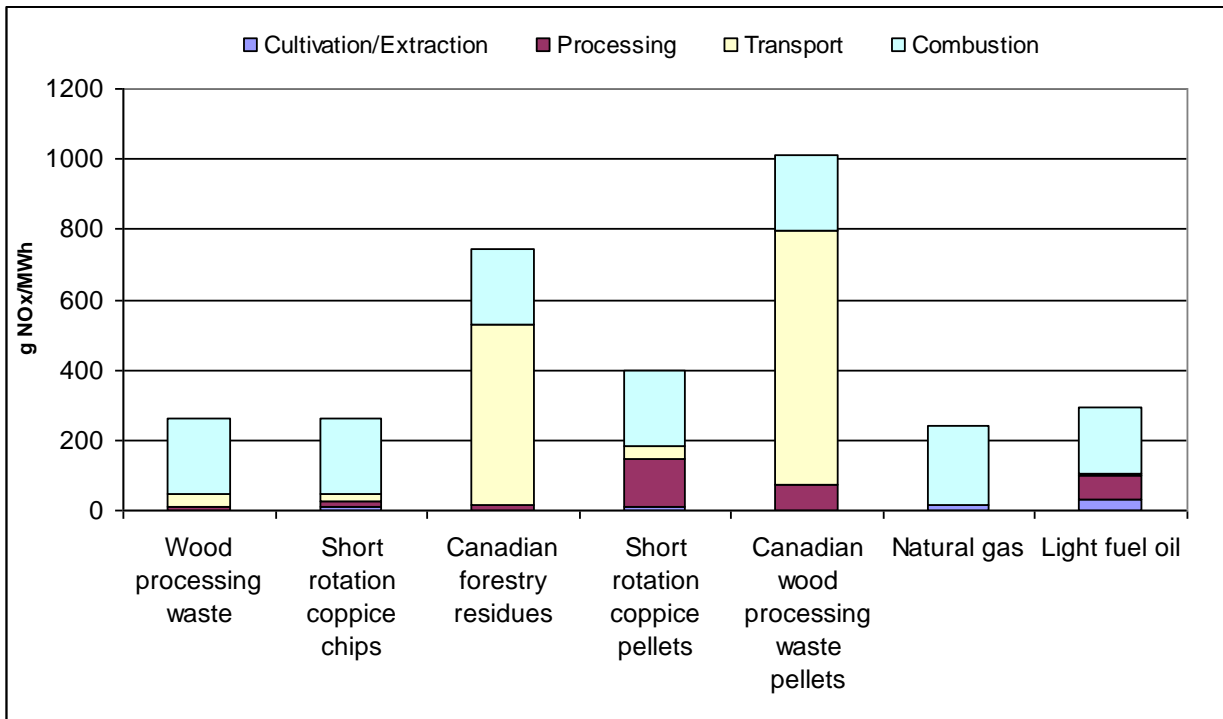
Source: Bates (1995) for production emissions from fossil fuels; NAEI for combustion emissions for fossil fuels (for public sector combustion) and this study for wood fuels.

3.4.2 NO_x and PM₁₀ emissions

NO_x and PM₁₀ emissions from fossil fuel and wood fuel production and combustion are compared in Figure 3.8 and Figure 3.9. In the case of fuel production, NO_x emissions for chips are of a similar order of magnitude as light fuel oil, unless they are transported long distances, in which case they are substantially higher, due to NO_x emissions from shipping. NO_x emissions for pelleted fuels are higher than for fossil fuels, again particularly so if they are transported long distances by ship. PM₁₀ emissions follow a similar pattern.

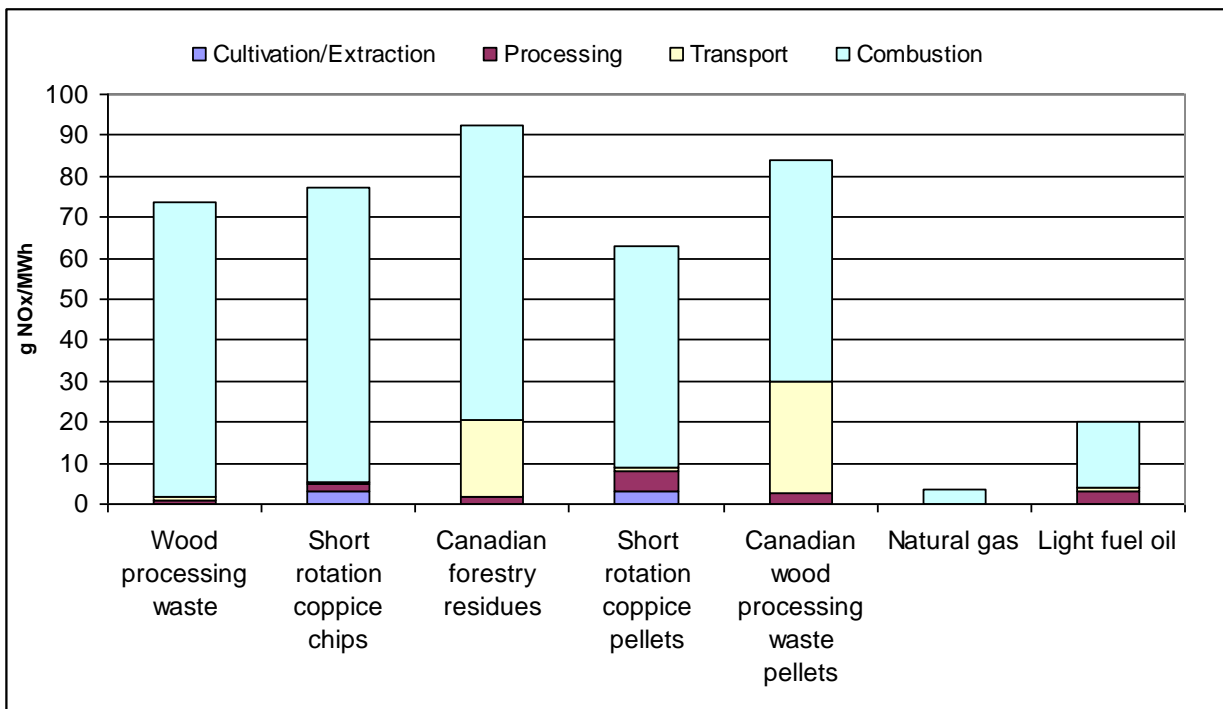
Combustion related NO_x emissions are similar for wood, oil and gas, but PM₁₀ emissions are three to four times higher than emissions from oil combustion.

Figure 3.8 NO_x emissions from production and combustion of fossil and wood fuels.



Source: Bates (1995) for production emissions from fossil fuels; NAEI for combustion emissions for fossil fuels (for public sector combustion) and this study for wood fuels.

Figure 3.9 PM₁₀ emissions from production and combustion of fossil and wood fuels.



Source: Bates (1995) for production emissions from fossil fuels; NAEI for combustion emissions for fossil fuels (for public sector combustion) and this study for wood fuels.

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5 Appendices

5.1 Tabulated GHG Emissions Data

Table 5.1 GHG emissions from combustion of wood chips (kg CO₂ eq per MWh fuel)

Feed stock	Fuel supply	Combustion	Total
UK forest residues	10.4	6.2	16.6
Baltic forest residues	22.2	6.2	28.4
Canadian forest residues	34.2	6.2	40.4
Short rotation coppice	16.7	6.2	22.9
Wood processing waste	6.9	6.2	13.1
Baltic wood processing waste	16.0	6.2	22.2
Canadian wood processing waste	27.8	6.2	34.0

Table 5.2 GHG emissions from combustion of wood pellets (kg CO₂ eq per MWh fuel)

Feed stock	Drying method	Fuel supply	Combustion	Total
UK forest residues	Bulk drying	38.3	6.2	44.4
	Batch drying (diesel)	36.3	6.2	42.5
	Batch drying (wood fuel)	23.7	6.2	29.9
Baltic Forest Residues	Bulk drying	49.9	6.2	56.1
Canadian Forest Residues	Bulk drying	59.8	6.2	66.0
Short rotation coppice	Bulk drying	99.9	6.2	106.1
	Batch drying (diesel)	95.5	6.2	101.7
	Batch drying (wood fuel)	52.4	6.2	58.6
UK wood processing waste	Bulk drying	51.1	6.2	57.3
	Batch drying (diesel)	48.4	6.2	54.6
	Batch drying (wood fuel)	24.4	6.2	30.6
Baltic Wood Processing Waste	Bulk drying	65.5	6.2	71.7
Canadian Wood Processing Waste	Bulk drying	84.1	6.2	90.3

Table 5.3 Life cycle GHG emissions from the combustion of a selection of wood chips and pellets. (kg CO₂ eq per MWh fuel)

Feedstock	Cultivation	Processing	Transport	Combustion	Total
Wood processing waste	0.00	1.98	4.88	6.23	13.10
Short rotation coppice chips	11.13	3.14	2.46	6.23	22.96
Canadian forestry residues	1.07	3.19	29.97	6.23	40.46
Short rotation coppice pellets	10.16	85.46	4.69	6.23	106.54
Canadian wood processing waste pellets	0.00	46.40	37.73	6.23	90.36

5.2 Tabulated GHG Emissions Data, by IPCC Report

Table 5.4 GHG emissions from combustion of wood chips (kg CO₂ eq per MWh fuel), using different GWPs from the three latest IPCC reports.

Feedstock	IPCC Report	Fuel supply	Combustion	Total	Rank
UK forest residues	SAR	10.45	6.19	16.64	1
	TAR	10.44	5.96	16.40	3
	AR4	10.45	6.03	16.48	2
Baltic forest residues	SAR	22.24	6.19	28.43	1
	TAR	22.22	5.96	28.18	3
	AR4	22.25	6.03	28.28	2
Canadian forest residues	SAR	34.23	6.19	40.42	1
	TAR	34.22	5.96	40.17	3
	AR4	34.25	6.03	40.28	2
Short rotation coppice	SAR	16.73	6.19	22.92	1
	TAR	16.59	5.96	22.55	3
	AR4	16.63	6.03	22.66	2
Wood processing waste	SAR	6.87	6.19	13.05	1
	TAR	6.86	5.96	12.81	3
	AR4	6.86	6.03	12.89	2
Baltic wood processing waste	SAR	15.98	6.19	22.17	1
	TAR	15.97	5.96	21.93	3
	AR4	15.99	6.03	22.02	2
Canadian wood processing waste	SAR	27.83	6.19	34.02	1
	TAR	27.82	5.96	33.78	3
	AR4	27.85	6.03	33.87	2

Note: SAR = Second Assessment Report, TAR = Third Assessment Report, AR4 = Fourth Assessment Report. The rankings indicate highest and lowest emissions, 1 = highest emissions, 3 = lowest emissions.

Table 5.5 GHG emissions from combustion of wood pellets (kg CO₂ eq per MWh fuel), using different GWPs from the three latest IPCC reports.

Feedstock	Drying method	IPCC	Fuel supply	Combustion	Total	Rank
		Report				
UK forest residues	Bulk drying	SAR	38.25	6.19	44.44	2
		TAR	38.35	5.96	44.31	3
		AR4	38.49	6.03	44.52	1
	Batch drying (diesel)	SAR	36.30	6.19	42.49	1
		TAR	36.34	5.96	42.30	3
		AR4	36.41	6.03	42.44	2
	Batch drying (wood fuel)	SAR	23.72	6.19	29.91	1
		TAR	23.75	5.96	29.71	3
		AR4	23.83	6.03	29.86	2
Baltic Forest Residues	Bulk drying	SAR	49.88	6.19	56.07	2
		TAR	49.98	5.96	55.94	3
		AR4	50.14	6.03	56.16	1
Canadian Forest Residues	Bulk drying	SAR	59.81	6.19	66.00	2
		TAR	59.92	5.96	65.87	3
		AR4	60.08	6.03	66.11	1
Short rotation coppice	Bulk drying	SAR	99.87	6.19	106.06	2
		TAR	100.06	5.96	106.02	3

		AR4	100.48	6.03	106.51	1
	Batch drying (diesel)	SAR	95.53	6.19	101.72	2
		TAR	95.51	5.96	101.47	3
		AR4	95.69	6.03	101.72	1
	Batch drying (wood fuel)	SAR	52.38	6.19	58.57	2
		TAR	52.33	5.96	58.28	3
		AR4	52.55	6.03	58.58	1
UK wood processing waste	Bulk drying	SAR	51.13	6.19	57.32	2
		TAR	51.30	5.96	57.26	3
		AR4	51.51	6.03	57.54	1
	Batch drying (diesel)	SAR	48.41	6.19	54.60	2
		TAR	48.47	5.96	54.43	3
		AR4	48.57	6.03	54.60	1
	Batch drying (wood fuel)	SAR	24.40	6.19	30.59	1
		TAR	24.45	5.96	30.41	3
		AR4	24.56	6.03	30.59	2
Baltic Wood Processing Waste	Bulk drying	SAR	65.48	6.19	71.67	2
		TAR	65.65	5.96	71.60	3
		AR4	65.87	6.03	71.90	1
Canadian Wood Processing Waste	Bulk drying	SAR	84.13	6.19	90.32	2
		TAR	84.30	5.96	90.26	3
		AR4	84.54	6.03	90.57	1

Note: SAR = Second Assessment Report, TAR = Third Assessment Report, AR4 = Fourth Assessment Report. The rankings indicate highest and lowest emissions, 1 = highest emissions, 3 = lowest emissions.

5.3 Tabulated NO_x Emissions Data

Table 5.6 NO_x emissions from combustion of wood chips (kg NO_x per MWh fuel)

Feedstock	Fuel supply	Combustion	Total
UK forest residues	0.06	0.22	0.28
Baltic forest residues	0.28	0.22	0.50
Canadian forest residues	0.53	0.22	0.74
Wood processing waste	0.05	0.22	0.26
Short rotation coppice	0.05	0.22	0.26
Short rotation coppice	0.05	0.22	0.26
Baltic wood processing waste	0.24	0.22	0.45
Canadian wood processing waste	0.48	0.22	0.70

Table 5.7 NO_x emissions from combustion of wood pellets (kg NO_x per MWh fuel)

Feed stock	Drying method	Fuel supply	Combustion	Total
UK forest residues	Bulk drying	0.11	0.22	0.32
	Batch drying (diesel)	0.09	0.22	0.31
	Batch drying (wood fuel)	0.11	0.22	0.33
Baltic Forest Residues	Bulk drying	0.29	0.22	0.50
Canadian Forest Residues	Bulk drying	0.49	0.22	0.71
Short rotation coppice	Bulk drying	0.18	0.22	0.40
	Batch drying (diesel)	0.12	0.22	0.34
	Batch drying (wood fuel)	0.22	0.22	0.43
UK wood processing waste	Bulk drying	0.11	0.22	0.33
	Batch drying (diesel)	0.08	0.22	0.30
	Batch drying (wood fuel)	0.12	0.22	0.33
Baltic Wood Processing Waste	Bulk drying	0.41	0.22	0.63
Canadian Wood Processing Waste	Bulk drying	0.80	0.22	1.01

Table 5.8 Life cycle NO_x emissions from the combustion of a selection of wood chips and pellets. (kg NO_x per MWh fuel).

Feedstock	Cultivation	Processing	Transport	Combustion	Total
Wood processing waste	0.00	0.01	0.04	0.22	0.26
Short rotation coppice chips	0.01	0.02	0.02	0.22	0.26
Canadian forestry residues	0.00	0.02	0.51	0.22	0.74
Short rotation coppice pellets	0.01	0.14	0.04	0.22	0.40
Canadian wood processing waste pellets	0.00	0.07	0.72	0.22	1.01

5.4 Tabulated PM₁₀ Emissions Data

Table 5.9 PM₁₀ emissions from combustion of wood chips (kg PM₁₀ per MWh fuel)

Feedstock	Fuel supply	Combustion	Total
UK forest residues	0.00	0.07	0.07
Baltic forest residues	0.01	0.07	0.08
Canadian forest residues	0.02	0.07	0.09
Wood processing waste	0.00	0.07	0.07
Short rotation coppice	0.01	0.07	0.08
Short rotation coppice	0.01	0.07	0.08
Baltic wood processing waste	0.01	0.07	0.08
Canadian wood processing waste	0.02	0.07	0.09

Table 5.10 PM₁₀ emissions from combustion of wood pellets (kg PM₁₀ per MWh fuel)

Feed stock	Drying method	Fuel supply	Combustion	Total
UK forest residues	Bulk drying	0.00	0.05	0.06
	Batch drying (diesel)	0.00	0.05	0.06
	Batch drying (wood fuel)	0.01	0.05	0.06
Baltic Forest Residues	Bulk drying	0.01	0.05	0.06
Canadian Forest Residues	Bulk drying	0.02	0.05	0.07
Short rotation coppice	Bulk drying	0.01	0.05	0.06
	Batch drying (diesel)	0.01	0.05	0.06
	Batch drying (wood fuel)	0.03	0.05	0.09
UK wood processing waste	Bulk drying	0.00	0.05	0.06
	Batch drying (diesel)	0.00	0.05	0.06
	Batch drying (wood fuel)	0.01	0.05	0.07
Baltic Wood Processing Waste	Bulk drying	0.02	0.05	0.07
Canadian Wood Processing Waste	Bulk drying	0.03	0.05	0.08

Table 5.11 Life cycle PM₁₀ emissions from the combustion of a selection of wood chips and pellets. (kg PM₁₀ per MWh fuel).

Feedstock	Cultivation	Processing	Transport	Combustion	Total
Wood processing waste	0	8.30×10^{-4}	9.30×10^{-4}	7.20×10^{-2}	7.38×10^{-2}
Short rotation coppice chips	3.23×10^{-3}	1.58×10^{-3}	4.69×10^{-4}	7.20×10^{-2}	7.73×10^{-2}
Canadian forestry residues	1.37×10^{-4}	1.68×10^{-3}	1.85×10^{-2}	7.20×10^{-2}	9.23×10^{-2}
Short rotation coppice pellets	2.95×10^{-3}	4.96×10^{-3}	8.93×10^{-4}	5.40×10^{-2}	6.28×10^{-2}
Canadian wood processing waste pellets	0	2.75×10^{-3}	2.71×10^{-2}	5.40×10^{-2}	8.39×10^{-2}



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