Including UK and international forestry in Biomass Environmental Assessment Tool (BEAT2)

Report – SC090022/R1

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Executive summary

BEAT$_2$ (Biomass Environmental Assessment Tool) is a software tool developed by AEA and North Energy Associates Ltd for the Environment Agency and the Department for Environment, Food and Rural Affairs (Defra). It presents and evaluates complex lifecycle data on the potential environmental impacts of bioenergy schemes in a user-friendly way.

Interest in biomass as a renewable energy source is growing. Several companies have recently announced plans to build large power plants fuelled mostly by imported wood and the introduction of the Renewable Heat Incentive in June 2011 is likely to create additional demand for wood fuels for heating. In addition, the UK government has announced mandatory sustainability criteria for electricity generation from solid biomass. As part of this, from April 2013 solid biomass electricity will need to demonstrate a 60 per cent emission saving over the lifecycle (carbon intensity of 285.12 kgCO_2/MWh or lower) to be eligible for Renewables Obligation Certificates (ROCs).

The original version of BEAT$_2$ included forestry residues (wood chips and pellets) but did not include UK or imported timber from forestry operations. It also did not assess changes in carbon stored in the forest that result from extracting forestry products. The Environment Agency was interested in understanding the lifecycle greenhouse gas (GHG) emissions attributable to wood when used as a fuel. We therefore commissioned work to include a range of UK and imported timber products and changes in forest carbon within BEAT$_2$ and use the revised tool to analyse the resulting energy production systems.

This project, undertaken by Forest Research, AEA and North Energy Associates Ltd:

- identifies a representative range of forest types and management profiles for inclusion in BEAT$_2$;
- develops a method for estimating the changes in forest carbon and GHG emissions from forestry options;
- incorporates these data into a set of three Microsoft Excel workbooks representing the combustion of forestry products to produce electricity and modifies BEAT$_2$ to include these options;
- generates illustrative results for forestry profiles to allow the effect of different management regimes and other factors on GHG emissions to be assessed.

Fourteen forestry profiles were developed to reflect different countries of origin, different forest types and different management techniques.

The change in forest carbon associated with each profile was modelled using Forest Research's CSORT model. CSORT is a forest carbon accounting tool which models changes in the carbon in trees, litter and soil on the basis of tree species composition, growth rate and management regime. CSORT was also used to provide estimates of fuels and materials used during operations to establish and regenerate the forest and harvest and to extract products from the forests. Data from the CSORT model were then embedded in three Excel workbooks for inclusion in BEAT$_2$.

Because there are plans for several electricity generating power stations in the UK the workbooks were used to calculate emissions resulting from electricity generation at a dedicated biomass power station using roundwood (timber), wood chips and pellets. Other processing and transport stages associated with conversion of the forestry

products to electricity were included. Components of $BEAT_2$ (other environmental aspects and the cost calculator) were also updated.

The results of the $BEAT_2$ analysis should be understood in the following context. $BEAT_2$ uses a different lifecycle assessment methodology to that set out in the Renewable Energy Directive (RED) and so the results presented here cannot be directly compared to the proposed UK Government sustainability criteria. The differences between the two methodologies will be most important where the result is close to the GHG target in the sustainability criteria (60 per cent emission reduction over the lifecycle). Despite these differences, this report gives an indication of which fuel supply chains are at risk of failing to meet the lifecycle GHG target once changes in forest carbon are taken into account. It also provides a comparison of emissions from changes in forest carbon with emissions from the rest of the lifecycle in order to understand the relative contribution of changes in forest carbon to overall GHG emissions.

For sustainably managed forests the time horizon over which emissions are evaluated does not influence the emissions, but the time horizon chosen is critical when evaluating emissions from harvesting primary forests and neglected forests being brought back into productive use. In these situations, there is generally a net removal of carbon over the short term (20 years), while in the longer term (100 years) the forest regenerates and the forest carbon stock regrows. In each case it is assumed that the forest is allowed to grow back after felling and does not suffer losses from disease or fire.

The type of forest management and age of the forest are also important determinants of overall GHG emissions. It is possible to generate electricity using timber and to reduce GHG emissions substantially even when changes to the carbon stored in forests are accounted for. However, emission savings vary widely and the use of timber from some forest management regimes will lead to emission increases in the short to medium term (see example results table below). The main findings are as follows.

- There is a considerable range in the results. Some forest profiles offer very high savings (80 to over 100 per cent) compared to EU average electricity generation, with others leading to very high GHG emissions (more than four times average emissions from EU electricity generation).
- The largest savings occur where forests are relatively young. In these cases the increase in carbon in litter and soil offsets emissions from other parts of the wood supply chain.
- Electricity produced from wood chips and roundwood from sustainably managed forests in the UK offer substantial savings (over 90 per cent) compared to EU average electricity generation.
- Electricity produced from wood chips from sustainably managed forests abroad offer savings of over 60 per cent compared to EU average electricity generation.
- Bringing neglected UK woodlands back into production can generate large greenhouse gas savings (over 80 per cent) in the short to medium term (over 20 years), but only if this is done by selective thinning rather than clear felling.
- Where restoration of neglected UK woodlands is by felling, GHG emissions are extremely high (more than four times average emissions from EU electricity generation) when evaluated over a 20-year time horizon due to the removal of carbon from the forest in the felled trees. However, by 100

years, the forest has regenerated such that the carbon stock has increased and net GHG emissions for electricity generation are almost zero.

- If electricity is produced from pellets then savings are lower mainly due to the additional energy required to pelletise the wood. Emissions associated with using pellets from sustainably managed forests abroad are high enough to raise the risk that these fuels may not meet the GHG target that is part of the government's mandatory sustainability criteria. These figures are based on using fossil fuel to dry the wood prior to pelletisation; savings would be higher using wood fuel.
- Emissions from old growth forests abroad where wood is extracted by clear felling have very high emissions and offer no savings over the short to medium term. However, by 100 years, savings are just over 60 per cent.

The modelling for this work has necessarily involved simplifying assumptions, such as a significant fraction of harvested wood continuing to supply the wood-based panel and board industries and sawn timber industries, and has only been able to consider a small number of potential forestry management scenarios. It should also be noted that calculations of changes in forest carbon may involve significant uncertainties.

Example emissions savings from selected forest profiles

Management type	Region	Timeline[1]	Forest type	Forest product	$kgCO_2e/MWh$	Savings compared to average EU electricity generation (713 kg CO_2e/MWh)[2]
Sustainably managed	UK	Not relevant[3]	conifer	Roundwood[4]	-65[4]	109%
				chip	-53	107%
				Pellet[6]	83	88%
			broadleaf	roundwood	51	90%
				chip	69	93%
				pellet	222	69%
	Fennoscandia and Baltic States[7]		conifer	chip	185	74%
				pellet	364	49%
	Boreal/Eurasia[7]			chip	210	71%
				pellet	392	45%
	Boreal North America[7]			chip	248	65%
				pellet	442	38%
	Fennoscandia and Baltic States[7]		broadleaf	chip	158	78%
				pellet	328	54%
Neglected (thinning and no felling)	UK	20 years	broadleaf	chip	122	83%
		100 years			202	72%
Neglected (clear felling)		20 years			2,923	Emissions over 4 times higher
		100 years			6	99%
Old growth[8] (clear felling)	Boreal Eurasia	20 years	conifer	chip	1,333	Emissions nearly twice as high
		100 years			280	61%
	Boreal North America	20 years			825	Emissions 1.2 times higher
		100 years			279	61%

Notes:
1 In each case it is assumed that the forest is allowed to grow back after felling and does not suffer losses from disease or fire.
2 Note that this is the same comparator used in the RED, but, as set out above, the $BEAT_2$ lifecycle assessment methodology is different from the methodology set out in the RED. Note also that this value is not a full life cycle value. For comparison, the average life cycle value for electricity from the UK grid (as calculated for $BEAT_2$) is 571 CO_2 eq per MWh and the value for electricity from a natural gas fired Combined Cycle Gas Turbine is 387 CO_2 eq per MWh.
3 For sustainably managed forests, only one set of results as presented because the results are the same for both time horizons (20 or 100 years).
4 Emissions associated with roundwood are slightly lower because there is less processing of the timber and lower wood losses along the supply chain.
5 Negative values arise for some types of wood fuel because the net increase in carbon stocks in these forests is so large that it more than compensates for the GHG emissions from cultivation, processing and transport of the feedstock.
6 In the case of wood pellets, total GHG emissions are higher due mainly to the additional energy required to pelletise the wood. These figures are based on using fossil fuel to dry the wood prior to pelletisation; savings would be higher using wood fuel.
7 GHG emissions for generation from wood from sustainably managed forests in the Baltic States and Fennoscandia, Boreal North America and Boreal Eurasia are higher than for wood from UK forests, not only because transport emissions are higher but also mainly because the greater age of the non-UK forests means that there is no increase in the carbon stock in the forest to offset emissions from processing and transport. GHG emissions from cultivation are very similar in all countries.
8 In the case of wood chips produced by clear felling old growth forests in Boreal Eurasia and Boreal North America, there is a very large change in carbon stock over the short term leading to very high GHG emissions per MWh,. This is mainly due to the removal of carbon in the trees that have been clearfelled and because 20 years after felling, the stand has not regenerated significantly.

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1 Background

$BEAT_2$ (Biomass Environmental Assessment Tool) is a software tool developed by AEA and North Energy Associates Ltd for the Environment Agency and the Department for Environment, Food and Rural Affairs (Defra). It presents and evaluates complex lifecycle data on the potential environmental impacts of bioenergy schemes in a user-friendly way and is aimed at bioenergy scheme developers, consultants and local authorities.

Since the tool was developed there have been several announcements from companies intending to build large power plants fuelled mostly by imported wood. This represents a step change in the UK biomass power sector, with potentially over 3,000 MW of generation capacity to be built over the next five years compared to current installed capacity of around 300 MW. In addition, the prospect of the introduction of the Renewable Heat Incentive in June 2011 suggests that much larger heat only and combined heat and power (CHP) plants will be built in the near future than is currently the case. There is a strong possibility that many of these will be fuelled by wood from UK and international sources.

The original version of $BEAT_2$ only included forestry residues and did not include timber from forestry. To investigate the potential impact of this change in the UK biomass power sector, $BEAT_2$ needs to be extended to include UK and imported timber products. The analysis of these feedstock sources also needs to include changes in carbon stored in the forest resulting from extraction of forestry products. This project therefore:

- identifies a representative range of forest types and management profiles for inclusion in $BEAT_2$ (Section 2);
- develops a method for estimating the changes in forest carbon, and greenhouse gas (GHG) emissions from forestry options (Section 3);
- incorporates the data into a set of three Microsoft Excel workbooks representing the combustion of forestry products to produce electricity, and modifies $BEAT_2$ to include these options (Section 4).

Section 5 illustrates some of the results from the workbooks and outlines the sensitivity of the GHG emissions from the use of forestry products for electricity generation to the location of the forest and type of forest management. Section 6 summarises the principal conclusions and recommendations.

2 Forestry options included in $BEAT_2$

A set of 'forestry profiles' to be considered were specified in terms of:

- country of origin;
- forest type;
- forest management type;
- time horizon for which a GHG emissions balance is calculated.

An essential feature of the brief for this project was a requirement to better represent a range of possible sources of forest biomass that might be used as feedstocks for UK electricity production. Four different countries or groups of countries were selected for the study:

- UK;
- Baltics and Fennoscandia (Scandinavia plus Finland);
- Boreal North America;
- Boreal Eurasia.

These were selected because they were either already supplying forest biomass to the UK or have the potential to supply significant quantities in the near future should demand expand.

Two broad classes of forest type were recognised, consisting of predominantly:

- conifer trees;
- broadleaf trees.

From the outset, it was recognised that the specific approach to management of forest stands would be a critical factor in determining the overall GHG emissions balance of the woody biomass supply and conversion system. Therefore, It is important to cover the types of forest management that would be (or might become) involved in the harvesting of woody forest material for the supply of biomass feedstock to the UK. It was agreed that five broad categories of forest management would be considered within the set of forestry profiles:

- conventional management involving periodic thinning and felling;
- restoration of management in neglected tree stands through thinning;
- restoration of management in neglected tree stands through felling and replacement;
- felling of old growth forest[1] followed by managed stand regeneration (that is natural regeneration of the stand assisted by active management);
- felling of old growth forest followed by unmanaged stand regeneration (that is natural regeneration of the stand without assistance from active management).

[1] 'Old growth forest' is used in a general sense to refer generally to primary forests not previously under active management for production.

A brief description of each of these management types is given below (Sections 2.1 to 2.5). This is followed by an explanation of selection of the time horizons (Section 2.6) and a summary of the main features of the selected forest profiles (Section 2.7).

2.1 Conventional management involving periodic thinning and felling

This type of management is widely practised in many countries and is the most likely type of management involved in the supply of biomass to the UK from the specified countries of origin.

Generally speaking, under the management regime selected to represent this case, forests are assumed to be managed as a collection of even-aged stands, with each stand following a characteristic lifecycle, or rotation. In broad terms, each stand is established by active management involving either tree planting or deliberate support to natural regeneration (such as control of competing vegetation, enrichment planting). The density of trees at time of establishment is usually very high, reflecting conditions which often occur when trees regenerate naturally. As the stand grows, the density of the trees is reduced by periodic thinning, which generally involves the removal of poor quality stems while releasing better quality trees from competition so as to maintain their rate of diameter growth. In temperate and boreal climates, thinning interventions generally start between 20–30 years into the rotation and are carried out every five or 10 years. At some point in the lifecycle of the stand, when the remaining trees have reached a large size and, generally around the time of maximum rate of production, the stand is clearfelled as a final harvest, with the life cycle then starting again with the establishment of a successor stand (possibly after a 'fallow' period of one or two years). The period between stand establishment and clearfelling is known as the rotation of the stand. In temperate and boreal climates, rotations typically range between 40 and 150 years depending on the tree species and growth rate of the stand.

There are a number of possible variations to this basic even-age, rotational type of management. For example, the final harvest may not always be carried out as a single clearfelling but may instead involve one or two heavy thinnings, leaving a small number of 'seed trees' which are removed somewhat later. The seed trees are managed to support natural regeneration of the successor stand. Further variations approach what would be regarded as 'continuous cover' stand management, in which tree cover is maintained on the ground at all times. For example, final removal of the trees forming a stand may take place over three to five heavy thinnings, during which time the successor stand is already starting to regenerate and grow.

These sorts of conventional approaches to forestry are widely regarded as consistent with sustainable forest management provided related criteria are also met such as:

- maintenance of tree species diversity and a wide age class structure;
- protection of habitats;
- constraints on the extent of contiguous areas clearfelled;
- consideration of impacts on stand structure and landscape.

2.2 Restoration of management in neglected tree stands through thinning

This type of management may be of specific relevance in the UK where, in past decades, there has been a history of initiatives that have led to the creation of new woodland but where the woodland owners have not continued to maintain the stands or manage them for production. As a consequence, there is believed to be a population of woodlands in the UK (particularly England) which may have become overstocked, (possibly with poor quality trees) because they have not been subjected to the conventional pattern of periodic thinning.

By bringing such stands back into active management, it may be possible to gain access to a pool of biomass that can be utilised for timber and energy, while at the same time improving the quality of the woodlands through thinning and enrichment of the remaining trees.

The restoration of management in neglected and overstocked tree stands is considered to provide many benefits apart from serving as a source of biomass (for example, through improving the general quality of woodlands, improving access for recreation, potentially meeting biodiversity objectives through changes to stand structure and light regime) and is being considered as a policy objective in the UK, notably in England.

While recognising the potential of gaining access to the biomass resource that may be associated with such stands, it is important to recognise that, under the 'reference scenario' (that is continuing neglect of the woodlands), these stands are likely to have high carbon stocks. Restoring management in these stands, however beneficial, is likely to result in a net reduction in these carbon stocks, which has to be accounted for in any analysis of the GHG emissions balance.

2.3 Restoration of management in neglected tree stands through felling and replacement

This type of management may be of specific relevance in the UK and is similar to the case considered above involving restoration of management through thinning.

Where new woodlands have been created but their subsequent neglect has effectively led to 'failure' (for example because of poor tree survival or large numbers of poor quality stems), restoration of management may potentially involve felling of the original stand followed by active planting or regeneration of an improved successor stand. Compared with an approach based on thinning, the net result is a large short-term reduction in carbon stocks, followed by a relatively quick increase in carbon stocks as the successor stand develops.

This approach to management restoration is not specifically under consideration as a policy objective in the UK, but is included to show the sensitivity of the GHG emissions balance to the details of how management objectives are put into practice.

2.4 Felling of old growth forest followed by managed stand regeneration

This type of management may not be widely practised in the countries being considered in this project, but could potentially occur in areas of old growth forests if concessions were granted for felling to take place for production.

This management type is of most relevance to forests in Boreal Eurasia and Boreal North America where such management has occurred in recent history. Essentially, stands forming old growth forests, which have developed naturally over many decades or centuries, are felled. Following felling, the land is managed actively to support the regeneration of a successor stand (such as control of competing vegetation and enrichment planting).

Under the ‘reference scenario’ (that is maintenance of the old growth forest), old growth stands are likely to have very high carbon stocks. Harvesting will result in a significant reduction in these carbon stocks, certainly in the short term, which has to be accounted for in any analysis of the GHG emissions balance.

There is increasing regulation and stewardship of forest management, which is likely to limit, if not completely restrict, the supply of biomass and timber arising from such a form of management. This approach to forest management and production has been included to illustrate the potential implications for the GHG emissions balance of harvested wood products should such sources come to constitute a significant element of biomass and fibre supply.

2.5 Felling of old growth forest followed by unmanaged stand regeneration

Again, this type of management may not be widely practised in countries being considered in this project, but could potentially occur in areas of old growth forests if concessions were to be granted for felling to take place for production.

This management type is of most relevance to forests in Boreal Eurasia and North America where such management has occurred in recent history. Essentially, stands forming old growth forests, which have developed naturally over many decades or centuries, are felled. Following felling, the land is left unmanaged. Eventually, after a protracted ‘fallow’ period, tree cover should be re-established as part of natural regeneration and succession processes.

Under the ‘reference scenario’ (that is maintenance of the old growth forest), old growth stands are likely to have very high carbon stocks. Harvesting will result in a significant reduction in these carbon stocks and recovery of carbon stocks will be slow due to the unmanaged nature of the regeneration. These aspects of stand carbon dynamics have to be accounted for in any analysis of the GHG emissions balance.

Comments made in the discussion of the preceding management type regarding the increasing regulation and stewardship of forest management also apply here.

2.6 Selection of time horizons

In addition to the specific aspects of forests and their management as discussed above, associated GHG emissions can be viewed over different periods of time, or time horizons.

Specification of the time horizon is necessary to take into account the fact that extraction of forest products from any given area may not be continuous. Actual rotations can span a number of decades, while some harvesting interventions (such as harvesting of primary forest or introduction of management in overstocked stands) generally involve a complex pattern of short- and long-term changes in carbon stocks. Various processes that lead to absorption or release of GHG emissions – principally carbon dioxide (CO_2) – occur at different points during a rotation. Hence, the specified time horizon can capture different processes and their accumulated effects depending on its actual duration.

In this instance, two time horizons were chosen; 20 years and 100 years. The 20-year time horizon reflects the need for current action to mitigate global climate change. In particular, there is an increasing focus on the variation of GHG emission releases over relatively short timescales, especially in relation to:

- negotiations over national GHG emissions inventories;
- the development of any post-Kyoto international agreement on global climate change;
- the deployment of mitigation measures such as bioenergy production and use.

In this context, the 20-year time horizon has specific resonance with policy formulation and implementation, especially in relation to the sustainability of biomass utilisation. This is the time horizon currently adopted to account for land use change in assessing the sustainability of biomass energy technologies by the European Commission (European Commission 2010).

In contrast to a 20-year time horizon, the 100-year time horizon can encompass longer term carbon stock dynamics occurring in response to stand management. From the perspective of realistic forest timescales, the 100-year time horizon is more appropriate. However, the countervailing perspective is that more immediate changes in GHG emissions are important. This is particularly the case for global climate change and subsequent mitigation measures. Hence, both 20-year and 100-year time horizons were addressed (where relevant) in this project. It is important to note that in each case it is assumed that the forest is allowed to grow back after felling and does not suffer losses from disease or fire.

2.7 Specification of forest profiles

Four countries/groups, two forest types, five management types and two time horizons result in a set of 80 possible forest profiles though not all combinations are realistic or even possible. Therefore, a subset of 14 final forest profiles was selected involving specific combinations that are relevant, or could potentially be relevant, to the supply of woody biomass for electricity generation in the UK. In particular it was noted that:

- Options involving conifer trees are relevant to all countries under consideration, while options involving broadleaf woodland are of most relevance to Baltic States and Fennoscandia and the UK.
- Options involving restoration of management in neglected stands are of primary relevance to the UK.
- Options involving production from old growth forests may potentially be of relevance in Boreal Eurasia and North America.

The final list of 14 forest profiles is given in Table 2.1.

Some forest profiles are distinguished in terms of a 20 or 100 year time horizon, whereas others do not take into account such a distinction. In the case of the former, management involves the introduction of harvesting in stands previously not in production, leading to short-term and long-term changes in carbon stocks. Hence, the carbon dynamics show significant sensitivity to time horizon. In the case of the latter, a given type of forest management is being maintained over a large number of stands, all at different stages in their rotations; that is some stands are regenerating, some stands are mid-way through the rotation, while other stands are being felled. Carbon stock changes take place in individual stands but, on average over the population, carbon stocks remain constant. Hence, for these forest profiles, the choice of time horizon has no effect on subsequent results. This is explained in more detail in Section 3.

The forestry case examples described in this report and incorporated into $BEAT_2$ were selected to represent a range of possible forest biomass sources. These cover a number of countries of origin, several tree species and site types, different tree growth rates and contrasting management regimes.

A general assumption has been made in this study that woody biomass will usually be supplied in the UK from sources based on sustainably managed forests. Accordingly, representative examples of such sources have been included for all countries of origin.

Other examples covered in this study are intended to illustrate the possible sensitivity of the GHG balance for woody biomass, for example, if harvesting is carried out in old-growth stands (forestry profiles 10, 11, 13 and 14) or as part of introduction of sustainable management in previously overstocked stands (forestry profiles 3–6). The inclusion of such cases should not be taken to suggest that practices such as harvesting in old-growth forests to supply biomass to the UK are common in Boreal Eurasia or Boreal North America. Equally, the non-inclusion of such an example based on UK forests should not be taken to mean that such practice would never occur here (although forestry regulation in the UK certainly tends to discourage it).

Table 2.1: Basic specifications of selected forest profiles

Profile number	Country or countries of origin	Forest type	Management type	Time horizon
1	UK	Conifer	Conventional management involving periodic thinning and felling	20 or 100
2	UK	Broadleaf	Conventional management involving periodic thinning and felling	20 or 100
3	UK	Broadleaf	Restoration of management in neglected tree stands through thinning	20
4	UK	Broadleaf	Restoration of management in neglected tree stands through thinning	100
5	UK	Broadleaf	Restoration of management in neglected tree stands through felling and replacement	20
6	UK	Broadleaf	Restoration of management in neglected tree stands through felling and replacement	100
7	Baltic States and Fennoscandia	Conifer	Conventional management involving periodic thinning and felling	20 or 100
8	Baltic States and Fennoscandia	Broadleaf	Conventional management involving periodic thinning and felling	20 or 100
9	Boreal Eurasia	Conifer	Conventional management involving periodic thinning and felling	20 or 100
10	Boreal Eurasia	Conifer	Felling of old growth forest followed by unmanaged stand regeneration	20
11	Boreal Eurasia	Conifer	Felling of old growth forest followed by unmanaged stand regeneration	100
12	Boreal North America	Conifer	Conventional management involving periodic thinning and felling	20 or 100
13	Boreal North America	Conifer	Felling of old growth forest followed by managed stand regeneration	20
14	Boreal North America	Conifer	Felling of old growth forest followed by managed stand regeneration	100

3 Estimating GHG emissions

The extended and refined representation of forest profiles within $BEAT_2$ required four essential developments of the existing method for representing forest dynamics. These were:

- improved representation of the potential supply of woody biomass, and its variation over time, by forest profile;
- more detailed description of the activities and processes involved in biomass harvesting and supply, particularly with regard to primary energy inputs and GHG emissions, by forest profile;
- explicit representation of the dynamics of forest carbon stocks within each forest profile;
- where needed, an indication of the sensitivity of primary energy inputs and GHG emission results to the time horizon adopted for calculations.

In this project, carbon stock dynamics of forestry systems have not been accounted for as in earlier versions of $BEAT_2$. This was because it had been assumed that forest carbon stock changes associated with biomass production were negligible for the range of forestry options covered. The basis for this earlier simplifying assumption is explained in the discussion of the extensions to the method presented below.

It was possible to apply the existing Forest Research CSORT model and analyse its outputs to provide results consistent with the developments specified above. These can then be used as inputs to $BEAT_2$ workbooks without the need for major developments. The CSORT model is a ‘second generation’ forest carbon accounting model under development by Forest Research, constituting a step-upgrade to the long-established CARBINE model. CARBINE was the world’s first forest carbon accounting model (Thompson and Matthews 1989). It has an established track record of application to the analysis of the impacts of forest management and policy options (see, for example: Matthews 1994, 1996; Matthews and Broadmeadow 2009).

CSORT represents emissions due to forestry activities and timber processing in terms of the major GHGs – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – though these calculations are in fact handled within the $BEAT_2$ tool, which refers to the more fundamental results produced by CSORT in terms of quantities of fuel and materials (see below). GHG emissions and removals due to changes in carbon stocks in the forest are assumed to be determined by CO_2, with the much smaller contributions due to CH_4 and N_2O not accounted for.

Figure 3.1 shows the essential structure of the CSORT model. Compared with the previous CARBINE model, the major improvements relevant to this project (shaded grey in Figure 3.1) involve the following:

- Integration with the M1 algorithm-based forest growth model (based on the growth relationships underlying the published Forestry Commission yield tables (see Edwards and Christie 1981). Linkage to M1 enables the simulation of GHG emission balances for a wider range of forestry systems in terms of tree species composition, growth rate and detailed management regime (see examples in Figure 3.2).
- Integration with the ASORT, BSORT and DSORT suite of models (Matthews and Duckworth 2005). Linkage to the ASORT–DSORT suite has permitted more accurate representation of carbon stocks in non-stem components of trees (foliage, branches, stump, roots) and of the allocation

of harvested biomass to primary products (branch wood, roundwood, sawlogs and bark). The structure of the ASORT–DSORT suite is illustrated in Figure 3.3.

- Improved representation of soil carbon dynamics associated with forestry systems (Morison et al. 2010).
- Stronger parameterisation of calculations for estimating GHG emissions associated with forestry operations and wood processing (quantities of fuel, materials, machinery required; see Morison et al. 2010).

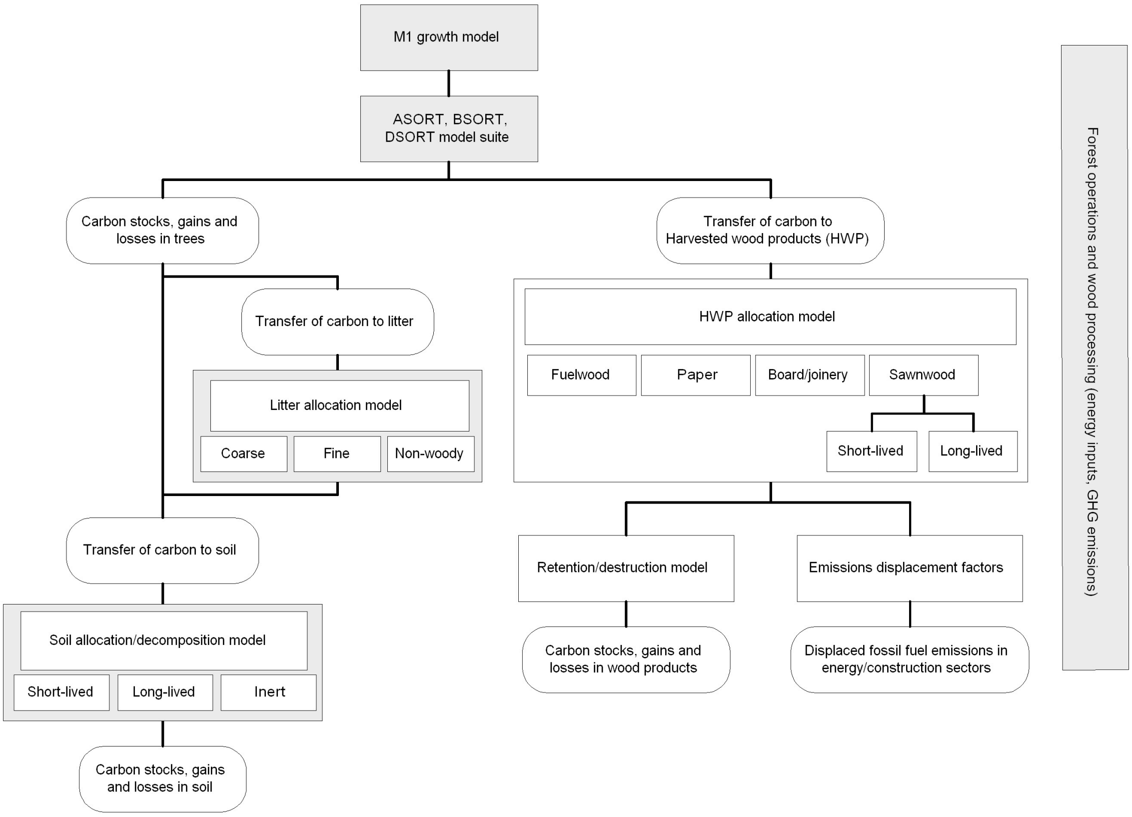

Figure 3.1: Structure of CSORT model

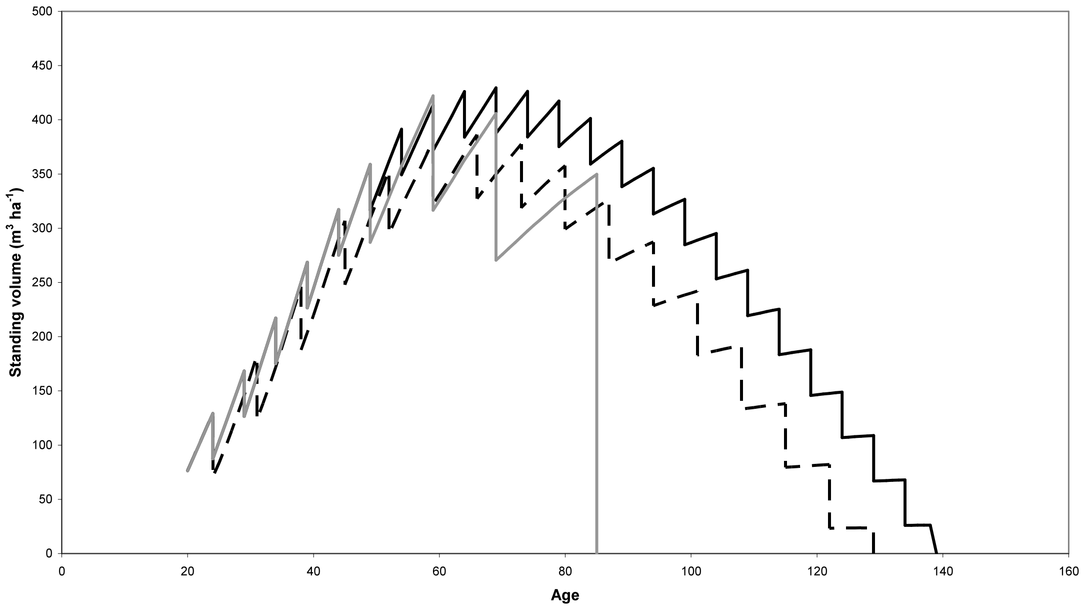

Figure 3.2: Example projections of the development of standing stem volume[1]

Note: [1] Example projections of the development of standing stem volume in a stand of trees made by the M1 growth model for a stand of Sitka spruce planted at 1.7 m spacing, with thinning starting at age 24.
Solid black line: standard thinning every five years.
Dashed black line: standard thinning every seven years.
Solid grey line: standard thinning every five years until age 49, then removal of growing stock over three heavy thinnings.

The application of CSORT to provide the results needed for representing different forestry profiles in $BEAT_2$ is described below. Two variants of the method were developed, the first being used to represent forestry profiles involving conventional management for production and the second being used to represent production from neglected/overstocked and old growth stands.

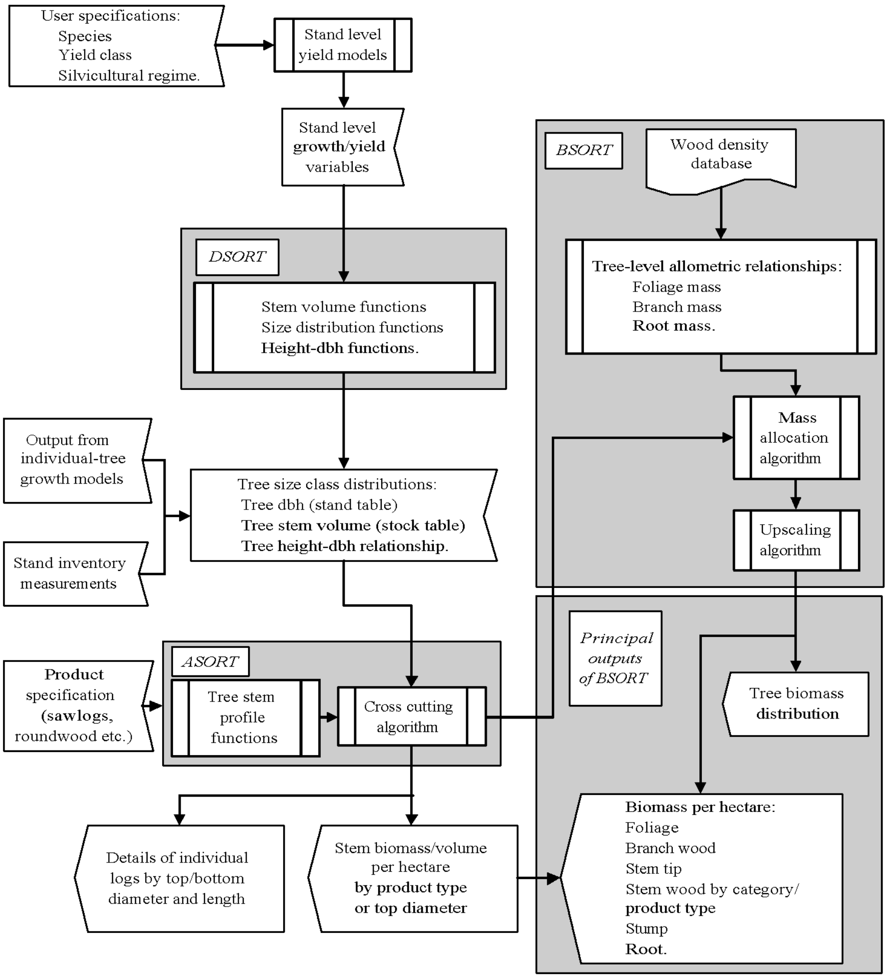

Figure 3.3: Structure of ASORT/BSORT/DSORT model suite

Note: dbh = diameter at breast height

3.1 Scale adopted in method

When estimating forest GHG balances the scale in terms of areas of forest and numbers of individual forest stands considered is crucial. For example, if calculations are made for an individual stand of trees (that is with the trees generally all of the same age and all managed in the same way), the GHG balance will show very large variations over time as follows:

- When the trees have just been planted or are still very young, carbon stocks will be small, as will growth and carbon sequestration rates.
- When the trees are at their most vigorous (say around 20 to 40 years old), carbon stocks will be moderate while growth and carbon sequestration rates will be large.
- In mature stands (50 years and older), carbon stocks will be large or very large but growth and carbon sequestration rates will be declining.
- Biomass production over time will be intermittent; depending on when and how harvesting is carried out, there will also be related reductions in forest carbon stocks at these times.

This typical pattern of development in an individual stand of trees is described in more detail in Sections 3.2 and 3.4.

The pattern of carbon stock changes and biomass production for an individual stand can (and usually does) contrast sharply with that observed when considering a bigger scale involving larger areas of forest formed of a population of individual stands. For example, if these areas of forest are being managed for sustainable production of timber and/or biomass, this generally involves maintaining range of stand ages in a forest (that is, areas of very young through to areas of mature stands). (If this was not done, it would be very difficult to achieve a continuous and even schedule of production.)

If the overall carbon stocks, rates of sequestration or emission and levels of production are estimated for a whole population of stands at different ages, the results for individual stands will tend to 'average out' when combined. Consequently, estimates for populations will generally be smoother over time than for an individual stand. In an idealised situation, estimates for a population will resemble time-averaged results for an individual stand when expressed on a per hectare basis (for more discussion of this point, see Sections 3.2 and 3.4)

Estimates of GHG balances (and biomass production potentials) for forestry systems depend strongly on the scale being considered. Thus a choice needs to be made as to the scale most appropriate as the basis for calculations in the $BEAT_2$ method. Such a decision had already been made in the original work (Elsayed et al. 2003) on which the $BEAT_2$ method is strongly based. Elsayed et al. estimated annualised timber and biomass production and annualised GHG emissions (and vegetation/soil carbon stock changes) for forestry systems by averaging results for individual years over a typical rotation (between 50 and 80 years for the cases considered in their study). In other words, the existing results for forestry systems presented in the original work and adapted for application as part of the original $BEAT_2$ software tool are already based on considering average emissions and stock changes for a collection of stands, rather than the complex, highly time-dependent dynamics that would be observed for an individual stand.

The same approach was adopted for the calculation of new GHG balances for the wider range of forestry systems considered in this study. Such a method, based on results for populations of stands, is appropriate when the objective is to evaluate the typical GHG balance for the supply of significant quantities of different types of biomass to a consumer from a range of possible sources. For example, the biomass supplied to a consumer such as a power station (or even a domestic wood burner who relies on a commercial supplier) will not normally come entirely from a single stand of trees, nor from a collection of stands that are all of the same age. Rather, biomass will usually be obtained from a range of sources involving forest stands at different stages of development and management. Results produced by this method may also be suitable for application when making an evaluation of the long-term potential of management options for an individual stand in terms of timber and/or biomass production and GHG balance, at least in some circumstances. However, estimates determined for a population of forest stands are not suitable for evaluating the short-term impacts of specific management interventions in individual stands.

3.2 Conventional management forest profiles

An example of the application of the CSORT model to provide the results needed for the extended method for forest profiles involving conventional management is illustrated in Figures 3.4 and 3.5, and Table 3.1, which show the results for forest profile 1 (UK conifer forest, conventional management involving periodic thinning and felling). These describe the patterns of biomass production and carbon stock dynamics expected in a typical productive stand of conifer trees in the UK. The essential assumptions behind the model simulation are as follows:

- Species composition is Sitka spruce.
- Spacing between trees at time of establishment is 1.7 m.
- The stand is established at time zero on land that was previously under grass.
- The texture of the soil is clay.
- Rotation (age of clearfell) is 50 years.
- Stem volume productivity over the rotation is 10 cubic metres per hectare each year ($m^3\ ha^{-1}\ yr^{-1}$).
- Thinning starts at age 26 and is repeated from that time every five years.
- Two 'fallow' years intercede between clearfelling and establishment of a successor stand.

3.3 Conventional management forest profiles: carbon stocks

Figure 3.4 shows the development of carbon stocks, measured in tonnes of carbon (tC), in the trees (that is not including debris, litter and soil) forming a stand of 'forestry profile 1' over a period (time horizon) of 100 years as estimated by the CSORT model. The time course followed by the carbon stocks exhibits a number of critical features:

- At the start of the first rotation, at time zero (when the trees are planted), carbon stocks in trees are negligible.
- As the trees grow, carbon stocks increase (at their maximum, just before clearfelling, carbon stocks reach about 90 tC ha^{-1}).
- The harvesting of some trees in thinning operations (ages 26, 31, 36, 41 and 46) causes reductions in the carbon stocks, after which the stocks recover as the remaining trees continue to grow. (After felling, the carbon in the trees is transferred to harvested wood products or left on site as debris or litter; this is not shown in Figure 3.4 and similar graphs.)
- When clearfelling takes place at age 50, all the remaining trees in the stand are felled with the consequence that the carbon stock in trees returns to zero (as with thinning the carbon is transferred to harvested wood products, debris and litter).
- Following the fallow period of two years, the pattern described above is repeated as trees are planted and grow, and are thinned and felled in the second rotation.

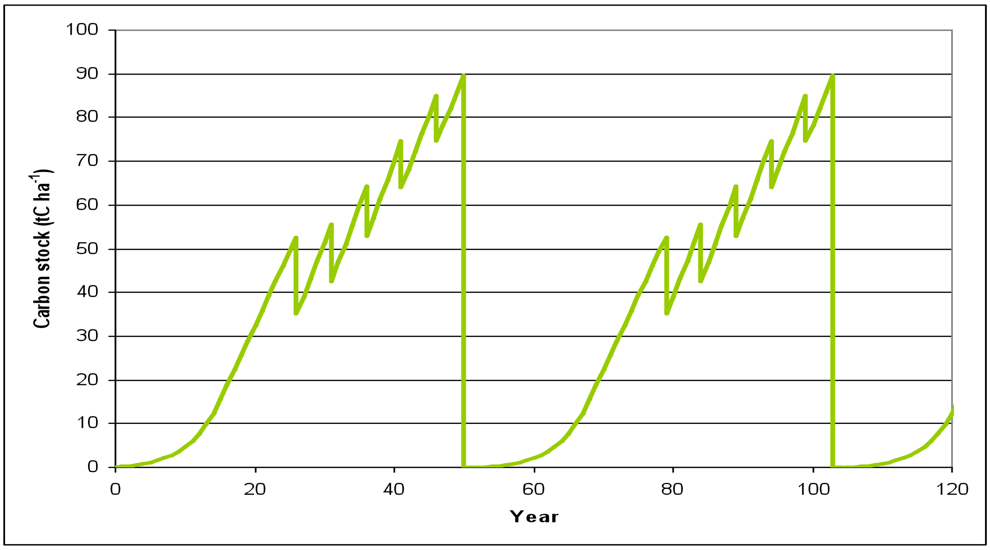

Figure 3.4: Development of carbon stocks in trees forming a stand of forest profile 1

The pattern of tree carbon stock development over time described in Figure 3.4 requires careful interpretation when applied in the $BEAT_2$ method.

First, if the aim is to evaluate the impact of a case involving the creation of a single new stand of 'forestry profile 1' at time zero, then a net carbon sink would be observed over a 20 year time horizon, with an annualised sequestration rate calculated at 1.6 tC ha^{-1} yr^{-1} for the period. However, no harvesting would take place over the first 20 years and therefore no biomass energy feedstock would be supplied. Over a 100-year time horizon, the full cycle of carbon dynamics for the first rotation would be captured, but the period would end just before the clearfell event for the second rotation when carbon stocks are almost at their greatest. The annualised carbon sequestration rate (based on the net stock change between year 0 and year 100) would be calculated to be 0.8 tC ha^{-1} yr^{-1}. These estimated net carbon sinks for the two time horizons are rather misleading because it is evident from the pattern of stock changes in Figure 3.4 that carbon is being accumulated over a rotation and then lost again when the trees are felled. Hence in reality carbon is neither sequestered nor emitted, meaning that the actual net carbon stock change must be zero.

Secondly, in reality under current conditions, biomass supplied from UK conifer forests comes from stands across a distribution of ages across the rotation period (some stands will be young and in the process of becoming established, some will be in the middle of their rotations and undergoing thinning, while some will be close to or at the point of clearfelling at the end of their rotations). If a forest consists of a large collection of stands with ages distributed evenly over the rotation then, in any particular year and over the whole population of stands, the total carbon stock would remain the same (as some stands get thinned or felled but others grow). Consequently the total forest area neither sequesters nor emits carbon as a result of stock changes in the individual stands of trees. In general forestry practice, the creation and maintenance of such an even distribution of age classes is often a fundamental management objective, because it ensures that:

- forest stocks are continuously being replenished as trees grow, are thinned or felled;

- the level of production of biomass and timber remains smooth from year to year rather than going through peaks and troughs;
- the achievement of such an outcome is a fundamental criterion for sustainable forest management.

Where production of biomass is from existing forests (that is not newly-created) under sustainable management as ‘business as usual’, the assumption of an even distribution of age classes and therefore zero carbon stock changes is a good model – certainly more appropriate than assuming that all stands are established at the beginning of the time horizon. Thus, in the modelling of the forestry profiles specified in Table 2.1, an even age class distribution has been assumed for those profiles involving conventional management over a rotation (profiles 1, 2, 7, 8, 9 and 12). This was also assumed in the original modelling of UK forestry systems that forms the basis of the existing $BEAT_2$ forestry options (Elsayed et al. 2003).

So far, the discussion has been concerned with the modelling of tree carbon stock changes only in the trees forming stands where sustainable forest management can be assumed. It is also necessary to consider carbon stock changes in litter and soil under such forest stands. Figure 3.5 shows the development of carbon stocks in trees, litter and soil in a stand of ‘forest profile 1’ over a 300-year time horizon. The same assumptions about stand characteristics as listed above apply, involving establishment of a new forest on land previously under grass by tree planting in year 0. Carbon stocks in litter are observed to be small compared to trees and soil, although they are not insignificant. Most importantly, carbon stocks in soil increase significantly as a result of conversion of the grassland to a forest stand. The time course of development of soil carbon stocks exhibits a number of features:

- Carbon stocks in soil increase in response to tree planting. Soil carbon stocks can also decrease in response to tree planting, generally in situations where carbon stocks were already high (under the previous land cover); for example, in very peaty soils or peat bogs. On the other hand, increases in soil carbon stocks very much greater than shown in Figure 3.5 are also possible; for example when trees are planted on land previously under arable management. The simulation in Figure 3.5 for forestry profile 1 was selected to represent typical site types on which productive conifer forests have been established in the UK over the last century.
- The rate of change of soil carbon stocks is relatively rapid in the early decades but becomes slower over time. In the example in Figure 3.5, most of the carbon stock change in soil takes place during the first rotation of the stand. There is a more modest stock change during the second rotation while in subsequent rotations, soil carbon stocks effectively cycle up and down, mirroring the growth and felling of the forest stand.

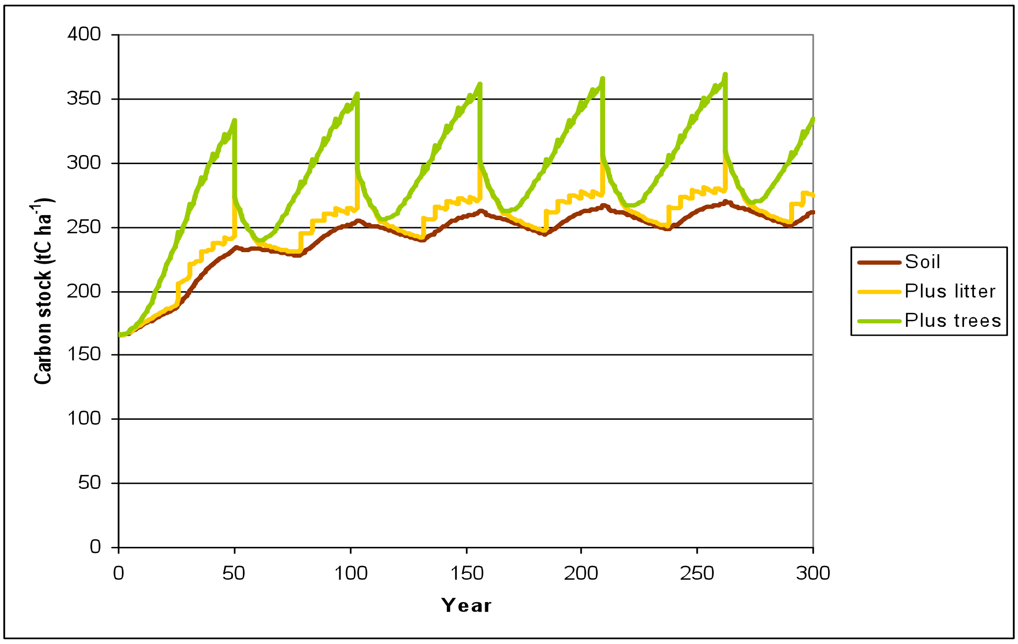

Figure 3.5: Development of carbon stocks in trees, debris/litter and soil forming a stand of forest profile 1

On the basis of these observations, different assumptions were made about carbon stock changes in litter and soil for the forestry profiles involving conventional management with thinning and clearfelling on a rotation depending on the country of origin:

- For Baltic States and Fennoscandia (forest profiles 7 and 8), Boreal Eurasia (forestry profile 9) and Boreal North America (forest profile 12), carbon stock changes in litter and soil were assumed to be zero over the rotation of a stand. In general, the stands under conventional management in these countries belong to long-established forest areas. Therefore, the dynamics of litter and soil carbon stocks are likely to be similar to that observed in Figure 3.5 during the period of the third or subsequent rotations, for which net carbon stock changes over a rotation are negligible. (Implicitly, in terms of impacts on forest carbon stocks for these forestry profiles, conventional forest management for production is taken to be ‘business as usual’ so the reference land use is the same as for the production system actually under consideration.)
- For the UK (forest profiles 1 and 2), carbon stock changes in litter and soil were assumed to follow a time course such as observed in a second rotation stand. For example, for forest profile 1, the carbon stock change in litter and soil over a rotation was estimated for the period from year 51 to year 103. The net stock change for this period (Figure 3.5) was estimated to be 26.5 tC ha^{-1}, or 0.5 tC ha^{-1} yr^{-1} annualised over the period. Typically, the stands under conventional management for production are in their second rotation from time of initial establishment. (Implicitly, a reference land use is being assumed which involves maintaining the original grassland on which, for the case under consideration, the forest stand has been established and has already been in existence for one rotation.)

These estimates for annualised tree, litter and soil carbon stock changes were applied regardless of time horizon (20 or 100 years) based on the assumption of an even distribution of stand age classes.

3.4 Conventional management forest profiles: biomass and timber production

Table 3.1 shows the schedule of biomass production by major product type for forest profile 1 over a rotation as estimated by the CSORT model. The quantities of products harvested depend on the method of harvesting and, in particular, the specifications to which particular products are cut. Three basic primary product types were assumed to be involved:

- branch wood;
- roundwood;
- sawlogs.

Specifications assumed for roundwood and sawlogs (for all forest profiles) are summarised in Table 3.2.

Table 3.1: Biomass production by major product type for forest profile 1[1,2]

Stand age (years)	Branch wood (odt ha^{-1})	Roundwood (odt ha^{-1})	Sawlogs (odt ha^{-1})	Sawn timber from sawlogs (odt ha^{-1})
26	-	6	-	-
31	-	8	-	-
36	-	9	-	-
41	-	7	3	2
46	-	6	5	3
50	19	25	71	39
Total over rotation	19	61	79	44
Annualised production (odt ha^{-1} yr^{-1})	0.37	1.17	1.52	0.85

Notes: [1] Products measured in oven dried tonnes (odt).
[2] Production is annualised over 52 years (50-year rotation plus two fallow years).

Table 3.2: Assumed specifications for harvested forest products (all forest profiles)

Product type	Top diameter (over bark, cm)	Length	
		Fixed or random	Metres
Roundwood	7	Fixed	3
Sawlogs	18 (conifer) 25 (broadleaf)	Random but with minimum length	3

The specifications in Table 3.1 illustrate how the production of different biomass products is intermittent and can be very variable over a rotation. In this example:

- The small trees removed in the first three thinnings (ages 26, 31 and 36) are converted entirely into roundwood (the potential for sawlog production from small trees is negligible). Production might be increased in these early thinnings by relaxing the specification for roundwood and harvesting whole tree stems. Interest is growing in such approaches to harvesting to supply wood fuel end uses. However, such possible variations in conventional harvesting methods were not considered here.

- Later thinnings (ages 41 and 46) consist of a mixture of roundwood and sawlogs, estimated explicitly as part of the functionality of the CSORT model system.
- The clearfell event (age 50) is assumed to involve harvesting of branch wood in addition to roundwood and sawlogs. The branch wood is assumed to be suitable only for supply of wood fuel as an end use. Only a fraction of the total available branch wood (60 per cent) is assumed to be harvested, the remainder is retained on site as part of the management of soil structure, acidity and nutrient regime. Some foliage (50 per cent of total) is also assumed to be harvested with the branch wood.

Both roundwood and sawlog material generally follow a complex set of pathways to end uses (and secondary uses).

- Of greatest relevance to this project, roundwood can be utilised by the pulp, pallet and board industries as well as for fuel.
- The principal end use for sawlogs is (generally) high value sawn timber, but processing efficiencies limit this to around 55 per cent of the original total overbark sawlog volume (as shown in the last column of Table 3.1). The remainder, consisting of slabwood and other types of offcut, can be utilised by the board industry or used as wood fuel. Some of this fuel may be consumed internally by the sawmill to heat drying ovens or possibly to provide electricity.

To simplify the representation of the biomass supply and processing chain it was assumed that:

- all roundwood was available for utilisation as wood fuel;
- slabwood and offcuts from sawlogs were utilised entirely within the sawmill (as fuel) or for non-fuel end uses.

In subsequent calculation stages of the revised $BEAT_2$ method, allocation of primary energy inputs and GHG emissions during forest management and production stages was made on the basis of the quantities of the three principal end-use materials (that is branch wood, roundwood and processed sawn timber; see Table 3.1), allowing for their relative value. A similar approach was taken to allocation of carbon sinks or sources arising from stock changes in forest stands.

Total production over a stand rotation of branch wood, roundwood and sawn timber was annualised, as illustrated in Table 3.1 for forest profile 1. For reasons discussed in the description of the modelling of forest carbon stock changes, these estimates of annualised production were assumed to apply regardless of time horizon (20 or 100 years) for production based on conventional forest management over a rotation.

3.5 Conventional management forest profiles: fuel and material inputs

The CSORT model already represents in detail the inputs of fuel and materials associated with forest establishment, management and harvesting operations. CSORT can therefore be used to simulate primary energy inputs and GHG emissions over any time horizon for a specified forest profile. However, the details of these calculations differ from those made in the $BEAT_2$ workbooks (for example, some emissions factors are different).

To achieve complete consistency with $BEAT_2$, CSORT was re-programmed to provide, directly as outputs, a set of estimates over time of actual quantities of fuel and materials used in forest management operations expressed, as appropriate, in litres, cubic metres, kilograms or other units.

For forestry profiles involving conventional management over a rotation, these different estimates were summed over the specified rotation and annualised on a similar basis to that adopted in the modelling of forest carbon stock changes and biomass production (see discussion above).

The main results calculated by the modified CSORT model were for:

- number of seedlings used in planting operations;
- fuel used in establishment, thinning and clearfelling operations;
- lengths of fencing required for forest protection;
- quantities of herbicide used in establishment operations;
- quantities of urea solution used for protection of felled tree stumps against fungal infection.

From the point at which forest products were harvested and delivered to roadside, all ensuing primary energy and GHG emissions calculations (such as transport, processing and conversion to electricity) were handled using the existing $BEAT_2$ method.

3.6 Neglected and old growth forest profiles

An example of the application of the CSORT model to provide the results needed for the extended method for forest profiles involving harvesting of old growth or previously neglected and overstocked stands is illustrated in Figure 3.6 and Table 3.3. These show the basic results for forestry profiles 13 and 14 (Boreal North America old growth conifer forest, clearfelled followed by managed regeneration with a 20 or 100 year time horizon). The essential assumptions behind the model simulation are as follows:

- Species composition is spruce.
- Spacing between trees at the time of establishment (of the original old growth stand) is 1.7 m.
- The original stand became established on land that was previously under grass.
- The texture of the soil is clay.
- Maximum stem volume productivity over rotation is 8 $m^3\ ha^{-1}\ yr^{-1}$.
- The stand has attained ‘old growth’ conditions (that is large carbon stocks) by year 0.
- Clearfelling takes place in year 0.
- Two ‘fallow’ years intercede between clearfelling and active establishment of a successor stand.

The old growth carbon stocks were estimated by ‘spinning up’ the CSORT model to estimate carbon stocks in an initial stand of 100-year-old spruce at year 0.

3.7 Neglected and old growth forest profiles: carbon stocks

Figure 3.6 shows the development of carbon stocks in the trees, litter and soil forming a stand of 'forestry profile 13 or 14' over a period (time horizon) of 100 years as estimated by the CSORT model. The time course followed by the carbon stocks exhibits a number of key features:

- Initial carbon stocks are quite large – just over 300 tC ha^{-1} in this example.
- Clearfelling takes place at the start of the period (year 0 in Figure 3.6). Consequently, there is a significant loss of carbon in standing trees. Some of this carbon is transferred to the debris/litter and soil carbon pools, which show increases in carbon stocks although not enough to offset the losses in trees. The carbon transferred to the debris pool decays more gradually.
- Overall, carbon stocks drop to about 130 tC ha^{-1} in the 10 years following clearfelling, with the bulk of the remaining carbon stock retained in the soil.
- As the trees in the successor stand grow, carbon stocks increase relatively slowly. In this example, the carbon stock in the original stand is not approached again until the end of the time horizon (100 years).

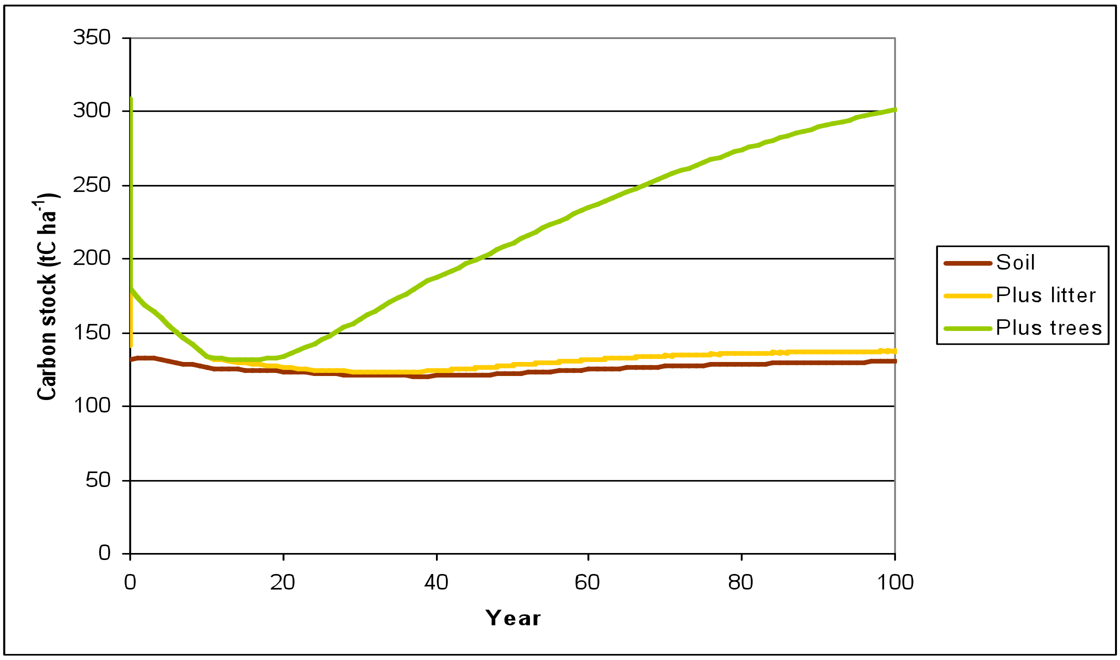

Figure 3.6: Development of carbon stocks in trees, debris/litter and soil forming a stand of forest profiles 13 or 14

Similar patterns of carbon stock changes are observed for all the forestry profiles involving introduction of management for production in neglected/overstocked or old growth stands, although with some important variations in the detail. For example, for forestry profiles 3 and 4, the introduction of management for production involves periodic thinning of the existing growing stock rather than clearfelling. The sequence of thinnings still results in a reduction in carbon stocks, but not to the extent observed in Figure 3.6; the reduction also takes place gradually over several decades, after which stocks begin to recover again as the stand regenerates towards the end of the 100-year period.

When interpreting these carbon stock changes and applying them within the extended $BEAT_2$ method, it is necessary to draw a distinction with the earlier analysis of carbon stock changes in forests managed conventionally through thinning and clearfelling for production of biomass and timber. A critical assumption is made for forestry profiles involving conventional management:

- Management for production constitutes 'business as usual management' for the stands forming the forest (forestry profiles 7, 8, 9 and 12).

or

- Stands have been newly created through planting in the recent past with the specific intention of management for production (forestry profiles 1 and 2).

This assumption does not hold for forestry profiles involving harvesting in neglected/overstocked or old growth stands.

Instead 'business as usual management' consists of leaving the neglected or old growth forests as they are. Interventions to produce timber and biomass constitute a clear change from business as usual management, introduced at the beginning (year 0) of the period (time horizon) over which consequent forest carbon stock changes must be accounted for. These carbon stock changes need to be calculated relative to the 'business as usual' reference case.

In the extended $BEAT_2$ method, the development of carbon stocks under the reference case was assumed to involve the indefinite maintenance of the carbon stocks estimated for the stand immediately before the introduction of harvesting at year 0. Therefore, for the example of forestry profile 13 or 14, the carbon stock was assumed to remain constant at just over 300 tC ha^{-1} under the reference case.

This represents the simplest possible representation of the development of carbon stocks for the reference case. A more sophisticated approach might involve accounting for ongoing accumulation of carbon stocks in neglected and old growth stands, had thinning or felling not taken place. This could be taken to suggest that an assumption of continuing constant carbon stocks is likely to lead to underestimation of losses of forest carbon (that would have accumulated in the future). However, a further complication involves accounting for the impacts of disturbance events – for example forest areas lost in fires, trees blown down in storms or killed by disease outbreaks. If such impacts were to be accounted for, this might suggest that an assumption of continuing constant carbon stocks would be an overestimate for the reference case, with the consequence that losses arising as a result of harvesting interventions would also be overestimated.

In the absence of any clear basis for making assumptions about further accumulation or losses of carbon stocks over time compared to a constant reference level at the point when clearfelling or a first thinning is carried out, a baseline of continuing constant (relatively high) forest carbon stocks was adopted within the extended $BEAT_2$ method for forest profiles involving introduction of management for production in neglected/overstocked or old growth stands.

A further crucial assumption in the modelling of forests managed conventionally through thinning and clearfelling for production of biomass and timber is that production during any time interval takes place from a population of stands with ages evenly distributed over a conventional rotation. Again, this assumption does not hold for forest profiles involving harvesting in neglected/overstocked or old growth stands because management for production is introduced in stands as a change to 'business as usual', effectively at year 0 – the beginning of the time horizon over which carbon stock changes and levels biomass production are calculated.

The particular time horizon adopted has a significant impact on annualised estimates of GHG emissions or sinks, and levels of biomass production. This can be illustrated for the example of forest profiles 13 and 14, as shown in Figure 3.6.

- The initial carbon stock in trees, litter and soil at time zero is 309 tC ha^{-1}. The clearfelling event at year 0 causes a large and rapid reduction in these carbon stocks.
- By the end of a 20-year period (that is for a 20-year time horizon, forest profile 13), carbon stocks are almost at their lowest point before new carbon stocks start to accumulate with the regeneration of a successor stand. The estimated carbon stock for year 20 is 134 tC ha^{-1}, giving a stock change for the period of -175 tC ha^{-1}. The annualised carbon stock change (emission) for the 20-year period is -8.8 tC ha^{-1} yr^{-1}.
- By the end of a 100-year period (that is for a 100-year time horizon, forest profile 14), carbon stocks have almost recovered due to the regeneration of a successor stand. The estimated carbon stock for year 100 is 302 tC ha^{-1}, giving a stock change for the period of -7 tC ha^{-1}. The annualised carbon stock change (emission) for the 100 year period is -0.07 tC ha^{-1} yr^{-1}.

These results illustrate the sensitivity of annualised estimates of carbon stock changes to the time horizon adopted for calculations.

3.8 Neglected and old growth forest profiles: biomass and timber production

Table 3.3 shows the schedule of biomass production by major product type for forest profile 13 or 14 as estimated by the CSORT model, applicable for time horizons of 20 and 100 years. For these forest profiles, production occurs from a single clearfelling event at year 0. The specific products harvested consist of branch wood, roundwood and sawlogs, with specifications as described earlier and in Table 3.2.

Table 3.3: Biomass production by major product type for forest profiles 13 or 14[1]

Time horizon (years)	Branch wood (odt ha^{-1} yr^{-1})	Roundwood (odt ha^{-1} yr^{-1})	Sawlogs (odt ha^{-1})	Sawn timber from sawlogs (odt ha^{-1} yr^{-1})
At time of clearfell	38	64	146	80
20	1.9	3.2	7.3	4
100	0.38	0.64	1.46	0.8

Note: [1] Results reported for time of clearfell are effectively in units of oven dry tonnes per hectare (odt ha^{-1}) because the time horizon is effectively one year.

As discussed in Section 3.7, two crucial assumptions made in the modelling of carbon stock changes for forest profiles concerned with conventional management through thinning and clearfelling for production of biomass and timber do not hold when considering forest profiles involving harvesting in neglected/overstocked or old growth stands.

This was shown to have significant implications for the calculation of annualised carbon stock changes for the types of forestry profile under consideration, particularly in terms of sensitivity to the time horizon adopted for calculations. The same reasoning also applies to the estimation of annualised quantities of biomass and timber production for forest profiles involving harvesting in neglected/overstocked or old growth stands.

Accordingly, values for annualised biomass production by major product type were estimated for time horizons of 20 years (forest profile 13) and 100 years (forest profile 14), as shown in Table 3.3. The sensitivity of these results to the adopted time horizon is evident.

Subsequent calculation stages of the updated $BEAT_2$ method (allocation of materials to end uses, allocation of primary energy inputs and GHG emissions during forest management and production stages) follow the conventions described in Section 3.4.

3.9 Neglected and old growth forest profiles: fuel and materials inputs

The approach taken to estimating the inputs of fuel and materials associated with forest establishment, management and harvesting operations is the same as described in Section 3.5. However, for reasons already discussed in Section 3.7, time horizon needs to be allowed for when calculating annualised estimates of energy and materials inputs for forestry profiles involving harvesting in neglected/overstocked or old growth stands.

4 Modelling of forestry options and inclusion in $BEAT_2$

4.1 Forestry product workbooks

Three main Excel workbooks have been developed to extend the calculation of total GHG emissions for the use of forest products from different types and locations of forestry for energy production in the UK in the $BEAT_2$. These cover:

- electricity only generation by combustion of timber, in the form of roundwood, delivered to a dedicated biomass power plant;
- electricity only generation by combustion of wood pellets, derived from roundwood, delivered to a dedicated biomass power plant;
- electricity only generation by combustion of wood chips, derived from roundwood and forest residues, delivered to a dedicated biomass power plant.

Due to funding limitations, it was only possible to evaluate one energy conversion technology for each of the fuel types. A dedicated biomass power plant for electricity generation was chosen as there is much interest in this type of plant at present and there are plans for several large plants of this type in the UK.

GHG emissions from the provision of forest products come from two general sources:

- forest operations;
- forest net carbon stock changes.

Depending on the characteristics of the forest profile under consideration, forest operations can consist of establishment, periodic thinning, clearfelling and regeneration. GHG emissions associated with these activities arise mainly from the consumption of diesel by machinery and equipment. As these activities occur at given intervals during a rotation, their associated GHG emissions have been annualised (as explained previously). This involves adding together all relevant GHG emissions from forest operations during the course of a rotation and dividing the total by the duration of the rotation in years. Results are expressed for a unit area of forest (hectare).

A similar approach was adopted for the evaluation of GHG emissions associated with net carbon stock changes in the forest, though these tend to be cumulative rather than intermittent. These GHG emissions consist of CO_2 emissions which are absorbed by, or released from various parts of the forest – soil and tree roots, debris/litter and trees (above ground). Whether CO_2 is absorbed or released over a given period depends on whether the forest components have, in net terms, been acting as a carbon stock or a carbon source. Within the existing convention adopted by $BEAT_2$, a net absorption of CO_2 (overall increase in a carbon stock) is recorded as a negative value and a net release of CO_2 (overall decrease in a carbon stock) is denoted by a positive value.

As described in Section 3, the CSORT model was used to estimate biomass production for a total of 14 selected forestry profiles (see Table 2.1) including associated carbon stock changes, primary energy inputs and GHG emissions due to consumption of fuel and materials during operations. Table 4.1 lists the input assumptions made in running CSORT for each of the forestry profiles. Calculations for all subsequent stages (transport, processing, conversion to power or heat) beyond biomass harvesting and extraction to roadside were carried out using the existing $BEAT_2$ method.

In order to ensure consistency, the previous features and functionality of $BEAT_2$ were incorporated, as far as possible, in the new workbooks. In particular, the procedure for the allocation of primary energy consumption and GHG emissions between forest products, which is primarily based on prices, was adopted. This reflects an attributional rather than a consequential approach in $BEAT_2$ (Brander et al. 2009). As with other $BEAT_2$ workbooks, it is possible to alter relative prices of co-products to determine changes in total primary energy consumption and GHG emissions. However, no attempt is made to simulate the effects of increases in biomass demand on relative prices and hence the estimated results. This requires further analysis of such market-mediated effects.

The method of incorporating relevant information on forest operations and changes to forest carbon stocks meant it was necessary to modify the evaluation of errors in the $BEAT_2$ workbooks. Previously, the potential for assessing the effect of cumulative errors in all primary energy consumption and GHG emission calculations was a fundamental part of the $BEAT_2$ workbooks. This was based on the assumption that all errors followed a normal symmetrical distribution so that they could be combined using a simple propagation of errors routine.[2] However, for this work, the primary energy consumption and GHG emissions for forest operation were derived from CSORT which calculates average results without estimated errors. To account for likely errors, percentage estimates for the regeneration, harvesting and extraction of relevant forest products (branch wood, roundwood and sawn timber) were obtained from previous $BEAT_2$ workbooks and applied to the average results from CSORT. No errors were evaluated for the carbon stock changes derived from CSORT. Final results from these new workbooks may underestimate errors in total primary energy consumption and GHG emissions.

[2] This consists of evaluating the square root of the sum of the squares of the individual errors.

Table 4.1: Details of assumptions made in preparing CSORT model runs for selected forest profiles

Profile no.	Country	Species	Maximum productivity (m^3 ha^{-1} yr^{-1})	Spacing (m)	Management	Soil texture	Soil/litter carbon change	Time horizon (years)
1	UK	Spruce	10	1.7	Thin every five years from age 26, clearfell at age 50, re-establish after two fallow years.	Clay	Based on second rotation	20/100
2	UK	Mixed broadleaf	4	1.5	Thin every five years from age 25, clearfell at age 100, re-establish after two fallow years.	Loam	Based on second rotation	20/100
3	UK	Mixed broadleaf	8	1.5	Introduce thinning every five years in neglected/overstocked stand, continuous thinning with regeneration (i.e. no clearfell).	Loam	For time horizon	20
4	UK	Mixed broadleaf	8	1.5	Introduce thinning every five years in neglected/overstocked stand, continuous thinning with regeneration (that is no clearfell).	Loam	For time horizon	100
5	UK	Mixed broadleaf	4	1.5	Clearfell neglected/overstocked stand, thin new stand every five years from age 25, clearfell at age 100, re-establish after two fallow years.	Loam	For time horizon	20
6	UK	Mixed broadleaf	4	1.5	Clearfell neglected/overstocked stand, thin new stand every five years from age 25, clearfell at age 100, re-establish after two fallow years.	Loam	For time horizon	100
7	Baltic States & Fennoscandia	Scots pine	4	1.4	Thin every five years from age 40, clearfell at age 100, re-establish after two fallow years.	Sand	Zero over rotation	20/100
8	Baltic States & Fennoscandia	Birch	4	1.5	Thin every five years from age 20, clearfell at age 120, re-establish after two fallow years.	Sand	Zero over rotation	20/100
9	Boreal Eurasia	Spruce	6	1.5	Thin every five years from age 35, clearfell at age 100, re-establish after two fallow years.	Loam	Zero over rotation	20/100
10	Boreal Eurasia	Spruce	6	1.5	Clearfell old growth stand, leave land to regenerate (10 fallow years), redeveloping as old growth.	Loam	For time horizon	20
11	Boreal Eurasia	Spruce	6	1.5	Clearfell old growth stand, leave land to regenerate (10 fallow years), redeveloping as old growth.	Loam	For time horizon	100
12	Boreal North America	Spruce	8	1.5	Thin every five years from age 31, clearfell at age 100, re-establish after two fallow years.	Loam	Zero over rotation	20/100
13	Boreal North America	Spruce	8	1.5	Clearfell old growth stand, re-establish after two fallow years and allow to redevelop as old growth.	Loam	For time horizon	20
14	Boreal North America	Spruce	8	1.5	Clearfell old growth stand, re-establish after two fallow years and allow to redevelop as old growth.	Loam	For time horizon	100

A number of sources of information were referred to when formulating the assumptions in Table 4.1.

- Tree species were selected based on country forest inventories and reports.
- Maximum stem volume productivity was inferred from an international review (Christie and Lines 1979) and individual country reports.
- Initial spacing between trees (at time of establishment) was based on standard assumptions made for different species in Forestry Commission yield tables (Edwards and Christie 1981).
- Management regimes were derived from the experience of Forest Research scientists and foresters as well as country reports (where available).
- Assumptions about typical soil texture under forests were based on values reported in a global database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009).
- The basis for treatment of soil/litter carbon stock changes and adoption of time horizons is described in Section 2 (time horizon) and Section 3 (time horizon and soil/litter carbon).

Different productivities were assumed in forestry profiles 3 and 4 compared with 5 and 6 for reasons already alluded to in Section 2. Essentially, forestry profiles 3 and 4 represent the introduction of management for production in relatively productive broadleaf stands through progressive thinning interventions, whereas forestry profiles 5 and 6 represent clearfelling and re-establishment in stands where the growth rate and growing stock are less productive.

4.2 Inclusion in BEAT$_2$

The new workbooks have the same essential structure as the existing BEAT$_2$ workbooks. The main changes have been to incorporate look-up tables (based on results derived from CSORT for each selected forest profile) in each workbook for:

- primary energy inputs and GHG emissions of forest operations, and annualised yields for forest products (in the Regeneration, Harvest and Extraction worksheets);
- carbon stock changes (in the Forest Carbon Stock worksheets).

Transfer worksheets were formulated and agreed default values for the main parameters were added accordingly.

The standard level of transparency in existing BEAT$_2$ workbooks has been maintained although extensive notes could not be incorporated for CSORT assumptions. Instead, this report provides the sources of detailed documentation.

Details of the biomass pathways represented by the three workbooks are set out in the respective Unit Flow Chart worksheets. Their main features are summarised below:

- Electricity only generation by combustion of timber assumes that whole roundwood is delivered to a dedicated biomass power plant where it is milled on site to a suitable feedstock size.
- Electricity only generation by combustion of wood pellets assumes that roundwood is chipped, milled and pelletised at or near the point of origin and shipped in this form to a dedicated biomass power plant.

- Electricity only generation by combustion of wood chips assumes that roundwood and forest residues are chipped at or near the point of origin and shipped in that form to a dedicated biomass power plant.

These new workbooks have been incorporated into $BEAT_2$. They are accessed by users as before through the Microsoft Access pages of $BEAT_2$. To simplify the choices for the non-expert user, only two choices of country of origin and type of forest management are included on the initial entry pages. These are:

- UK sustainably managed coniferous forest;
- 'international' sustainably managed coniferous forest, where international is represented by the Baltics and Fennoscandia.

These two profiles were chosen as the most likely source of timber in the UK at the present.

Other management profiles and countries of origin can be chosen in the 'customise parameters' section of $BEAT_2$, under cultivation and harvesting. The time profile over which neglected woodlands brought back into management and old growth forests should be evaluated can also be chosen in this way. The default value has been set to 100 years.

The $BEAT_2$ user guide has been updated to cover these new workbooks.

A 'switch' has been included in the workbooks and $BEAT_2$ to allow the inclusion or exclusion of forest carbon in the calculations. The default is for forest carbon to be included in the results, with the contribution shown as a separate line. However, users can exclude it in the 'customise parameters' part of $BEAT_2$, under cultivation and harvesting.

The other sections of $BEAT_2$ have all been updated to include the three types of forest products. These sections consist of:

- the cost calculator;
- assessment of other environmental impacts;
- calculation of area of forest (in ha) required per MWh of electricity output;
- number of deliveries.

5 Results

5.1 Major factors influencing results

A substantial range of results can be generated from the new $BEAT_2$ workbooks. These results should be understood in the following context; $BEAT_2$ uses a different lifecycle assessment methodology to that set out in the Renewable Energy Directive. This means that the results presented here cannot be directly compared to the proposed GHG target in the UK Government's sustainability criteria (60 per cent emission reduction over the lifecycle) that will become mandatory in April 2013 . The differences between the two methodologies will be most important where the result is close to the 60 per cent sustainability target.

The most significant influence on the results is that caused by net changes in forest carbon stocks. Their resulting influence on estimated GHG emissions associated with the subsequent use of a forest product (such as wood fuel for electricity generation as in this case) depends on the relatively complex interaction of a number of important factors:

- net carbon stock changes in the forest;
- overall productivity of the forest;
- specific composition of forest products;
- relative prices of forest products.

5.1.1 Net carbon stock changes in the forest

As explained previously, net carbon stock changes arise from different components of the forest and whether, over a given period, they are storing or emitting CO_2. This is determined by the essential features of each forest profile and the outcomes are summarised in Table 5.1.

The main features of variation arise directly from assumptions made as part of the extended $BEAT_2$ method as described in detail in Section 3, specifically:

- For forestry profiles involving conventional management for production, net carbon stock changes in standing trees in forests are estimated at zero over a rotation, regardless of the time horizon adopted for calculations (forestry profiles 1, 2, 7–9 and 12, Section 3.3).
- For forestry profiles involving conventional management for production where the assumption is made that production is a long-standing activity from forests that have been in existence for centuries, net carbon stock changes in soil and debris/litter under forests are also estimated at zero over a rotation, regardless of the time horizon adopted for calculations (forestry profiles 7–9 and 12, Section 3.3).
- For forestry profiles involving conventional management for production from forests that have been newly created in the recent past (generally one rotation ago), net carbon sinks in soil and debris/litter are estimated at between 200 and 1,500 $kgCO_2\text{-eq}\ ha^{-1}\ yr^{-1}$ over a rotation, regardless of the time horizon adopted for calculations (forestry profiles 1 and 2, Section 3.3). The magnitude of the soil and litter carbon sink depends to some

extent on the growth rate of the trees, but depends mainly on the texture of the soil, with the larger carbon sinks being associated with finer soil textures such as clays.

- For forestry profiles involving production from neglected/overstocked and old growth stands, net carbon emissions from soil, debris/litter and trees are estimated when a 20-year time horizon is adopted for calculations (forestry profiles 3, 5, 10 and 13, Section 3.7). The estimated net emissions are much smaller when a time horizon of 100 years is adopted for calculations because the longer time horizon covers the period over which carbon stocks recover as forest stands regrow.

All other things being equal, the higher the net carbon stock changes, the higher their effect on total GHG emissions per unit of electricity generated (expressed here in $kgCO_2$-eq ha^{-1} yr^{-1}) and vice versa.

Table 5.1: Net carbon stock change by forest profile

Forest profile	Net carbon stock change (kg CO_2/ha^{-1} yr^{-1})			
	Soil	Debris/litter	Remaining trees	Total
1	-1,503	-258	0	-1,245
2	-79	-155	0	-234
3	-4,346	-1,731	6,131	54
4	-1,723	-614	3,705	1,368
5	-7,468	1,070	36,565	28,027
6	-1,707	-44	871	-880
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	5,782	784	24,334	19,336
11	22	-1	395	416
12	0	0	0	0
13	938	863	29,110	30,911
14	-52	-2	114	60

5.1.2 Overall productivity of the forest

This factor is specifically in relation to the forest products that can be extracted for subsequent use. For current purposes, relevant forest products consist of sawn timber from sawlogs, roundwood and forest residues. Assumed values for forest productivity, expressed in annualised terms per unit area, are summarised in Table 5.2.

The main features of variation arise from the detailed assumptions made for each country profile regarding tree species, tree growth rate and management regime (Section 3 and Table 5.1) specifically:

- If forestry profiles calculated using a time horizon of 20 years are excluded (that is, specifically long-term productivity is considered), total biomass productivity is observed to be reasonably well correlated with the assumed growth rate (given in Table 4.1 as maximum stem volume productivity, Figure 5.1).

- It is possible to discern a secondary influence of conifer/broadleaf forest type on long-term biomass productivity (Figure 5.1), with greater biomass productivity potentially associated with broadleaf forests. Although volume growth rates of broadleaf forests tend to be lower than for conifer forests growing in a similar region, wood density (odt per m^3) tends to be greater. More importantly, an assumption was made in calculations using the CSORT model that a greater proportion of tree stemwood in broadleaf stands would be converted into roundwood and therefore available for utilisation as fuel (Table 3.3, Section 3).
- For forestry profiles involving production from neglected/overstocked and old growth stands, estimates of biomass productivity are generally large for the stated growth rate when a time horizon of 20 years is adopted for calculations (forestry profiles 3, 5, 10 and 13). The effect is more pronounced for cases involving clearfelling of old growth forests (forestry profiles 10 and 13) compared with clearfelling in neglected/overstocked forests (forestry profile 5) and the effect is marginal when harvesting involves thinning rather than clearfelling (forestry profile 3). The apparently high levels of biomass productivity are not observed when long-term productivity is considered over a 100-year time horizon (forestry profiles 4, 6, 11 and 14).

All other things being equal, the higher the forest productivity the lower will be the effect of net carbon stock changes on total GHG emissions per unit of electricity generated, and vice versa.

Uncertainties in carbon stock change estimates

A general point must be made about uncertainties in GHG balance estimates, particularly due to forest (tree, debris and soil) carbon stock changes. In many of the forestry profiles, the accumulation of carbon stocks due to forest growth are estimated to be very large; the reductions in carbon stocks due to harvesting or clearfelling of trees are also estimated to be large. An estimate of carbon stock changes for a given time horizon therefore usually involves calculating the difference between large accumulations and large reductions, with both terms in the subtraction subject to uncertainty. It follows that the resultant stock change estimates may involve significant uncertainties and, in some cases, it may not even be clear that the net outcome is an emission, a removal or indistinguishable from zero.

The estimates for carbon stock changes included in the forestry profiles considered in this study should be regarded as representative of the typical trends in forest carbon stocks likely to be observed in the example forestry systems considered. However, significant variation in these indicative results will occur depending on local circumstances (for example particular trees species, growth rates and soil types encountered within a particular region of a country) or differences in the details of management regimes practised in forests.

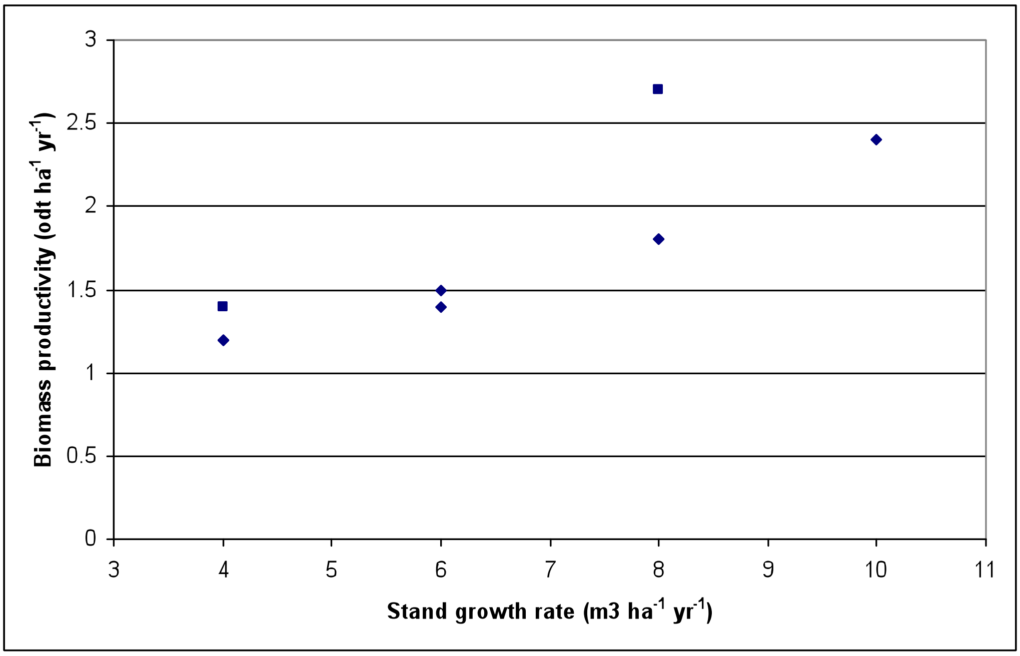

Figure 5.1: Analysis of biomass (wood fuel) productivity in relation to forest stand growth rate

Notes: Diamond symbols = conifer stands
Square symbols: broadleaf stands

Table 5.2: Assumed forest productivity by forest profile

Forest profile	Forest productivity (odt/ha.a)			
	Sawn timber from sawlogs	Roundwood	Forest residues	Total
1	0.8	1.2	0.4	2.4
2	0.2	0.9	0.3	1.4
3	0.7	2.1	0.0	2.8
4	1.2	1.5	0.0	2.7
5	0.7	1.0	0.0	1.7
6	0.4	0.8	0.0	1.2
7	0.4	0.6	0.2	1.2
8	0.2	0.7	0.3	1.2
9	0.7	0.5	0.2	1.4
10	2.5	3.6	1.7	7.8
11	0.5	0.7	0.3	1.5
12	0.0	1.4	0.4	1.8
13	0.2	7.1	2.1	9.4
14	0.0	1.4	0.4	1.8

5.1.3 Specific composition of forest products

In this context, this factor is determined by the amounts of relevant forest products (roundwood, or roundwood and forest residues) available for use in electricity generation relative to other forest products with other uses.

The estimated amounts of different forest products are shown in Table 5.2 and the relative proportions which are used in different electricity generation options are provided in Table 5.3. Note that only roundwood is used as fuel for the “timber” and "wood pellet" options, while roundwood and forest residues are used in the "wood chip" option. Forest residues are not generally used in pellet production due to the high proportion of bark, which leads to a high ash content. The major market for pellets is expected to be the domestic sector, where boilers have small combustion grates without automatic ash removal. High ash is not acceptable in these units due to clinkering and the need for excessive manual input from the owner.

As shown in Table 5.3, the analysis has included an assumption that a significant fraction of harvested wood will continue to supply the wood-based panel and board industries and sawn timber industries. The utilisation of wood in these industries also involves greenhouse gas impacts, often beneficial. These impacts are not estimated as part of this analysis as it is beyond the scope of the study and could potentially lead to misrepresentation of the impacts due to the use of wood as fuel (for example, this might occur if the benefits due to use of wood in other sectors were also counted). However the potential for additional impacts on greenhouse gas emissions due to utilisation of some harvested wood for non-energy purposes should be noted.

All other things being equal, the higher the proportion of forest products used for electricity generation, the higher the effect of net carbon stock changes on total GHG emissions per unit of electricity generated, and vice versa.

Table 5.3: Proportion forest products used for electricity generation by forest profile and wood fuel option

Forest profile	Wood fuel as a proportion of forest products by option (%)		
	Timber	Wood chips	Wood pellets
1	50	67	50
2	57	86	57
3	75	75	75
4	55	55	55
5	59	59	59
6	67	67	67
7	50	67	50
8	58	83	58
9	36	50	36
10	46	68	46
11	47	67	47
12	78	100	78
13	76	98	76
14	78	100	78

5.1.4 Relative prices of forest products

Forest products are in effect co-products and therefore it is necessary to allocate all relevant GHG emissions, including those from net carbon stock changes, between them.

The allocation procedure used in $BEAT_2$ is based on relative value, which depends on the relative amounts of forest products and their relative prices. Table 5.4 summarises the relative prices for sawn timber from sawlogs, roundwood and forest residues adopted for softwood (all conifer forest profiles) and hardwood (all broadleaf forest profiles). Assumptions about prices were based on informal commercial data obtained as part of management of Forestry Commission woodlands.

All other things being equal, the higher the prices of roundwood, or roundwood and forest residues, relative to the price of sawlogs, the higher the effect of net carbon stock changes on total GHG emissions per unit electricity generated, and vice versa.

The combined influence of the proportions of forest products and their relative prices for the different electricity generation options is demonstrated in Table 5.5.

Table 5.4: Prices of forest products by forest profile

Forest profile	Forest product prices (£ per odt)		
	Sawn timber from sawlogs	Roundwood	Forest residues
1	276	38	19
2	509	42	14
3	509	42	14
4	509	42	14
5	509	42	14
6	509	42	14
7	276	38	19
8	509	42	14
9	276	38	19
10	276	38	19
11	276	38	19
12	276	38	19
13	276	38	19
14	276	38	19

Table 5.5: Allocation to forest products used for electricity generation by forest profile and wood fuel option

Forest Profile	Percentage of total GHG emissions allocated to wood used as fuel (%)		
	Timber	Wood chips	Wood pellets
1	16	18	16
2	22	24	22
3	19	19	19
4	10	10	10
5	10	10	10
6	14	14	14
7	16	18	16
8	23	26	23
9	8	10	8
10	16	20	16
11	16	20	16
12	6	8	6
13	10	12	10
14	10	12	10

5.2 Illustrative results for sustainably managed forests

The estimated total GHG emissions from electricity generation using wood chips, wood pellets and roundwood (timber) from UK sustainably managed coniferous and broadleaf forests are shown in Figure 5.2. For these sustainably managed forests the results are the same which ever time horizon (20 or 100 years) is considered, thus only one set of results is presented. In each case it is assumed that the forest is allowed to grow back after felling and does not suffer losses from disease or fire.

For parameters that $BEAT_2$ users can vary, the results are based on the default values in $BEAT_2$. These are intended to represent 'good practice'; a full list of the default values is given in Appendix 1.

GHG emissions associated with 'cultivation' (that is regeneration, harvesting and extraction) are based on values produced by the CSORT model (as described earlier). A full set of the results from $BEAT_2$ using default values for all forest profiles, and for wood chips, wood pellets and roundwood are included in Appendix 1.

The results show that wood sourced from these sustainably managed forests offers substantial GHG emissions savings compared to average EU electricity generation.[3] Negative values arise for some types of wood fuel because the net increase in carbon stocks in these forests is so large that it more than compensates for the GHG emissions from cultivation, processing and transport of the feedstock.

For example, for coniferous wood chips (the most common fuel form for electricity generation at present), total GHG emissions are -53 kg CO_2 eq/MWh, giving savings of around 107 per cent compared to average EU generation. The main contributions to emissions are from cultivation and from the conversion of the feedstock to electricity. Within the cultivation stage, the main source of GHG emissions is diesel fuel used in forest operations, though fencing and herbicides also contribute. GHG emissions from the conversion stage are due to emissions from power plant construction and maintenance of the power station, though there are also emissions of methane and nitrous oxide when the wood is combusted.

Emissions associated with the use of roundwood are slightly lower because there is less processing of the timber and lower losses of wood along the supply chain. In the case of wood pellets, total GHG emissions are higher but at 83 CO_2 eq/MWh still give savings of 88 per cent compared to average EU generation. The higher GHG emissions are mainly due to the additional energy required to pelletise the wood; emissions from cultivation are also slightly higher, as more losses during the processing chain mean more roundwood must be grown than when roundwood is used directly. This increase is partially offset by the fact that the carbon sink allocated to the pellets is higher because more timber must be harvested.

In the case of broadleaf forests, there is still an accumulation of carbon in the forest but it is not as large and so does not completely negate GHG emissions from other stages of the biomass pathway (details of these important carbon stock changes are provided in Section 3.3). GHG emissions from cultivation are, however, lower than for coniferous forests compared to average EU generation so that overall GHG emissions are fairly low (for example 69 CO_2 eq/MWh for chips) and savings are still substantial – 90 per cent for wood chips and 93 per cent for roundwood. In the case of pellets, processing emissions are higher (as discussed above) and savings fall to 69 per cent.

[3] The value of 713 kg CO_2 eq per MWh of electricity to represent average generation in the EU is taken from the European Commission's recent report on the sustainability requirements for the use of solid and gaseous biomass sources (European Commission 2010). It is not a full life cycle value. For comparison, the average life cycle value for electricity from the UK grid (as calculated for $BEAT_2$) is 571 CO_2 eq per MWh and the value for electricity from a combined cycle gas turbine (CCGT) fired with natural gas is 387 CO_2 eq per MWh.

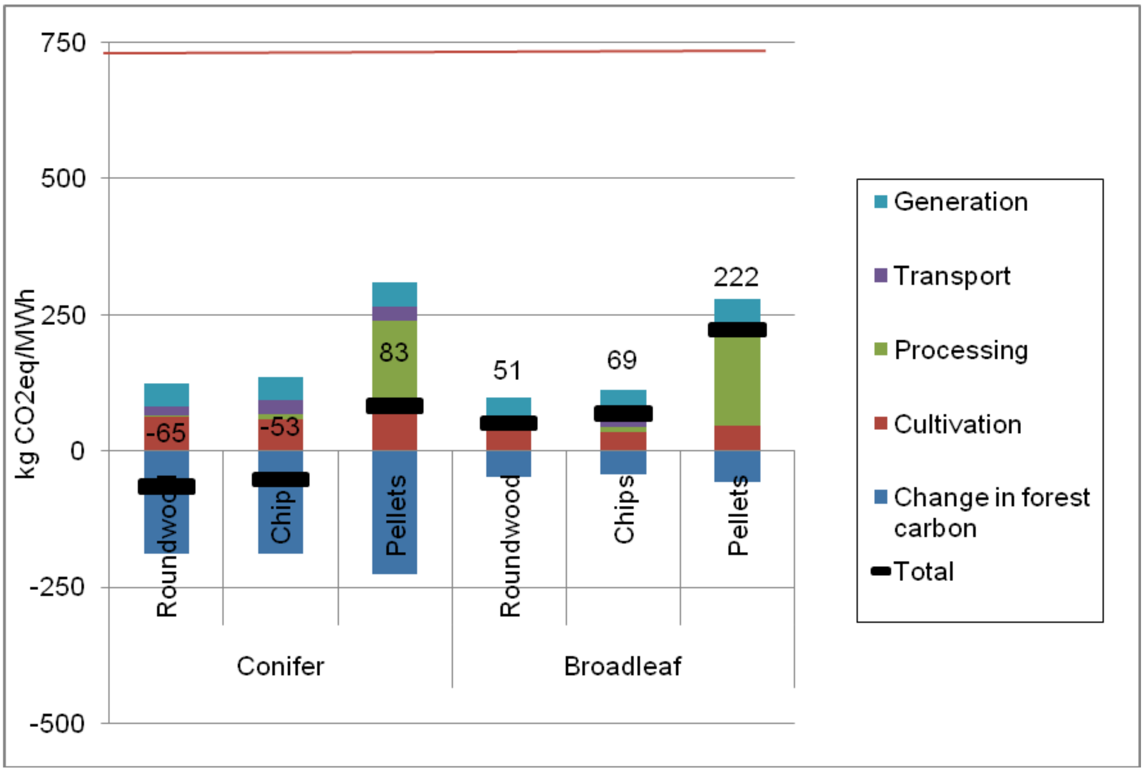

Figure 5.2: GHG emissions of electricity generated from UK sustainably-managed forests (forest profiles 1 and 2)

Note: The estimated errors in total GHG emissions for conifer are ±17, 15 and 33 kg CO2 eq/MWh for roundwood, chips and pellets respectively. For broadleaf, errors are ±10, 9 and 29 kg CO_2 eq/MWh for roundwood, chips and pellets respectively.

Figure 5.3 shows the total GHG emissions associated with electricity generation from wood chips from sustainably managed forests in a number of different countries. As discussed in Section 3.3, the stands under conventional management in the Baltic States and Fennoscandia, Boreal North America and Boreal Eurasia belong to long established forest areas which are into their third or subsequent rotation. It was therefore assumed that there was no increase in the carbon in the litter and soil in these forests, and as the change in carbon stocks in the trees is also assumed to be zero (as it is for UK sustainably managed forests), there is no change in forest carbon. In contrast, stands in UK forests are assumed to be in their second rotation, and over this rotation there is an increase in carbon in litter and soil. Once again the choice of time horizon makes no difference to the results.

GHG emissions for generation from wood from sustainably managed forests in the Baltic States and Fennoscandia, Boreal North America and Boreal Eurasia are therefore higher than for wood from UK forests. This is not only because transport emissions are higher but also mainly because the greater age of the non-UK forests means that there is no increase in the carbon stock in the forest to offset emissions from processing and transport. GHG emissions from cultivation are very similar in all countries.

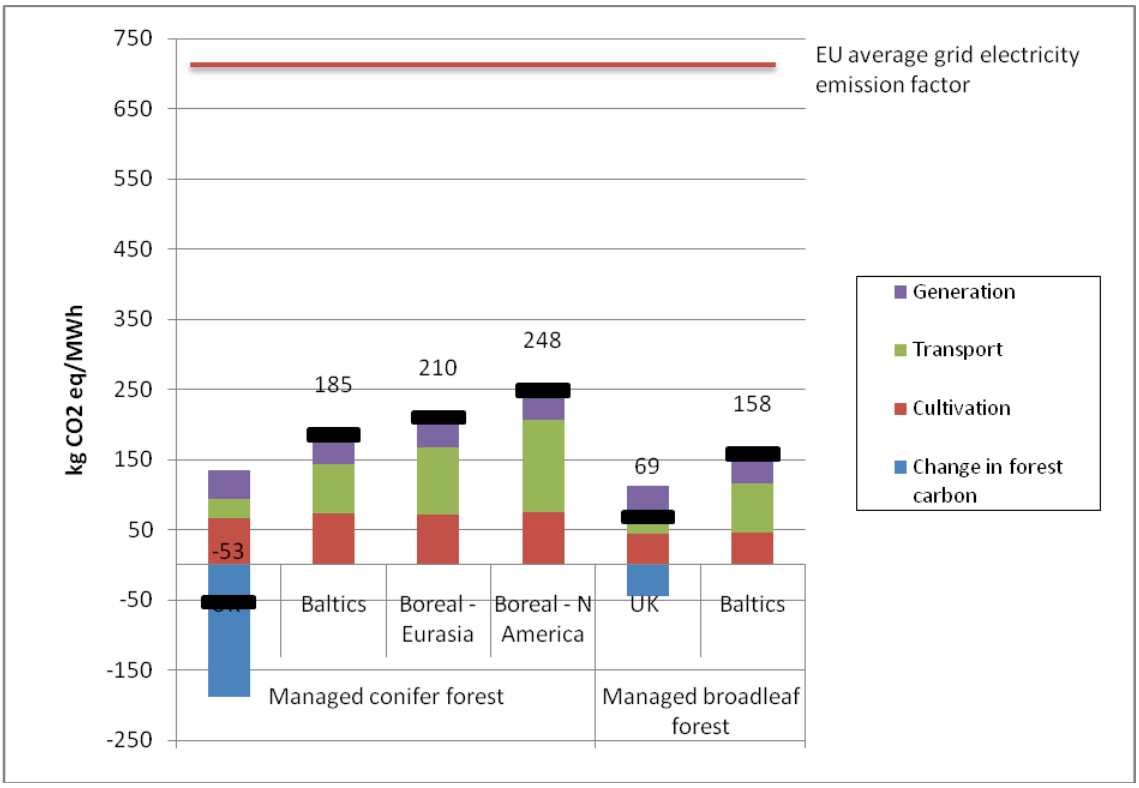

Figure 5.3: GHG emissions of electricity generated from sustainably-managed forests (forest profiles 1, 2, 7, 8, 9 and 12)

Note: The estimated errors in total GHG emissions for conifer are ± 15, 16, 16 and 17 kg CO_2 eq/MWh for UK, Baltics, Boreal Eurasia and Boreal North America respectively. The estimated errors in total GHG emissions for broadleaf are ± 9 kg CO_2 eq/MWh for the UK and the Baltics respectively.

5.3 Illustrative results for neglected UK woodland

Two methods of extracting wood fuel from neglected broadleaf woodland in the UK and returning them to productive use were considered:

- thinning and no felling;
- felling for initial clearance.

Figure 5.4 shows that, when considered over the short-term (20-year time horizon), the felling management option causes a very large reduction in carbon stock in the forest as mature trees are removed, leading to extremely large total GHG emissions of 2,923 kg CO_2 eq/MWh (over four times the average emissions from EU electricity). Over the longer term (100-year time horizon), the recovery of carbon stocks can result in an increase in carbon stock which is substantial enough to almost offset the GHG emissions from processing and transport leading to a very small net GHG emission of 6 kg CO_2 eq/MWh.

In the ‘no felling case’, the thinning process gives a much slower rate of loss of carbon stocks leading to only a small reduction in the forest carbon over the 20-year time horizon (equivalent to 4 kg CO_2 eq/MWh). However, the cumulative effect of progressive thinnings over a 100-year time horizon results in higher emissions, even though carbon stocks are being replenished as trees regenerate, with a net change in carbon stocks over 100 years equivalent to emissions of 79 kg CO_2 eq/MWh.

The thinning but no felling' option still gives significant savings though of 83 per cent over a 20-year time horizon and 72 per cent over a 100-year time horizon compared to EU average electricity generation.

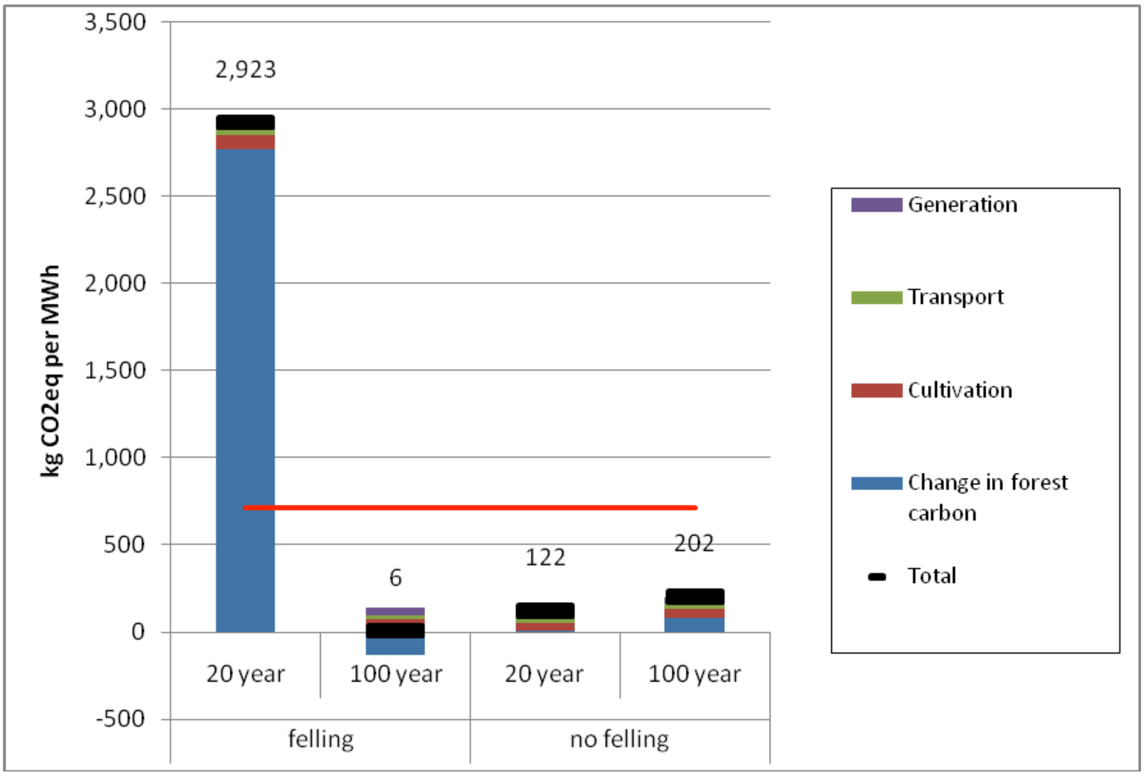

Figure 5.4: GHG emissions of electricity generation from wood chips obtained from neglected UK broadleaf forests (forest profiles 3, 4, 5 and 6)

Note: The estimated errors in total GHG emissions are 11, 12, 19 and 17 kg CO_2 eq/MWh for felling (20-year time horizon), felling (100-year time horizon), no felling (20-year time horizon) and no felling (100-year time horizon) respectively.

5.4 Illustrative results for old growth forests

In the case of wood chips produced by clear felling old growth forests in Boreal Eurasia and Boreal North America (Figure 5.5), there is a very large change in carbon stock over the short term leading to very high GHG emissions per MWh, which are greater than the average emissions associated with electricity generated for the EU grid. This is mainly due to the removal of carbon in the trees that have been clear felled and because 20 years after felling the stand has not regenerated significantly.

In the case of old growth Boreal Eurasian forests, even when considered over 100 years, the reduction in forest carbon stock accounts for about a quarter of overall emissions, which at 280 kg CO_2 eq/MWh gives savings of 61 per cent compared to the EU grid average. In the case of Boreal North America, the reduction in carbon stocks is much less than estimated for the Boreal Eurasian forests (37 compared to 76 kg CO_2 eq/MWh) due to the assumption that regeneration of the succession stand will be entirely left to natural processes in the Boreal Eurasia case (profile 10), while for Boreal North America, it is assumed that the forest is regenerated through active management and thus happens more quickly. As in the examples shown in Section 5.3, this shows the importance of the type of forest management on changes in carbon stock and, hence, on GHG emissions.

Transport emissions (131 kg CO_2 eq/MWh) are the most significant contribution to the overall emissions from using wood chip from Boreal North America old growth forest, accounting for just over half of total GHG emissions. Overall savings compared to the EU grid average are 61 per cent.

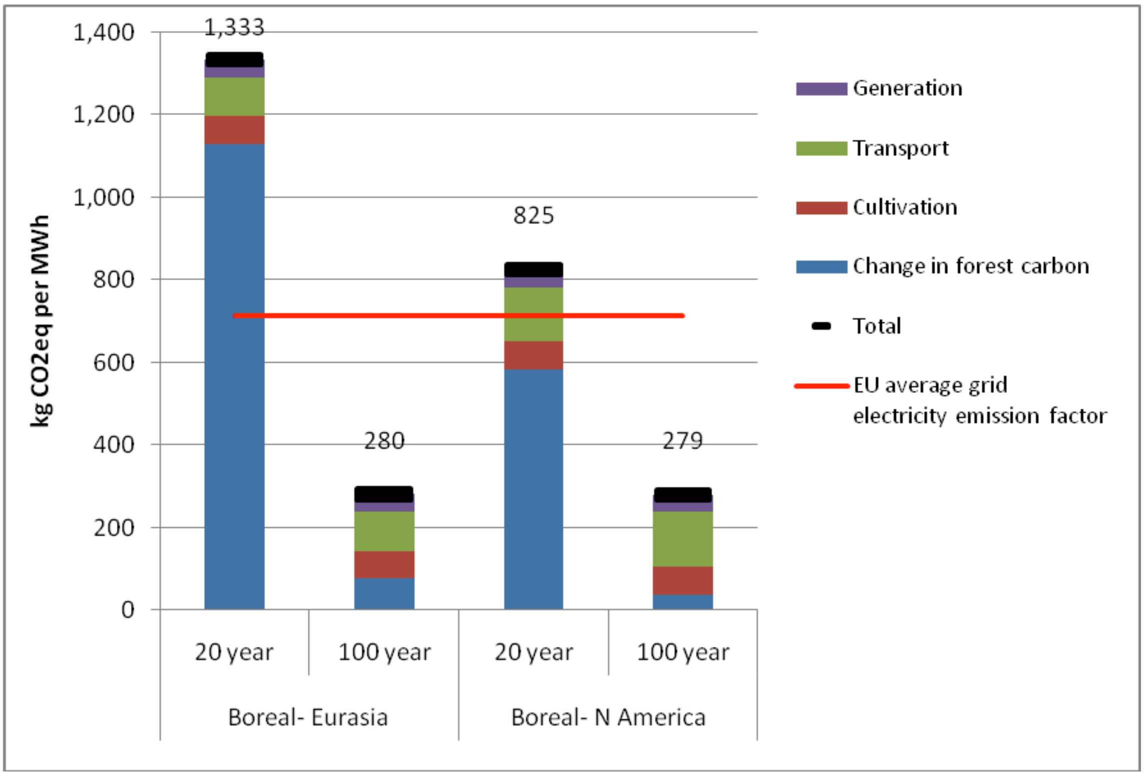

Figure 5.5: GHG emissions for electricity generation from wood chips obtained from old growth forests

Note: The estimated errors in total GHG emissions are 15 kg CO_2 eq/MWh for all profiles.

6 Conclusions and recommendations

A significant range of forest types and management practices for the UK and other major potential international suppliers of woody biomass for the UK have been simulated using the CSORT model, incorporated into three workbooks representing electricity only generation from timber (roundwood), wood chips and wood pellets, and included in $BEAT_2$.

The report presents details of these forest types and management practices for 14 selected forest profiles, and describes in depth, the variations of carbon stocks over time (simulated by the CSORT model). In addition the report explores and summarises the interplay of major factors, such as:

- net carbon stock changes;
- annualised forest productivity for different products;
- allocation by means of the values (price x amount) of these products.

Illustrative results based on the default values in the extended version of $BEAT_2$ are presented for:

- sustainably managed forests in the UK, Baltic States and Fennoscandia, Boreal Eurasia and Boreal North America;
- neglected UK forests which can be brought back into production in various ways;
- old growth forests in Boreal Eurasia and Boreal North America.

These illustrative results demonstrate that the type of forest management and the age of the forest are important determinants of overall GHG emissions. For each time horizon it is assumed that the forest is allowed to grow back after felling and does not suffer losses from disease or fire.

For sustainably managed forests, the time horizon over which emissions are evaluated does not influence the emissions. However, the time horizon chosen is critical when evaluating emissions from old growth forests and neglected forests being brought back into productive use.

- GHG emissions from electricity generation with roundwood (timber) and wood chips from sustainably managed coniferous and broad leaf forests in the UK and abroad are in the range of -65 to 258 kg CO_2 eq/MWh, and offer substantial savings (of at least 65 per cent) compared to the average GHG emissions of 713 kg CO_2 eq per MWh (European Commission 2010) associated with electricity generation in the EU.
- Savings from the use of pellets are lower due to the additional energy needed to dry and process the wood into pellets. For pellets from sustainably managed forests, GHG emissions range from 83 to 442 kg CO_2 eq/MWh, giving net GHG emissions savings of 84 to 35 per cent. These GHG emissions could be reduced if wood fuel was used to supply the heat needed to dry wood prior to pelletisation rather than fossil fuels.
- The range in fuel values from sustainably managed forests is mainly the result of differences in the change in carbon stock, which is due to differing ages of the forests considered. For older forests, where the stand from

which wood is obtained may be in at least its third rotation, there is generally no increase in carbon in the soil and litter over the rotation period. This was assumed to be the case for forests in Baltic States and Fennoscandia, Boreal Eurasia and Boreal North America. In contrast, forests in the UK are often younger, with stands more typically in their second rotation, so that carbon in the soil and litter does increase over the period of the rotation. GHG emissions associated with electricity production are therefore lower when wood comes from sustainably managed forests in the UK than from older sustainably managed forests in the other countries considered where, as well as no 'offset' from an increase in carbon stock, GHG emissions from the transport stage are higher. In the case of the UK coniferous forest example, if wood is supplied as wood chips or roundwood, the increase in carbon stocks is enough to more than offset the GHG emissions associated with all other stages (cultivation, processing, transport and generation) and so savings are over 100 per cent.

- In the case of UK neglected forests that are brought back into productive use, emissions are heavily dependent on the time horizon over which changes in carbon stock are evaluated and on the method used to regenerate the forest.
  - Where the forest is regenerated by progressive thinning, then (for wood chips) savings are 83 per cent when evaluated over a 20-year time horizon but fall to 72 per cent when evaluated over a 100-year time horizon. This is because the carbon stock of the forest continues to diminish as more carbon is removed in the thinnings than is increased in the regenerating trees.
  - Where restoration is by felling, GHG emissions are extremely high (more than four times average emissions from EU electricity generation) when evaluated over a 20-year time horizon due to the removal of carbon from the forest in the felled trees. However, by 100 years, the forest has regenerated such that the carbon stock has increased and net GHG emissions for electricity generation are almost zero.
- The time horizon over which emissions for electricity from wood from old growth forests is evaluated is also critical. The clear felling policy assumed as a typical management profile for these forests means that, over a 20-year time horizon, GHG emissions from these forests are extremely high - typically one and a half times those associated with average electricity production in the EU. Over a 100-year time horizon, however, when the forest has regenerated, savings are about 61 per cent (for wood chips and roundwood) and 34 per cent for wood pellets. For Boreal North America, where regeneration of the forest is assumed to be managed, this is close to the savings from sustainably managed forests.

In summary it can be concluded that (based on typical values):

- Electricity produced from wood chips and roundwood (timber) from sustainably managed forests in the UK and abroad, and from UK neglected forests regenerated through thinning but no felling, offers substantive savings (of at least 60 per cent). There is a considerable range in the savings and some forest profiles offer very high savings (80 to over 100 per cent).
- If electricity is produced from pellets from sustainably managed forests in the UK and abroad, and from UK neglected forests regenerated through thinning but no felling, then savings are considerably reduced (38–88 per

cent). These savings are based on using fossil fuel to dry the wood prior to pelletisation and would be higher if wood fuel was used to dry the wood.

- Emissions from forests where wood is extracted by clear felling (old growth forests in Boreal Eurasia and Boreal North America, and UK neglected forests regenerated by clear felling) have very high emissions and offer no savings when evaluated over the short term (20-year time horizon). Over a 100-year time horizon, when the forest has regenerated and carbon stocks have grown again, emissions are much closer to those from sustainably managed forests, and for chips and roundwood are all greater than 60 per cent.

The following recommendations are made concerning the further extension of $BEAT_2$ to accommodate different forest types and management practice:

- Other types and locations of forests could be considered, especially if new proposals are put forward to import biomass into the UK from other countries in the future. The incorporation of further forestry options in $BEAT_2$ should be reasonably straightforward given the work carried out to develop the method for including the forestry options described in this report and the related integration of CSORT model outputs.
- The addition of an option for drying of wood prior to pelletisation using wood fuel, rather than fossil fuel, would allow the impact of this type of drying to be fully evaluated.
- Further workbooks can readily be developed from the new workbooks developed in this study to address other applications for these biomass feedstocks. These include:
  - electricity generation by co-firing in existing coal-fired power plants;
  - electricity generation by gasification and pyrolysis in dedicated biomass power plants;
  - combined heat and power generation by combustion, gasification and pyrolysis in dedicated biomass plants.

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Appendix 1: Illustrative input values and results

Table A.1: Provision of wood chips

Parameter	Default value	Data type/units
Wood processing parameters		
Moisture content of roundwood after roadside drying	35	% by weight
Drying system	natural	bulk drying, batch drying, continuous drying and cooling, natural drying and storage.
Days in storage	40	days
Moisture content of stored forest products after drying	25	% by weight
Ash content of stored forest products	0.4	% by weight (odt)
Losses roundwood roadside drying	1	%
Losses chipping roundwood	5	%
Losses drying and storage	0	%
Prices used for allocation (need to have hardwood and softwood prices as in pellets)		
Price of waste wood and needles (softwood)	0	£/tonne
Price of harvested branch wood (softwood)	19	£/tonne
Price of harvested roundwood (softwood)	38	£/tonne
Price of sawn timber (softwood)	276	£/tonne
Price of waste wood (hardwood)	0	£/tonne
Price of harvested branch wood (hardwood)	14	£/tonne
Price of harvested roundwood (hardwood)	42	£/tonne
Price of sawn timber (hardwood)	509	£/tonne
Transport parameters		
Transport mode – transport of branch wood to chipping plant	road	road/rail/ barge/ship
Average round trip distance – transport of branch wood to chipping plant	90	km
Transport mode – transport of branch wood chips to storage	road	road/rail/ barge/ship
Average round trip distance – transport of branch wood chips to storage	90	km
Transport mode – transport of waste wood chunks to chipping plant	road	road/rail/ barge/ship
Average round trip distance – transport of waste wood chunks to chipping plant	90	km
Transport mode – UK port to power station	road	road/rail/ barge/ship
Average round trip distance – transport of wood chips from UK port to power station	90	km
Losses – transport from UK port to power station	3	%
Reference round trip distance for disposal to landfill with waste recovery	100	km

Parameter	Default value	Data type/units
Transport mode – transport of waste wood chips to storage	road	road/rail/ barge/ship
Average round trip distance – transport of waste wood chips to storage	90	km
Round trip distance for disposal of losses from waste wood chipping	100	km

Table A.2: Provision of wood pellets

Parameter	Default value	Data type/units
Wood processing parameters		
Moisture content of roundwood after roadside drying	35	% by weight
Losses during roadside drying (e.g. spoilage)	1	%
Drying system	bulk	bulk/batch/ continuous/natural
Days in storage	40	
Moisture content after storage (pre-milling)	10	% by weight
Losses during chipping of roundwood	5	%
Losses during milling	3	%
Losses during pelleting	3	%
Losses during drying and storage	0	%
Ash content of stored wood	0.5	% by weight (odt)
Prices used for allocation		
Price of waste wood and needles (softwood)	0	£/tonne
Price of harvested branch wood (softwood)	19	£/tonne
Price of harvested roundwood (softwood)	38	£/tonne
Price of sawn timber (softwood)	276	£/tonne
Price of waste wood (hardwood)	0	£/tonne
Price of harvested branch wood (hardwood)	14	£/tonne
Price of harvested roundwood (hardwood)	42	£/tonne
Price of sawn timber (hardwood)	509	£/tonne
Transport parameters		
Transport mode – transport of roundwood to chipping plant	road	road/rail/barge/ship
Average round trip distance – transport of roundwood to chipping plant	90	km
Losses – transport of roundwood to chipping plant	3	%
Transport mode – transport of chips to pelleting plant	road	road/rail/barge/ship
Average round trip distance – transport of chips to pelleting plant	90	km
Losses – transport of chips to pelleting plant	3	%
Transport mode – transport of pellets from UK port to power station	road	road/rail/barge/ship
Average round trip distance – transport of pellets from UK port to power station	90	km
Losses – transport of pellets from UK port to power station	3	%

Table A.3: Provision of roundwood

Parameter	Default value	Data type/units
Wood processing parameters		
Ash content of stored wood	0.4	% by weight (odt)
Moisture content of roundwood after roadside drying	35	% by weight
Losses during roadside drying (e.g. spoilage)	1	%
Drying system	natural	bulk/batch/ continuous/natural
Days in storage	40	
Moisture content after storage	25	% by weight
Moisture content of timber when combusted	10	% by weight
Losses during drying and storage	0	%
Prices used for allocation		
Price of waste wood and needles (softwood)	0	£/tonne
Price of harvested branch wood (softwood)	19	£/tonne
Price of harvested roundwood (softwood)	38	£/tonne
Price of sawn timber (softwood)	276	£/tonne
Price of waste wood (hardwood)	0	£/tonne
Price of harvested branch wood (hardwood)	14	£/tonne
Price of harvested roundwood (hardwood)	42	£/tonne
Price of sawn timber (hardwood)	509	£/tonne
Transport parameters		
Transport mode – transport of roundwood to storage	road	road/rail/ barge/ship
Average round trip distance – transport of roundwood to storage	90	km
Losses – transport of roundwood to storage	0	%
Transport mode – transport of timber from UK port to power station	road	road/rail/ barge/ship
Average round trip distance – transport of timber from UK port to power station	90	km
Losses – transport of timber from UK port to power station	3	%

Table A.4: Country-specific transport parameters

Country	Round trip distance to port (km)	Round trip shipping distance to the UK (km)
Baltic States and Fennoscandia	100	3,600
Boreal North America	200	9,220
Boreal Eurasia	200	5,360

Table A.5: Electricity power plant combustion

Parameter	Default value	Data type/units
Size of plant (thermal input rating)	40	MWth
Net generating efficiency	25	%
Lifetime of plant	25	years
Annual load factor	85	%
Average energy consumption per start-up	57.6	GJ/start up
No of start up operations per year	6	per year
Round trip distance for ash disposal	100	km
Allow for ash displacing application of lime to land	yes	yes/no

Table A.6: Greenhouse gas emissions (kg CO2e/MWh electricity generated) using values listed above (and as used in graphs in report)

Forestry profile no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Results for roundwood														
Change in forest carbon	-189	-47	4	70	2,450	-118	0	0	0	1,191	80	0	632	40
Provision of feedstock	63	38	36	40	63	54	70	40	77	70	70	95	77	77
Processing of feedstock	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Transport of feedstock	16	16	16	16	16	16	58	58	83	83	83	119	119	119
Conversion of feedstock to electricity	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**-65**	**51**	**100**	**171**	**2,574**	**-3**	**173**	**143**	**205**	**1,389**	**278**	**258**	**873**	**280**
% saving compared to EU average grid	**109**	**93**	**86**	**76**	**no saving**	**100**	**76**	**80**	**71**	**no saving**	**61**	**64**	**no saving**	**61**
Results for wood chips														
Change in forest carbon	-189	-44	4	79	2,774	-134	0	0	0	1,129	76	0	582	37
Provision of feedstock	58	35	40	45	72	62	64	36	63	58	58	66	60	60
Processing of feedstock	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Transport of feedstock	26	26	26	26	26	26	70	70	95	95	95	131	131	131
Conversion of feedstock to electricity	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**-53**	**69**	**122**	**202**	**2,923**	**6**	**185**	**158**	**210**	**1,333**	**280**	**248**	**825**	**279**
% saving compared to EU average grid	**107**	**90**	**83**	**72**	**no saving**	**99**	**74**	**78**	**71**	**no saving**	**61**	**65**	**no saving**	**61**
Results for wood pellets														
Change in forest carbon	-225	-56	5	84	2,916	-140	0	0	0	1,418	95	0	753	47
Provision of feedstock	75	45	42	48	76	65	83	48	91	83	83	113	92	92
Processing of feedstock	164	164	164	164	164	164	175	175	175	175	175	175	175	175
Transport of feedstock	26	26	26	26	26	26	62	62	83	83	83	112	112	112
Conversion of feedstock to electricity	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Total	**83**	**222**	**280**	**364**	**3,225**	**157**	**363**	**327**	**391**	**1,801**	**478**	**442**	**1,174**	**469**
% saving compared to EU average grid	**88**	**69**	**61**	**49**	**no saving**	**78**	**49**	**54**	**45**	**no saving**	**33**	**38**	**no saving**	**34**

Table A.7: Estimated errors for values in table of results above (kg CO2e/MWh electricity generated)

Forestry profile no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Results for roundwood														
Change in forest carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provision of feedstock	17	10	10	11	17	15	19	11	20	19	19	25	21	21
Processing of feedstock	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transport of feedstock	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Conversion of feedstock to electricity	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**17**	**10**	**10**	**11**	**17**	**15**	**19**	**11**	**21**	**19**	**19**	**25**	**21**	**21**
Results for wood chips														
Change in forest carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provision of feedstock	15	9	11	12	19	17	17	10	17	15	15	18	16	16
Processing of feedstock	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Transport of feedstock	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Conversion of feedstock to electricity	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**15**	**9**	**11**	**12**	**19**	**17**	**16**	**9**	**16**	**15**	**15**	**17**	**15**	**15**
Results for wood pellets														
Change in forest carbon	20	12	11	13	20	17	22	13	24	22	22	30	25	25
Provision of feedstock	20	12	11	13	20	17	22	13	24	22	22	30	25	25
Processing of feedstock	33	33	33	33	33	33	35	35	35	35	35	35	35	35
Transport of feedstock	1	1	1	1	1	1	1	1	2	2	2	2	2	2

Conversion of feedstock to electricity	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Ash disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**33**	**29**	**29**	**30**	**34**	**32**	**36**	**31**	**37**	**36**	**36**	**41**	**38**	**38**

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