Department
of Energy &
Climate Change

Life Cycle Impacts of Biomass Electricity in 2020

Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK

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Executive Summary

1. Bioenergy is expected to contribute significantly to the UK's target for renewable sources to represent at least 15% of total energy consumption by 2020 (as required by the EU Renewable Energy Directive 2009/28/EC). It has been estimated that by 2020, between 3.4 and 7.5% of the UK's projected energy consumption will be generated from biomass, and the UK will require 12.9 to 23.5 Modt/y of solid biomass for energy, of which 9.0 to 16.0 Modt/y will be used for electricity generation.
2. Under the Climate Change Act of 2008, the UK must reduce its greenhouse gas (GHG) emissions by at least 80% on 1990 levels, by 2050. The UK Government therefore committed in its 2012 Bioenergy Strategy to support bioenergy that delivers genuine carbon reductions and helps to meet the UK's decarbonisation targets (DECC, DfT and DEFRA, 2012).
3. To inform policy and decision making, the overall GHG emissions associated with the delivered bioenergy can be estimated using the technique of Life Cycle Assessment (LCA). In August 2013, DECC published sustainability criteria for biomass feedstocks supported under the Renewable Obligation (RO), stating that by 2020, electricity from solid biomass subsidised by the RO must be proven to generate electricity with a GHG emission intensity under 200 kg CO_2e/MWh[1] (DECC, 2013a), calculated based on the LCA methodology[2] set out in Annex V of the EU Renewable Energy Directive (2009/28/EC)[3]. This intensity is lower than that of electricity generated from fossil fuels in the UK (*e.g.* ~ 437 kg CO_2e/MWh for electricity from natural gas, ~ 1018 kg CO_2e/MWh for electricity from coal; DUKES, 2013; DEFRA, 2013)[4], but higher than other renewables (*e.g.* 3 to 41 kg CO_2e/MWh for electricity from wind; Turnconi *et al.*, 2013). The Renewable Energy Directive LCA methodology considers the emissions from the cultivation, harvesting, processing and transport of the biomass feedstocks. It also includes direct land use change where the land use has changed category since 2008, *e.g.* from forest to annual crop land, grassland to annual crop land. However, the Renewable Energy Directive LCA methodology does not account for changes in the carbon stock of a forest, foregone carbon sequestration of land, or indirect impacts on carbon stocks in other areas of land.
4. If the carbon stored in a forest reduces, carbon dioxide (CO_2) is released to the atmosphere, whereas if the carbon stock of a forest increases, CO_2 is removed from the atmosphere and sequestered as biomass in the forest. These CO_2 fluxes can be significant; as a result the UK is committed to the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD)[5]. Recent reports have shown that the above factors

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[1] The unit kg CO_2e/MWh is equivalent to g CO_2e/kWh.

[2] As recommended by the European Commission in their 2010 report on biomass sustainability (European Commission, 2010).

[3] Electricity generators can report their bioenergy GHG emissions using the UK Solid and Gaseous Biomass Carbon Calculator. The purpose of the calculator is to demonstrate compliance with the EU Renewable Energy Directive (2009/28/EC), and therefore factors beyond the scope of the Renewable Energy Directive LCA methodology are not accounted for.

[4] Includes emissions at the point of generation, as well as those emitted prior to the point of generation, including those from extracting and transforming the primary energy source into the energy carrier, and distributing the fuel; emissions from the production of vehicles, machinery or infrastructure are not included.

[5] A financial value is created for the carbon stored in forests in developing countries, offering incentives for these countries to reduce emissions from forested lands.

omitted in the Renewable Energy Directive LCA methodology can have significant impacts on the total GHG intensities of some types of bioenergy feedstocks, and therefore need to be considered if we wish to understand the true GHG intensities of different bioenergy feedstocks and technologies (Agostini *et al.*, 2013; European Environment Agency, 2011; Mitchell *et al.*, 2012; Guest *et al.*, 2013; Repo *et al.*, 2010; Baral and Malins, 2014; Daigneault *et al.*, 2012).

5. Energy resources are limited, therefore as well as determining the GHG emissions associated with bioenergy, policy-makers and decision-makers may also wish to understand the additional energy input required by a bioenergy scenario in order to deliver the final energy output.

6. Industry indicates that a large proportion of the feedstock used for electricity generation in the UK in 2020 is likely to be imported from North American forests (NNFCC, 2013). The aims of this report are therefore to:

- quantify the woody biomass resources that are likely to be available for pellet production from forests in North America by 2020;
- estimate the GHG emission intensities (in kg CO_2e/MWh delivered energy) of using these resources for electricity generation in the UK, accounting for the impacts omitted by the EU RED methodology (emissions or sequestration from carbon stock changes on the land, foregone carbon sequestration, and indirect impacts); and
- estimate the Energy Input Requirements (EIR) (in MWh energy input per MWh delivered energy) of using these resources for electricity generation in the UK and compare to other electricity generating technologies. The energy input is considered to be energy carriers which are ready for final use, *e.g.* electricity, diesel, natural gas, fuel oil. The primary energy of the biomass is not included as an energy input in the calculation, just as the energy in the wind, sunshine, or nuclear fuel is not included in the Energy Input Requirement for wind, solar and nuclear technologies.

7. Scenarios have been constructed to represent North American woody feedstocks that are currently used for the production of woody pellets (*e.g.* pellets from saw-mill residues, beetle-killed trees, and pulpwood), as well as potential future scenarios that might conceivably come to pass in a world with an increased demand for biomass (*e.g.* pellets from wood derived from new, dedicated plantations). We have included a wide range of scenarios, including some that may not necessarily be likely; environmental, economic and social factors will all play a part in determining which of these scenarios could play out in the future. Our intention is to shed light on which scenarios are potentially satisfactory (from the points of view of GHG intensity and EIR) and which scenarios are potentially not satisfactory, so as to guide and justify future policy decisions. A literature review was conducted to estimate the likely available resource of each scenario by 2020, and DECC's Biomass Emissions And Counterfactual Model (BEAC) was used to estimate the GHG intensity and EIR of each scenario, taking into account the counterfactual land use for each scenario, *i.e.* what the land would be used for if it were not used to grow the bioenergy feedstocks. We first summarise our findings for scenarios involving woody residues, then summarise our findings for scenarios involving roundwood and energy crops.

Woody Residues

GHG Intensity for Scenarios Involving Woody Residues

8. Currently, a major feedstock for the production of North American wood pellets is woody residues (*e.g.* saw-mill residues, forest residues, or trees killed by natural disturbances). The projected resource of these feedstocks that may be available by 2020, along with their GHG intensities when used for dedicated electricity generation in the UK, are shown in Figure 1 and Figure 2, with the GHG intensities analysed over time horizons of 40 and 100 years, respectively.

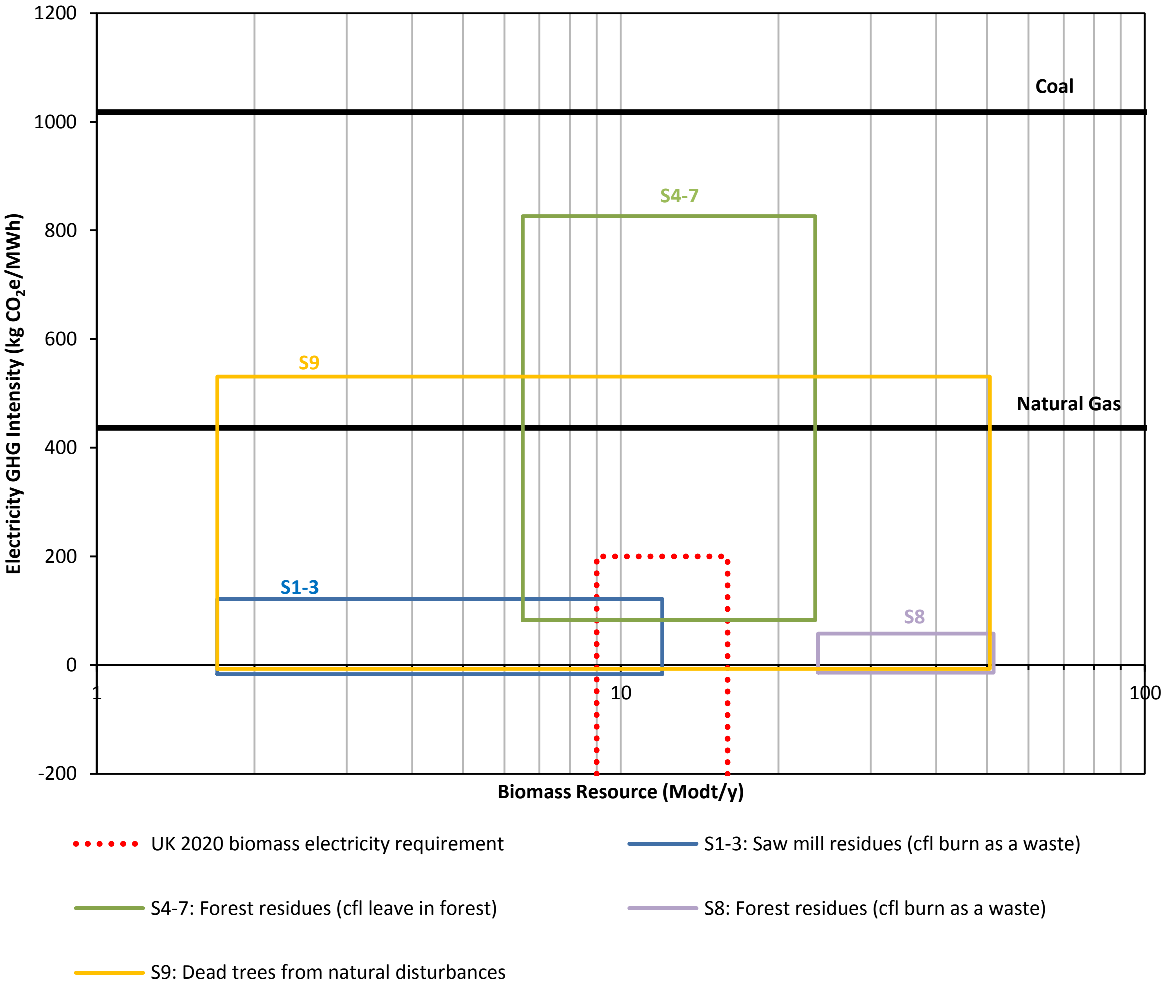

Figure 1. Summary of resource of North American woody residues that may be available by 2020, and their GHG intensity over 40 years. cfl: counterfactual.

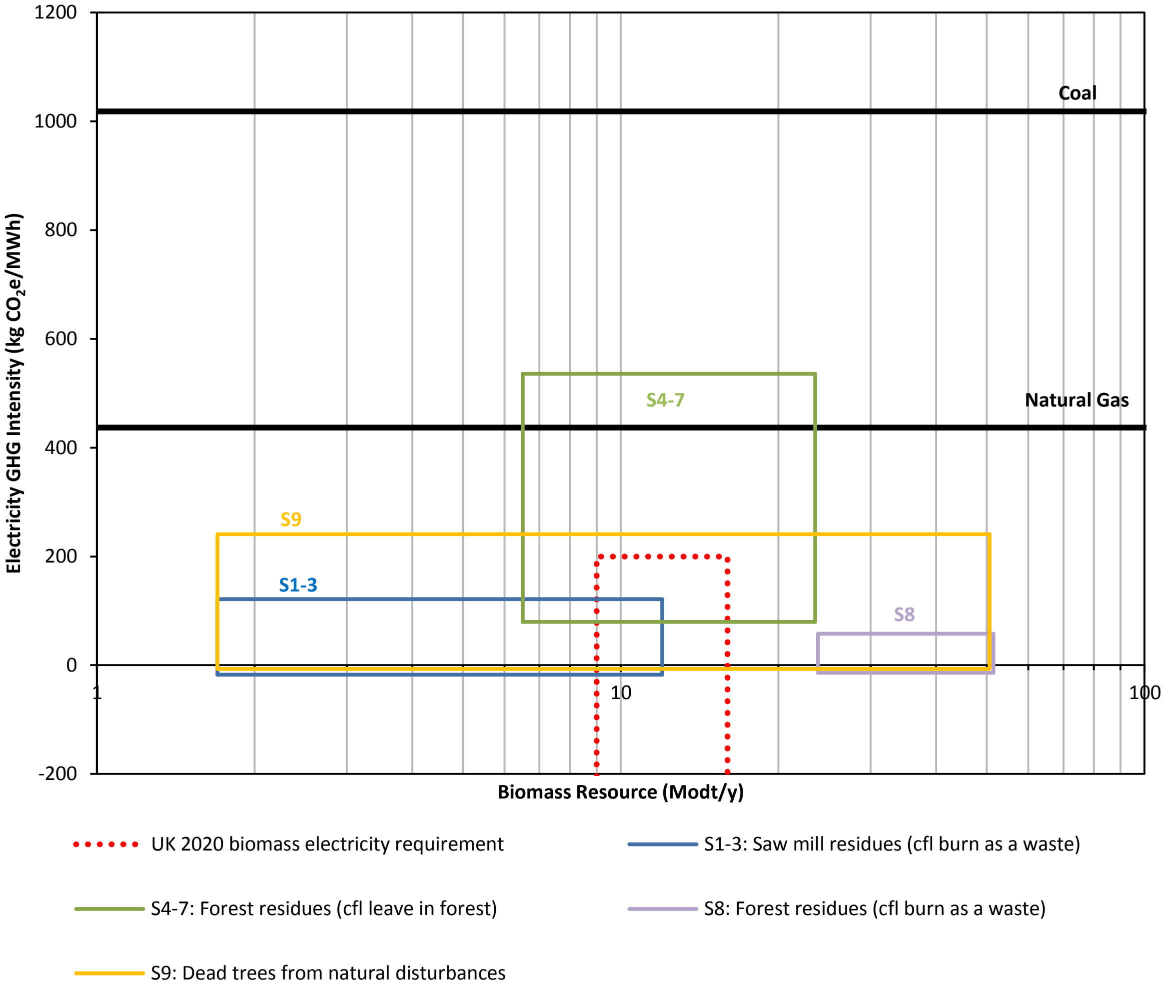

Figure 2. Summary of resource of North American woody residues that may be available by 2020, and their GHG intensity over 100 years. cfl: counterfactual.

9. Figure 1 and Figure 2 show that the GHG implications of using wood residues for bioenergy strongly depend on whether the residue would otherwise be burned as a waste, or left in the forest to decay, with typical practices varying from region to region in North America. The electricity from the combustion of pellets made from saw-mill residues that would otherwise be burned as a waste (**S1-3** in Figure 1 and Figure 2) or forest residues that would otherwise be burned as a waste (**S8** in Figure 1 and Figure 2) has GHG emission intensities significantly lower than electricity from natural gas. However, if the residues would have been left to decay in the forest, the introduction of practices to remove them for electricity generation would result in a reduction of carbon being stored in the forest (**S4-7** in Figure 1 and Figure 2); the GHG intensity of the generated electricity in that case can be significant, particularly when coarse residues are removed from forests in boreal regions (*e.g.* 677 kg CO_2e/MWh delivered energy over 40 years, and 425 kg CO_2e/MWh delivered energy over 100 years, for BEAC Scenario 4b, where residues are removed continuously over the entire time horizon from a forest in Pacific Canada, using the default BEAC key parameters[6] detailed in Table 29 of the Annex).

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[6] Key parameters: Transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station.

Energy Input Requirement for Scenarios Involving Woody Residues

10. The projected resource of North American woody residues and wastes is plotted against the Energy Input Requirement (EIR) in Figure 3.

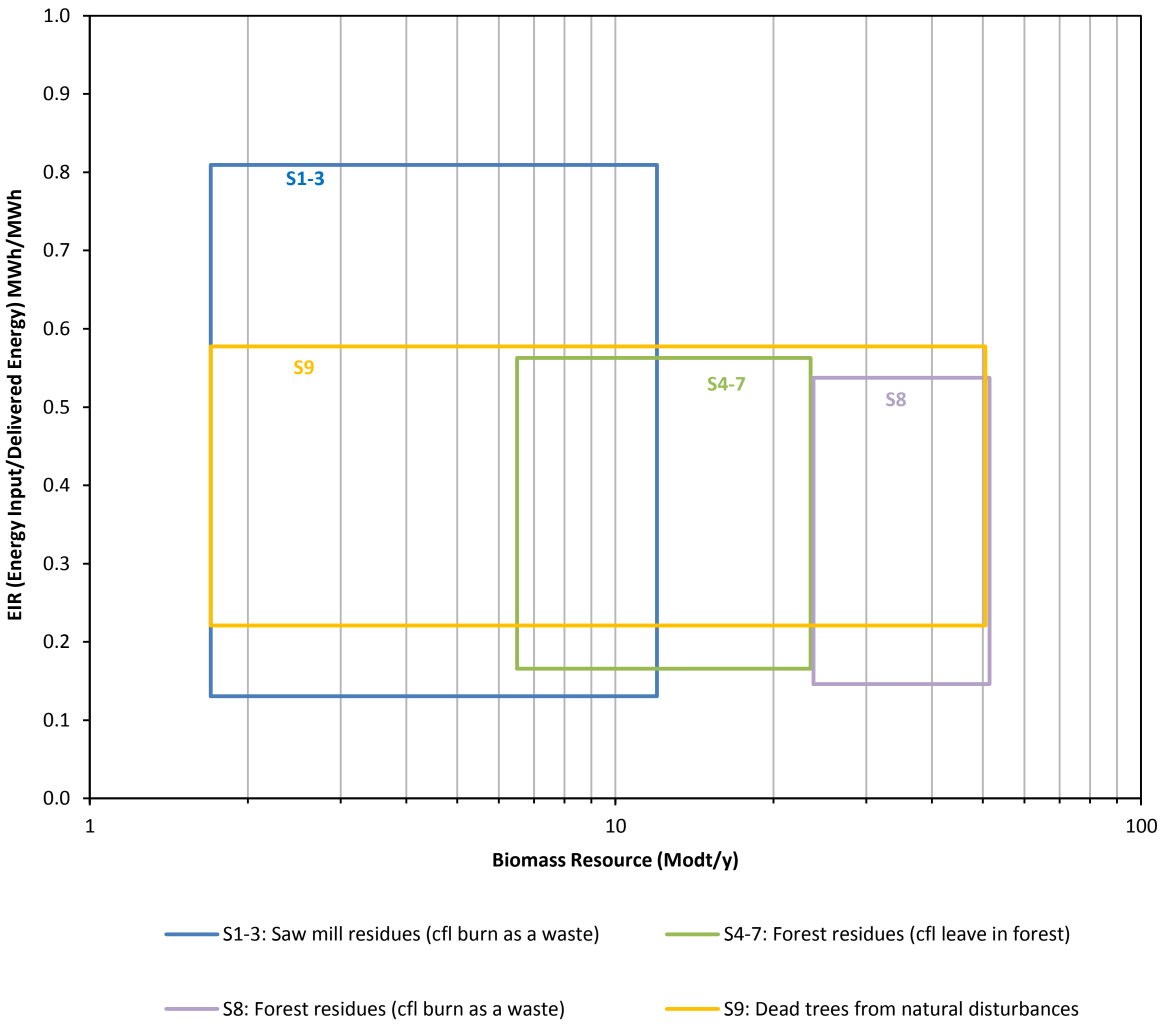

Figure 3. Summary of resource of North American woody residues that may be available by 2020, and their Energy Input Requirement (see page 50 for definition). The EIR is calculated using energy carrier inputs. cfl: counterfactual.

11. The energy input required to produce the electricity from woody residues was found to vary between 0.13 and 0.81 MWh energy carrier input per MWh electricity output. This value is sensitive to the transport distances involved, with the highest value in this range representing scenarios where pellets are shipped from the Pacific Coast of North America to the UK. The method of drying also significantly affects the EIR, with residues that are already dry (*e.g.* sander dust, with a moisture content of 2 - 10 wt%; FAO, 2013) having lower energy requirements for drying than residues with higher moisture contents (*e.g.* saw dust, with a moisture content of between 25 and 55 wt%; Cal Recycle, 2014), and drying fuelled by natural gas requiring a greater external energy input than drying using local biomass residues.

12. The EIR range for electricity from North American biomass residues is compared to other electricity generating technologies in Figure 4. The EIR values for UK electricity generated from pellets from South USA and Pacific Canada have been presented as two separate ranges, calculated using parameters representing current practice;

pellets from South USA generally use biomass to dry the wood, therefore the range for that region assumes that drying method. In Canada, it has been reported that both natural gas and biomass are used as fuels for drying (Magelli *et al.*, 2009; Sikkema *et al.*, 2010), therefore that range has been calculated using both drying fuels. Other studies often extend the system boundary when calculating the energy inputs, using primary energy inputs rather than the energy carrier inputs, therefore the EIR for the bioenergy scenarios has also been calculated on this basis (shown in red in Figure 4), to allow comparison with other studies. Biomass electricity was found to require greater energy inputs than most other electricity-generating technologies.

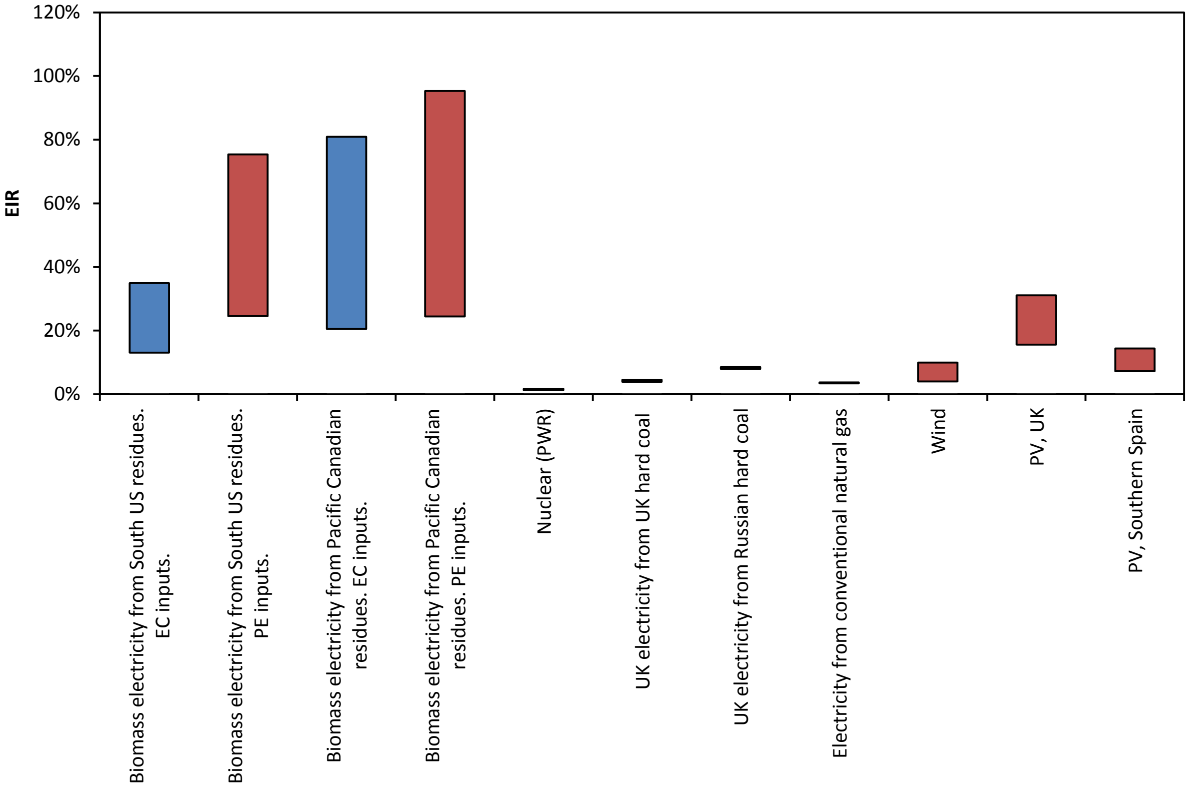

Figure 4. Energy Input Requirement (EIR) values for UK biomass electricity from North American woody residues (ranges calculated using the BEAC model, by varying key parameters within the ranges given in Table 29), and other electricity generating technologies (ranges determined using published literature). EIR for bioenergy is calculated using energy carrier inputs (blue), and primary energy inputs (red). References: Nuclear (Pressurized Water Reactor, PWR): Weissbach *et al.*, 2013; World Nuclear Association, 2014. UK hard coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal 32 km by truck (UK Coal, 2014). Russian coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal by rail for 1200 km, ship 2800 km, and rail 122 km (EWS Energy, 2014). Natural gas: Weissbach *et al.*, 2013 (owing to limited literature data, only one data point was available, which uses US and German data). Wind: Kubiszewski *et al.*, 2010; Weissbach *et al.*, 2013. PV: data from Raugei *et al.*, 2012, assuming UK average irradiance of 925 kWh/m^2/y; low value is for ground-mounted CdTe panels, high value is for roof-mounted monocrystalline Si panels.

Summary for Scenarios Involving Woody Residues

13. It has been estimated that by 2020, there could be approximately 23.8 - 51.5 Modt/y of North American forest residues available, that would otherwise be burned on the roadside, and between 1.7 and 12 Modt/y of unused saw-mill residues, depending on the recovery of the lumber market. If the UK had access to between 14% and 63% of

this residue (9.0 to 16.0 Modt/y), this could provide the required amount of biomass projected for electricity generation in the UK, with a GHG intensity of -17 to 121 kg CO_2e/MWh. There could also be the potential to use dead trees that have been killed by natural disturbances and would otherwise be burned as a waste at the roadside (and hence would have a low GHG intensity), although a significant issue associated with this feedstock is the inconsistency of the annualised volumes within a designated landscape, and the high costs associated with its recovery and utilisation.

14. The USA and Canada also plan to use forest residues for electricity generation in the future (Biomass Energy Resource Centre, 2012; Bradley, 2010; Shore, 2013). This local use could limit the availability of residues for export to Europe. Furthermore, forest residues often have high contents of bark and non-combustible elements, such as alkali metals, which can cause problems of slagging, fouling and corrosion in boilers, therefore some electricity stations require pellets produced from biomass with low bark contents, such as roundwood. It is therefore conceivable that a significant proportion of the feedstock used for the production of biomass pellets in the future might be roundwood. Indeed, many pellet producers are already using pulpwood[7] as their feedstock, and using forest residues as the fuel to dry the pulpwood prior to pelletisation (Forest2Market, 2013).

Roundwood and Energy Crops

15. Currently roundwood is harvested from North American forests at a rate of ~ 210 Modt/y, a rate significantly greater than the UK's anticipated demand for biomass electricity feedstocks. Roundwood is generally classified as saw logs and pulpwood, with saw logs used for construction, and pulpwood and residues from saw log processing used for the production of particleboard, fibreboard (*e.g.* Oriented Strand Board, OSB) and paper products. Pulpwood is also used as a feedstock for the production of wood pellets; if pulpwood had no alternative use to bioenergy, but had to be harvested for forest management purposes and therefore would otherwise be treated as a waste, the GHG intensity and energy input requirement of the biomass electricity generated from pulpwood would be similar to that associated with electricity from forest residues. However, if the North American demand for pulpwood for paper products and OSB increases up to 2020 as projected (Ince and Nepal, 2012; FAO and UNECE, 2012), it is unlikely that a significant quantity of this product would otherwise be left in the forest or burned at the roadside, therefore the GHG intensity and EIR would be different (discussed below). For example, in South USA, where many new pellet facilities that use pulpwood as a feedstock are being established, it has been reported that the demand for pine pulpwood from OSB and pellet manufacture increased between Quarter 2 of 2012 and 2013, contributing to a 10% increase in the stumpage price of pine pulpwood (Forest2Market, 2013). Considering a more recent time period between September/October 2012 and 2013, the stumpage price of pine pulpwood in the region increased by 22% (Forest2Market, 2013a).

GHG Intensity for Scenarios Involving Roundwood and Energy Crops

16. The projected resource of North American roundwood and woody energy crops that may be available by 2020, along with their GHG intensities when used for dedicated electricity generation in the UK, are shown in Figure 5 and Figure 6, for time horizons of 40 and 100 years, respectively.

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[7] Pulpwood is a sub-category of roundwood. Exact definition varies between different saw-mills. In South USA, this consists of roundwood that has a small end diameter typically less than a saw log (5 - 8 inches), but greater than 2.5 inches (0.064 m), and low quality larger logs that cannot be used for sawn timber.

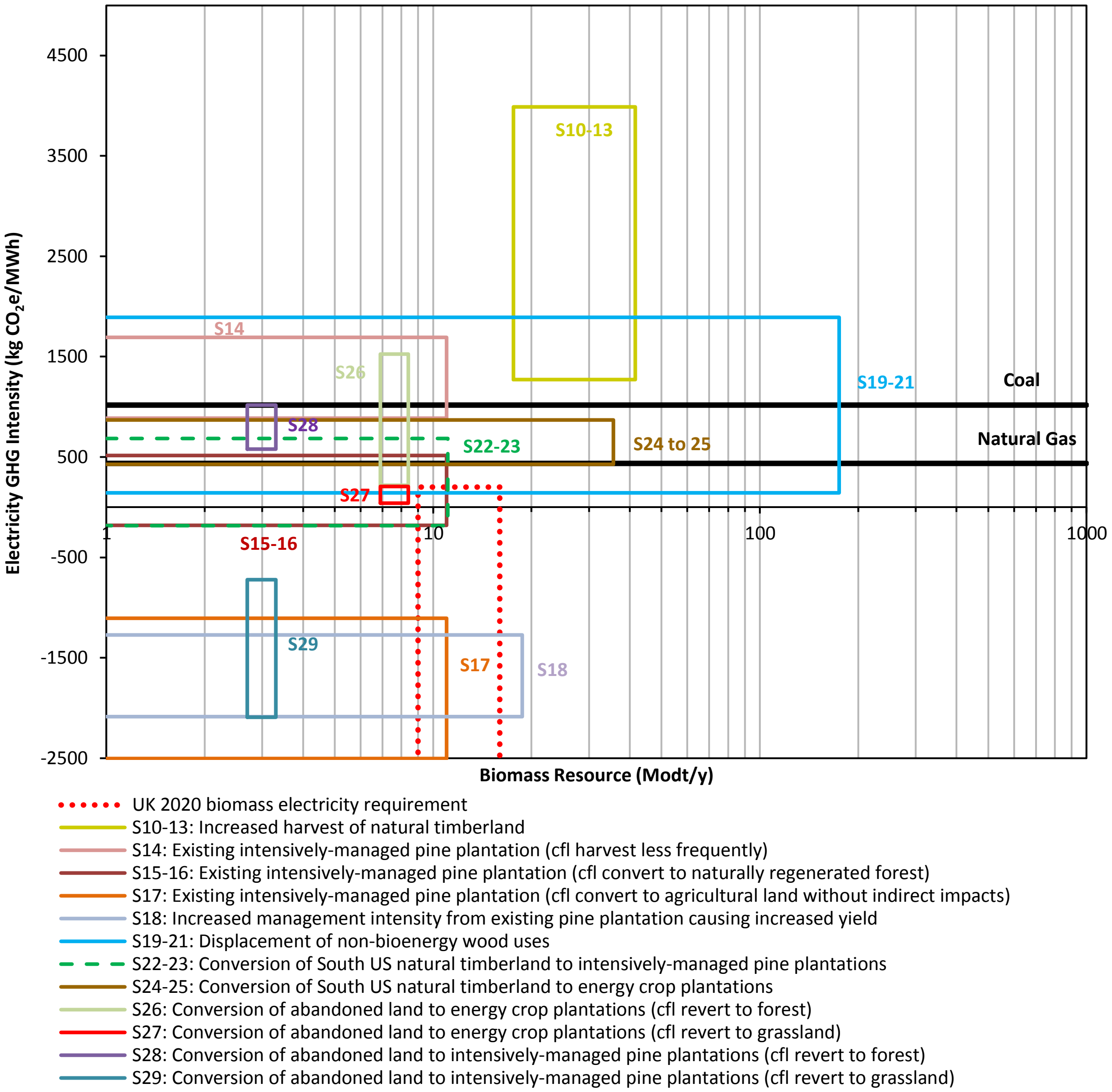

Figure 5. Summary of resource of North American roundwood and energy crops that may be available by 2020, and their GHG intensity over 40 years. cfl: counterfactual.

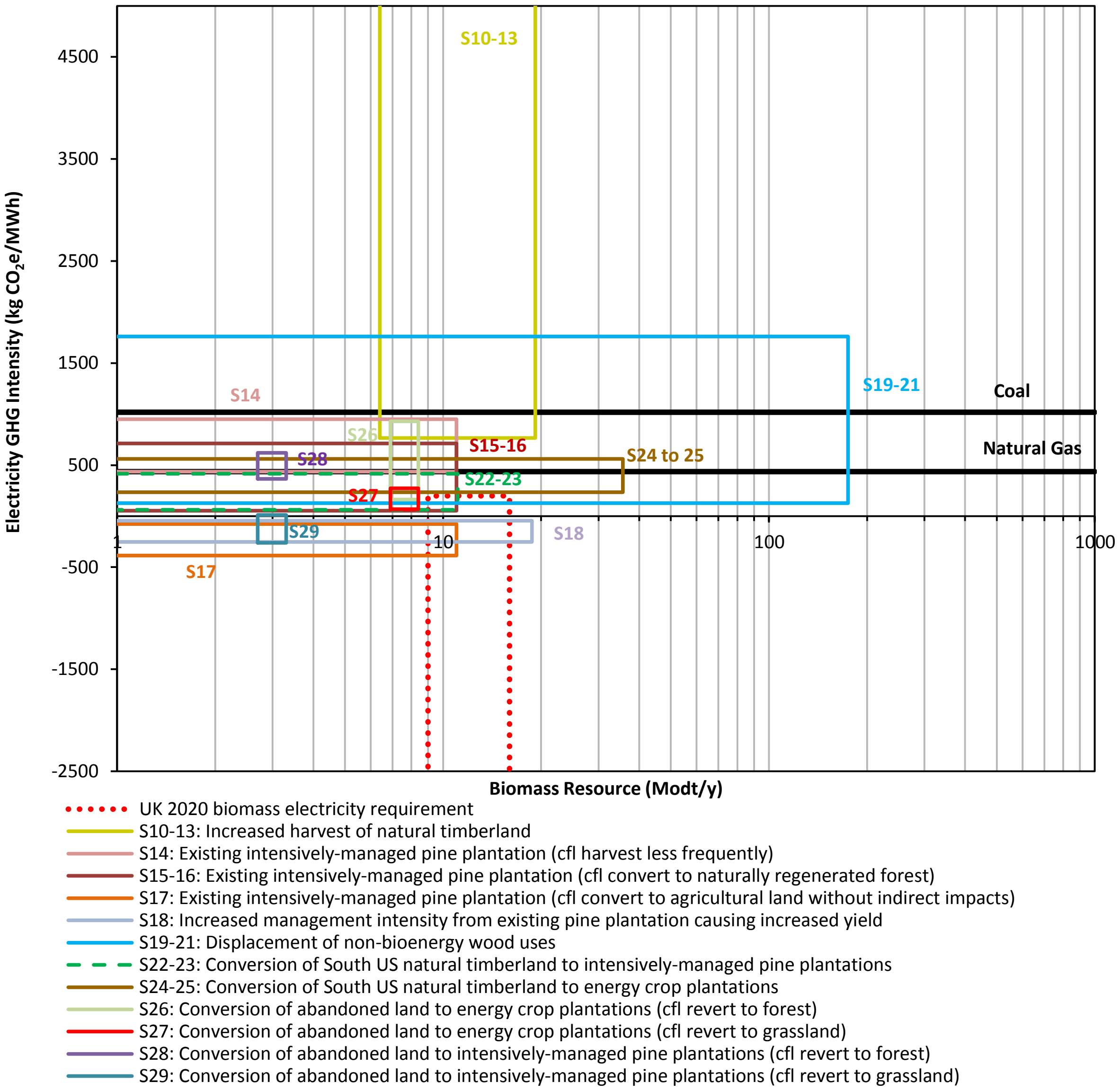

Figure 6. Summary of resource of North American roundwood and energy crops that may be available by 2020, and their GHG intensity over 100 years. cfl: counterfactual.

17. The GHG intensities of the generated electricity were found to vary significantly, depending on the scenario:

    i. **Naturally-regenerated forests.** In the past, an increased demand for pulpwood has led to increased harvest of naturally-regenerated forests in North America (S10-13 in Figure 5 and Figure 6). If this scenario were to materialise again, and naturally-regenerated forests were harvested at a greater rate than if the demand for bioenergy were not there, the GHG emission intensity of the electricity generated from the additional wood output from the forest would be 1270 to 3988 kg CO_2e/MWh (greater than electricity from coal) when analysed over a time horizon of 40 years, and 766 to 5174 kg CO_2e/MWh when analysed over 100 years.

    ii. **Existing, intensively-managed plantations.** Existing, intensively-managed plantations (*e.g.* Loblolly pine plantations in South USA), could be used to produce bioenergy feedstocks, as well as wood products. In this case, the GHG intensity would depend on the counterfactual land use, which, in turn, would depend on the overall demand for wood in the region.

Low demand for wood:

a) If the demand for wood in the region were low, and the plantation would otherwise be harvested less frequently (**S14** in Figure 5 and Figure 6), the GHG emission intensity of the electricity generated from the additional wood output from the forest would, again, be greater than electricity from coal when analysed over a time horizon of 40 years, as the counterfactual would result in greater storage of carbon in the forest.

b) However, if the intensively-managed plantation would otherwise be left to revert to a naturally-regenerated forest after harvest (**S15-16** in Figure 5 and Figure 6), the GHG intensity of the electricity would be lower, as naturally-regenerated forests have slower growth rates than intensively-managed plantations.

   - For example, if the demand for bioenergy resulted in the plantation remaining as an intensively-managed forest that is harvested every 25 years, but would be converted to a naturally-regenerated forest that is harvested every 50 years without the demand for bioenergy (BEAC Scenario 15a), the counterfactual (naturally-regenerated forest) would have a lower carbon stock than the bioenergy scenario (intensively-managed plantation), therefore electricity generated from the additional wood output[8] would be low (-178 kg CO_2e/MWh over 40 years, and 86 kg CO_2e/MWh over 100 years, using the default BEAC key parameters).
   - However, if the plantation would otherwise be left to revert to a naturally-regenerated forest that is not harvested (BEAC Scenario 16a), the carbon stock on the land would continue to increase over time, and over longer time horizons (*e.g.* 100 years) would be greater than the carbon stock of an intensively-managed forest. In this case, the GHG intensity of the electricity produced from the additional wood would still be low after 40 years (44 kg CO_2e/MWh using the default BEAC key parameters), but similar to electricity from natural gas over 100 years (488 kg CO_2e/MWh).
   - For both of the cases above, if the increased demand for bioenergy resulted in the harvest rate of the intensively-managed plantation increasing from every 25 years to every 20 years (Scenarios 15b and 16b), causing the carbon stock of the plantation to reduce, the GHG intensity of the generated biomass electricity would be significantly greater than if the plantation had continued to be harvested every 25 years (*e.g.* 461 kg CO_2e/MWh over 40 years and 202 kg CO_2e/MWh over 100 years for BEAC Scenario 15b; 375 kg CO_2e/MWh over 40 years and 561 kg CO_2e/MWh over 100 years for BEAC Scenario 16b, using the default BEAC key parameters).

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[8] Additional wood output of the bioenergy scenario (plantation), in comparison to the counterfactual scenario (naturally-regenerated forest).

c) Alternatively, a potential counterfactual to using wood from an intensively-managed plantation for bioenergy could be that the plantation would be converted to agricultural land, *e.g.* a cotton plantation (**S17** in Figure 5 and Figure 6). Assuming no indirect impacts, the GHG intensity of the electricity produced from the additional wood would be negative (-2082 kg CO_2e/MWh over 40 years, and -293 kg CO_2e/MWh over 100 years, using the using the default BEAC key parameters). Although this scenario shows large GHG savings, it is important to note that if this land were used for bioenergy, rather than cotton, the cotton could instead be grown somewhere else, with indirect GHG implications (which have not been modelled here).

High demand for wood:

d) If the demand for wood in the region were high, and the additional demand from bioenergy resulted in some plantations being managed more intensively to achieve greater yields (*e.g.* by genetic selection, improved silvicultural techniques, or fertilisation) (S18 in Figure 5 and Figure 6), the GHG intensity of the electricity generated from the additional wood output from the forest would be negative (-1730 kg CO_2e/MWh over 40 years, and -179 kg CO_2e/MWh over 100 years, using the default BEAC key parameters).

e) However, a high demand for wood could alternatively result in the displacement of wood used for other purposes (*e.g.* paper and OSB) (**S19-21** in Figure 5 and Figure 6). In this case, the wood products, or pulpwood, might be imported to North America from other countries. The GHG intensity of the electricity would then vary greatly, depending on the land management practices employed to produce the additional wood in other countries. In this study, indirect impacts from additional wood imports to the USA from Canada and Brazil have been considered, and have been shown to result in the electricity having a GHG intensity varying between 144 and 1893 kg CO_2e/MWh over 40 years, and between 127 kg CO_2e/MWh and 1761 kg CO_2e/MWh over 100 years.

iii. **New plantations on naturally-regenerated forest land.** Another potential implication of increased demand for pulpwood for bioenergy feedstocks could be the establishment of new plantations on naturally-regenerated forest land (**S22-23** and **S24-25** in Figure 5 and Figure 6). The GHG intensity depends strongly on the carbon stock of the plantation and the counterfactual land use (naturally-regenerated forest), which both depend on the forest or plantation type and the frequency of harvest. The conversion of naturally-regenerated pine and hardwood forests in South USA that are harvested every 50 or 70 years, to intensively-managed pine plantations that are harvested every 20 to 25 years (**S22-23** in Figure 5 and Figure 6) and short rotation coppice (SRC) plantations that are coppiced every 3 years (**S24-25** in Figure 5 and Figure 6) have been considered in this study. The additional wood from the conversion of a naturally-regenerated pine forest that is harvested every 50 years, to an intensively-managed plantation that is harvested every 25 years (BEAC Scenario 22a), would have a low GHG intensity (-123 kg CO_2e/MWh over 40 years, 97 kg CO_2e/MWh over 100 years, using the default BEAC key parameters). However, the other scenarios considered (22b, 23, 24 and 25) were shown to produce electricity with significantly greater GHG intensities (lowest for Scenario 22b: 253 kg CO_2e/MWh over 40 years and 196 kg CO_2e/MWh over 100 years; highest for Scenario 24b: 709 kg CO_2e/MWh over 40 years and 339 kg CO_2e/MWh over 100 years, using the default BEAC key parameters).

iv. **New plantations on abandoned agricultural land.** In another class of scenarios (BEAC Scenarios 26 to 29), rather than using land that is already forested for the harvest of additional biomass, abandoned or marginal agricultural land could be used for the establishment of new bioenergy plantations (*e.g.* intensively-managed pine plantations, or SRC plantations). The GHG intensities of electricity generated from the feedstocks would depend strongly on how the counterfactual land carbon stocks would change over time. If the land would otherwise revert to forest (**S26** and **S28** in Figure 5 and Figure 6), the GHG emission intensity would be greater than if the land would otherwise revert to grassland (**S27** and **S29** in Figure 5 and Figure 6); over a time horizon of 40 years, the GHG intensity would be 219 to 1526 kg CO_2e/MWh for biomass electricity from land reverting to forest, and -2093 to 206 kg CO_2e/MWh for biomass electricity from land reverting to grassland, in the cases explored in this study (assuming the use of this land does not lead to the displacement of other commodities). The likely availability of such land is uncertain; it has been estimated that 43 million hectares of degraded, low-quality cropland exists in the USA, which is either already abandoned, or, owing to its low productivity, would have little impact on food production if it became abandoned (Cai *et al.*, 2011). However, others have concluded that owing to increased global demand for food, it is unlikely that significant areas of land will be available for new biomass plantations in the future, without impacting food supplies (The World Resources Institute; 2013).

EIR for Scenarios Involving Roundwood and Energy Crops

18. The projected resource available in 2020 is plotted against the Energy Input Requirement (EIR) in Figure 7. The energy input required to produce the electricity from North American pellets using wood with 50 wt% moisture content was found to vary between 0.16 and 0.96 MWh energy carrier input per MWh electricity output, with the value being most sensitive to the transport distance and method of drying.

19. In Figure 8, the EIR for UK electricity from North American roundwood and energy crops is presented as ranges associated with pellets from South USA and Canada, and compared to other electricity generating technologies. As in Figure 4, the EIR has also been displayed using primary energy inputs, to allow comparison to other studies.

Summary for Scenarios Involving Roundwood and Energy Crops

20. It is evident that the GHG intensity of electricity generated from North American roundwood and energy crops varies significantly, depending on the carbon stock of the land and the counterfactual. Some scenarios can have very low (even negative) GHG intensities, if they result in increased carbon stored on the land. However, other scenarios can result in GHG intensities greater than electricity from fossil fuels, even after 100 years. In all cases, the energy input required to produce the electricity from

North American pellets is greater than electricity from fossil fuels and other renewables (except the most energy-intensive PV systems) and nuclear.

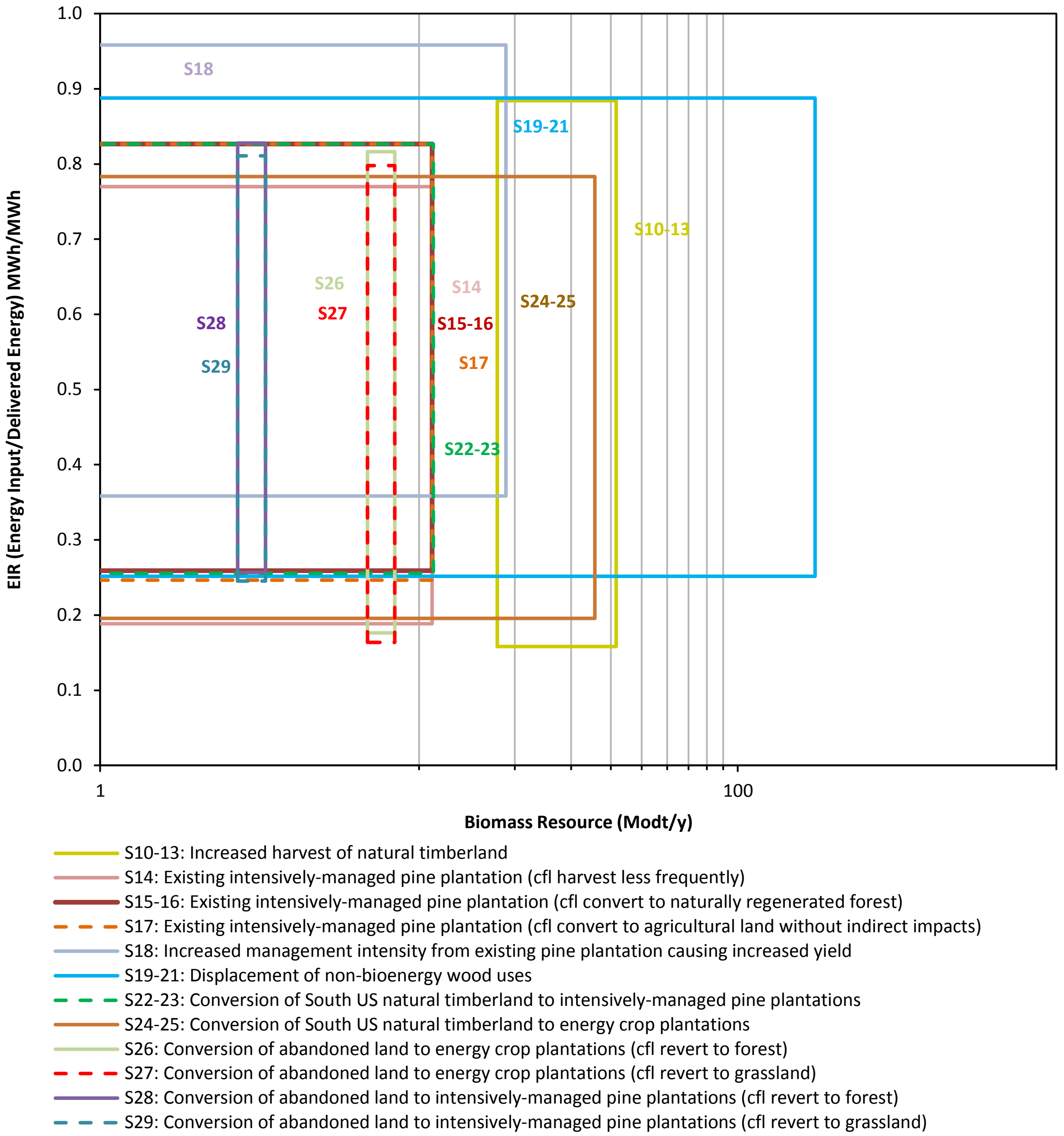

Figure 7. Summary of resource of North American roundwood and energy crops that may be available by 2020, and their Energy Input Requirement (40 year time horizon). The EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. cfl: counterfactual.

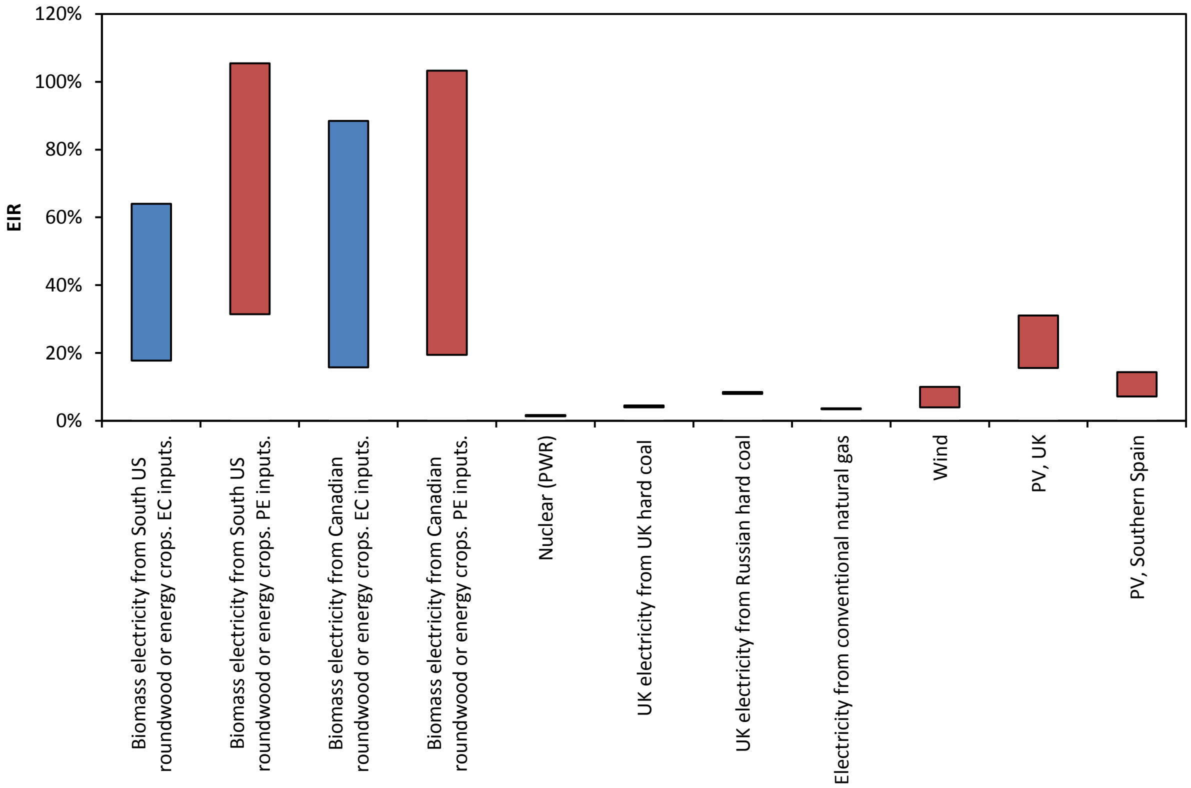

Figure 8. Energy Input Requirement (EIR) values for UK biomass electricity from North American roundwood and energy crops (ranges calculated using the BEAC model, by varying key parameters within the ranges given in Table 29), and other electricity generating technologies (ranges determined using published literature). EIR for bioenergy is calculated using energy carrier inputs (blue), and primary energy inputs (red). References: Nuclear (Pressurized Water Reactor, PWR): Weissbach *et al.*, 2013; World Nuclear Association, 2014. UK hard coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal 32 km by truck (UK Coal, 2014). Russian coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal by rail for 1200 km, ship 2800 km, and rail 122 km (EWS Energy, 2014). Natural gas: Weissbach *et al.*, 2013 (owing to limited literature data, only one data point was available, which uses US and German data). Wind: Kubiszewski *et al.*, 2010; Weissbach *et al.*, 2013. PV: data from Raugei *et al.*, 2012, assuming UK average irradiance of 925 kWh/m^2/y; low value is for ground-mounted CdTe panels, high value is for roof-mounted monocrystalline Si panels.

Conclusions

21. A summary of the GHG impacts of different scenarios is shown below in Table 1.

22. This work shows that in 2020 it may be possible to meet the UK's demand for solid biomass for electricity[9] using biomass feedstocks from North America that result in electricity with GHG intensities lower than 200 kg CO_2e/MWh, when fully accounting for changes in land carbon stock changes[10]. However, there are other bioenergy scenarios that could lead to high GHG intensities (*e.g.* greater than electricity from coal, when analysed over 40 or 100 years) but would be found to have GHG intensities less than 200 kg CO_2e/MWh by the Renewable Energy Directive LCA methodology.

23. The energy input requirement of biomass electricity generated from North American wood used by the UK in 2020 is likely to be in the range 0.13 to 0.96 MWh energy

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[9] Projected to be 9.0 to 16.0 Modt/y.

[10] Using the BEAC methodology, where forest carbon stocks, foregone carbon sequestration and indirect impacts are taken into consideration.

carrier input per MWh delivered energy, significantly greater than other electricity generating technologies, such as coal, natural gas, nuclear and wind. The Energy Input Requirement is smallest when (i) the transport distances are minimised, (ii) the moisture content of the biomass is reduced by passive drying and drying using local biomass resources as fuel, and (iii) the energetic efficiency of the technology is maximised.

Table 1. Overview of GHG impacts of bioenergy scenarios, for continuous bioenergy generation over 40 years.

	GHG Impact in kg CO_2e/MWh electricity			
	less than 100	**between 100 and 400**	**greater than 400**	**varies significantly, depending on precise details of scenario**
Woody residues	Forest residues that would otherwise be burned as a waste. Saw-mill residues that would otherwise be burned as a waste. Trees killed from natural disturbances (*e.g.* beetles), that would otherwise burned as a waste.	Fine residues that would otherwise be left to decay in a forest (all regions). Coarse residues that would otherwise be left to decay in a Southern US forest.	Coarse residues that would otherwise be left to decay in a boreal forest (*e.g.* Canada). Trees killed from natural disturbances (*e.g.* beetles), that would otherwise be left in a boreal forest (*e.g.* Canada)[11].	
Roundwood and energy crops	Increasing the yield of a plantation, without increasing the rate of harvest. Wood from a forest that would otherwise be converted to agricultural land (if no indirect impacts). Converting land that would otherwise revert to grassland to biomass plantations (pine or energy crops).		Additional wood output from increasing the harvest rate of forests (reducing the rotation length). Wood from a forest that would otherwise be harvested less frequently[12]. Converting forests into energy crop plantations (*e.g.* Short Rotation Coppice). Converting land that would otherwise revert to forests to biomass plantations (pine or energy crops)[13].	Converting naturally-regenerated forests into pine plantations (increasing the growth rate)[14]. Additional wood output from an intensively-managed plantation that would otherwise be converted to a naturally-regenerated forest.

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[11] It was assumed that the increase in carbon stock of the forest by natural regeneration would occur at the same rate if the beetle-killed trees were salvaged or left untreated in the forest. Further research into the future carbon stocks of both scenarios would be beneficial, accounting for different species compositions, and different future natural disturbances.

[12] Additional wood in comparison to the counterfactual used for energy, where the counterfactual forest management involves longer rotation times, hence a greater carbon stock.

[13] For all scenarios considered in this report, the GHG intensity of energy crops grown on land reverting to forest is greater than 400 kg CO_2e/MWh over 40 years, apart from if the yield of the energy crop is 30 odt/ha/y, in which case the GHG intensity was calculated to be 277 kg CO_2e/MWh using the default BEAC key parameters.

[14] Depends strongly on the rotation lengths and growth rates of both the bioenergy scenario and the counterfactual.

Acknowledgements

Professor MacKay and Dr Stephenson thank all stakeholders who provided input to the study. We also warmly acknowledge the work of DECC officials, especially Damitha Adikaari, Martin Meadows, Philip Sargent, David Warrilow, Alec Waterhouse, Liz McDonnell, Emma Peterson, Andrew Welfle, and Emma Frost.

Definitions

Table 2. Glossary of terms.

Name	Description
Bedding (forestry site preparation)	The formation of a continuous mound of soil. This treatment is usually done on sites with poor surface drainage, but is also common on sites with good surface drainage. Soils near the top of the bed are drier and warmer sooner in the spring than unbedded areas, which promotes early root growth.
Biomass	Biomass is biological material derived from living, or recently living organisms. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material.
Carbon Debt	When a stand of trees are harvested all at once, it takes time for the trees to re-grow to their pre-harvest mass. Until that time, the amount of carbon stored on the land is lower than it was before harvest. If the wood removed from the land is combusted, the net reduction in carbon stored on the land would cause an equivalent temporary increase in carbon in the atmosphere.
Chopping (forestry site preparation)	Breaking or crushing existing vegetation in place.
Disking (forestry site preparation)	To break up or till the soil surface, improving soil aeration and moisture movement, and helping young trees to root. Disking also incorporates organic surface layers into the underlying mineral soils.
Even-aged forest	A forest consisting of a number of stands of trees, with each stand being composed of trees of the same age, and the age distribution of stands in the forest being uniform.
Foregone carbon sequestration	When trees are harvested regularly from an even-aged forest, the forest reaches an average carbon stock, but this is generally lower than the carbon stock of a forest that is not harvested. Foregone carbon sequestration is the sequestration which would have happened if the forest had not been harvested, and had been left to continue growing.
Genetic selection	Using selective breeding to improve the desired qualities of a population (*e.g.* tree species).
Green tonne	A tonne of wood, containing approximately 50 wt% moisture.
Growth-to-Drain Ratio	The ratio between the volumetric growth of a forest and the volumetric removal. A ratio of one means that growth equals removal.
Indirect GHG impact	If land used for bioenergy would otherwise have been used for the production of a different commodity, the displaced commodity may be produced by another method (*e.g.* from wood harvested elsewhere, or using non-biomass alternatives), which would have associated resource costs and greenhouse gas emissions.
Indirect land use change	When biomass for bioenergy is produced on existing productive land, the demand for the commodity originally produced on the land remains, and may lead to someone producing more commodities somewhere else. This can imply land use change (by changing *e.g.* old growth forest into productive forests), which implies that a substantial amount of CO_2 emissions are released into the atmosphere.
Mineral soil	The UK Forestry Commission classifies mineral soils as having an organic

Name	Description
	layer of less than 5 cm.
Naturally-regenerated timberland	Productive forests that are of natural origin; these forests regenerate naturally through seeding, root suckers, or stump sprouts from existing trees.
Organic soil	The UK Forestry Commission classifies organic soils as having an organic layer greater than 45 cm.
Organo-mineral soil	The UK Forestry Commission classifies organo-mineral soils as having an organic layer greater than 5 cm, but less than 45 cm.
Oriented Strand Board	Engineered wood particle board formed by adding adhesives and then compressing layers of wood strands in specific orientations.
Overstorey trees	The uppermost layer of foliage in a forest, forming the canopy.
Paper products	Includes paper, card, cardboard, packaging material, fluff pulp *etc*.
Piling (forestry site preparation)	Gathering up logging debris into piles.
Plantation	An area where trees have been planted, especially for commercial purposes.
Primary processing mills	Mills that convert roundwood into primary mill products such as lumber, plywood, and wood pulp.
Secondary processing mills	Mills that convert primary mill products into other products, such as pallets, furniture, and flooring.
Solid biomass	Biomass in the solid form. Includes wood, energy crops and agricultural residues.
Stand	An area of the forest that is relatively uniform in species composition or age and can be managed as a single unit.
Stem-only harvesting	The removal of the stem wood from a harvesting site. The branches, needles and stump are left *in situ*.
Stumpage price	The price paid to landowners for standing timber.
Whole-tree harvesting	The removal of most branches and needles from a harvesting site in addition to the stem wood that is removed in conventional harvesting. The stump and roots are left *in situ*.
Yield class	In the UK, the yield of wood from forests is usually described in terms of “yield class”; this is a measurement of increment (the amount of solid stem wood added to an area of woodland) in cubic meters per hectare per year (m^3/ha/y).

Table 3. Definition of different categories of wood.

Wood Category	Classification	Description
Roundwood	Saw logs	Exact definition varies between different saw-mills. In South USA, a saw log is usually defined as a log with a small end diameter greater than 5 - 8 inches (0.13 - 0.20 m).
	Chip-n-saw	US term. Exact definition varies between different saw-mills. In South USA, this consists of small saw logs and large pulpwood, with minimum diameters of 4 - 6 inches (0.10 - 0.15 m) and maximum diameters of 9 - 16 inches (0.23 - 0.41 m).
	Pulpwood	US term. Exact definition varies between different saw-mills. In South USA, this consists of roundwood which has a small end diameter typically less than a saw log (5 - 8 inches), but greater than 2.5 inches (0.064 m) (also known as small roundwood in the UK), and low quality roundwood with dimensions of saw logs and chip-n-saw, that can't be used for sawn-timber.
Forest Residues	Fine forest residues	Tree tops, limbs, non-merchantable harvested trees and tree components, and downed trees which are left over from traditional timber harvesting. Includes pre-commercial thinnings (described below). Diameter < 0.1 m (Fritsche *et al.*, 2012).
	Coarse forest residues	Tree tops, limbs, non-merchantable trees and tree components, and downed trees which are left over from traditional timber harvesting. Includes pre-commercial thinnings (described below). Diameter > 0.1 m (Fritsche *et al.*, 2012).
Thinnings	Commercial thinnings	Trees removed during thinning operations, the purpose of which is to reduce the density of trees in a stand of forest, and enhance diameter growth and volume of the residual stand. Commercial thinnings include roundwood which is of sufficient size and quality to have a commercial value.
	Pre-commercial thinnings	Trees removed during thinning operations, the purpose of which is to reduce stand density and enhance diameter growth and volume of the residual stand. Pre-commercial thinnings are of insufficient size and quality to have a commercial value.
Saw-mill residues	Fine residues	Saw dust, wood flour, shavings and bark, produced as by-products of primary and secondary processing mills.
	Coarse, chippable residues	Saw-mill slabs and edgings, produced as by-products of primary and secondary processing mills.

Introduction

24. The UK Government's 2012 Bioenergy Strategy recognised that bioenergy, used wisely, has an important role to play if the UK is to meet its energy security and decarbonisation objectives (DECC, DfT and DEFRA, 2012). Bioenergy is also expected to contribute significantly to the UK's target for renewable sources to contribute at least 15% of total energy consumption by 2020 (as required by the EU Renewable Energy Directive 2009/28/EC).

25. The Bioenergy Strategy also identified that there are risks and uncertainties associated with bioenergy, including (i) whether it genuinely contributes to carbon reductions; (ii) the availability and price of sufficient sustainably-sourced biomass; (iii) the relationship between bioenergy and other uses of land, such as food production, and other uses of biomass, such as for construction materials; and (iv) the environmental impacts on air quality, biodiversity and water resources.

26. Four principles were therefore included in the Bioenergy Strategy, to act as a framework for future government policy on bioenergy. These are:

- Policies that support bioenergy should deliver genuine carbon reductions that help meet UK carbon emissions objectives to 2050 and beyond.
- Support for bioenergy should make a cost effective contribution to UK carbon emission objectives in the context of overall energy goals.
- Support for bioenergy should aim to maximise the overall benefits and minimise costs (quantifiable and non-quantifiable) across the economy.
- At regular time intervals and when policies promote significant additional demand for bioenergy in the UK, beyond that envisaged by current use, policy makers should assess and respond to the impacts of this increased deployment on other areas, such as food security and biodiversity.

27. The Bioenergy Strategy noted that at the time of publication, the sustainability standards applied to renewables incentives needed to be more stringent in order to meet the principles. In response, DECC has published stricter sustainability criteria for the use of biomass feedstocks for energy under the Renewable Obligation (RO)[15] (DECC, 2013a) and the Renewable Heat Incentive (RHI)[16] (DECC, 2013d).

28. The RO sustainability criteria have initially been introduced on a reporting basis; the intention is however to make compliance with the criteria mandatory in order to receive support from April 2015. The RO sustainability criteria include trajectories for greenhouse gas emissions (GHG) for electricity from biomass, calculated based on

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[15] The Renewables Obligation is the main support mechanism for renewable electricity projects in the UK.

[16] The Renewable Heat Incentive is the main support mechanism for renewable heat projects in the UK.

the LCA methodology[17] set out in Annex V of the EU Renewable Energy Directive (2009/28/EC)[18]. These trajectories are:

(i) New dedicated biomass power (with or without CHP):

- 240 kg CO_2e/MWh electricity from 1 April 2014 to 31 March 2020
- 200 kg CO_2e/MWh electricity from 1 April 2020 to 31 March 2025
- 180 kg CO_2e/MWh electricity from 1 April 2025 to 31 March 2030

(ii) All other biomass power, including co-firing coal stations, coal stations converting to biomass, and existing dedicated biomass power (with or without CHP):

- 285 kg CO_2e/MWh electricity from 1 April 2014 to 31 March 2020
- 200 kg CO_2e/MWh electricity from 1 April 2020 to 31 March 2025
- 180 kg CO_2e/MWh electricity from 1 April 2025 to 31 March 2030

29. The RHI sustainability criteria will also become mandatory in order to receive support from Spring 2015. Suppliers will have to meet a lifecycle emissions target of 125.28 kg CO_2e/MWh heat, again calculated based on the LCA methodology set out in Annex V of the EU Renewable Energy Directive (2009/28/EC). The GHG emission targets are lower per MWh for heat generation than for electricity generation, owing to the higher efficiency of heat generating technologies.

30. The Renewable Energy Directive LCA methodology accounts for GHG emissions from the cultivation, harvesting, processing and transport of the biomass feedstocks. It also includes direct land use change where the land use has changed category since 2008. The methodology, however, does not include changes in carbon stocks of forests, foregone carbon sequestration, carbon debt, or indirect impacts such as displacement effects. See page 40 for more details.

31. Principle 1 of the Bioenergy Strategy recognised the importance of understanding carbon impacts for the whole system, including any changes to carbon stocks. DECC has committed to including protection of land carbon stocks into the sustainability criteria for bioenergy in the coming years, with a review of the effectiveness of the approach in 2016/17, as part of the planned UK Bioenergy Strategy Review (DECC, 2013a).

32. This report presents analysis carried out since the publication of the Bioenergy Strategy. The analysis is intended to shed light on the full carbon impacts of using woody biomass for energy, by accounting for the factors not considered by the Renewable Energy Directive LCA Methodology.

33. Energy resources are limited, therefore this report also investigates the additional energy input required by a bioenergy scenario in order to deliver the final energy output.

34. In 2020, the greatest demand for solid biomass in the UK is projected to be from the electricity sector, and the majority of the biomass feedstocks are likely to be in the form of imported woody pellets, mainly from North American forests. The aims of this report are therefore to:

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[17] As recommended by the European Commission in their 2010 report on biomass sustainability (European Commission, 2010).

[18] Electricity generators can report their bioenergy GHG emissions using the UK Solid and Gaseous Biomass Carbon Calculator is used by. The purpose of the calculator is to demonstrate compliance with the EU Renewable Energy Directive (2009/28/EC), and therefore factors beyond the scope of the Renewable Energy Directive LCA methodology are not accounted for.

- quantify the woody biomass resources that are likely to be available for pellet production from forests in North America by 2020, in million oven dry tonnes per year (Modt/y);
- estimate the GHG emission intensities (in kg CO_2e/MWh delivered energy) of using these resources for electricity generation in the UK, accounting for the impacts omitted by the EU RED methodology (emissions or sequestration from carbon stock changes on the land, foregone carbon sequestration, and indirect impacts); and
- estimate the Energy Input Requirements (EIR) (in MWh energy input per MWh delivered energy) of using these resources for electricity generation in the UK and compare to other electricity generating technologies. The energy input is considered to be energy carriers which are ready for final use, *e.g.* electricity, diesel, natural gas, fuel oil. The primary energy of the biomass is not included as an energy input in the calculation, just as the energy in the wind, sunshine, or nuclear fuel is not included in the Energy Input Requirement for wind, solar and nuclear technologies.

35. The final results are compared to the projected solid biomass requirements for UK biomass electricity, shown in Figure 9.

36. This study does not address other issues which are also integral to the development of bioenergy policies, such as cost effectiveness, wider impacts across the economy, possible risks to food security, and potential impacts on biodiversity. It also does not examine the impacts of woody biomass use for heat, which we understand utilises mostly domestic rather than imported biomass feedstocks.

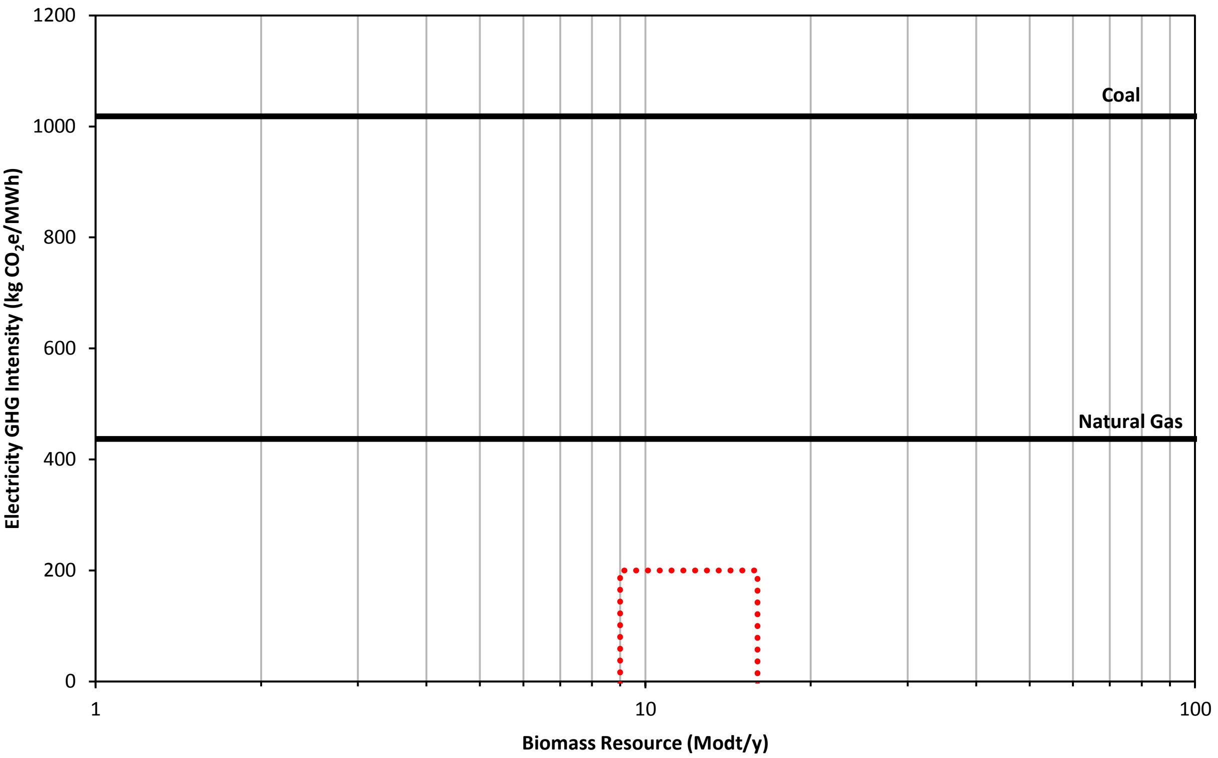

Figure 9. Summary of solid biomass requirements for UK electricity from biomass in 2020. The projected biomass requirement is between 9.0 and 16.0 Modt/y (see page 29 for details) and its GHG intensity, as defined by the EU Renewable Energy Directive LCA methodology, must be below 200 kg CO_2e/MWh.

Background

2020 Projections for Bioenergy in the UK

37. The projected delivered energy from biomass in the UK in 2020 is shown below in Figure 10; the total delivered energy (used for electricity, heat and transport) represents between 3.4 and 7.5% of projected 2020 energy consumption[19].

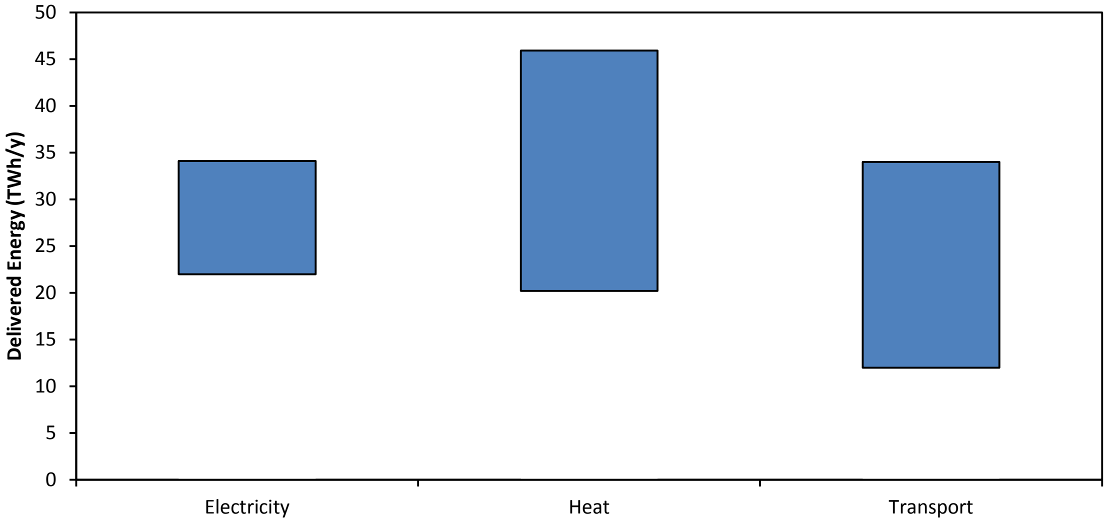

Figure 10. Projected delivered energy from biomass in 2020. The electricity figure corresponds to the EMR Delivery plan projections[20] of bioenergy from biomass conversions, dedicated CHP biomass, small-scale dedicated biomass, anaerobic digestion, landfill gas and sewage gas. Heat includes energy from solid biomass, biogas, biomethane, landfill gas, and biogenic waste[21].

38. In 2011, approximately 2.9 million oven dry tonnes (2.9 Modt) of solid biomass was used for electricity generation in the UK[22]. In 2020, we estimate that between 9.0 and 16.0 Modt/y of solid biomass will be required for electricity generation in the UK; this biomass will be used in power stations which have converted from being coal-fired to biomass-fired, as well as in new, dedicated biomass plants (including Combined Heat and Power plants). The UK will also require approximately 3.9 to 7.5 Modt/y of solid biomass for heat by 2020, resulting in a total demand of 12.9 to 23.5 Modt/y. The upper value is comparable to the total consumption of wood for all wood products (*e.g.* paper, furniture) in the UK in 2010 of approximately 21 Modt/y[23] (Forestry Commission, 2014). As the greatest demand for solid biomass in the UK is projected to be from the electricity sector in 2020, the use of biomass for electricity is the focus of this report.

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[19] Projected energy consumption in 2020 is 1530 to 1597 TWh/y (DECC, 2013b). This range includes projected aviation energy consumption.

[20] Future deployment of and generation by biomass technologies is uncertain, as this will depend on the relative costs of these technologies going forward. Given these uncertainties, DECC's Electricity Market Reform Delivery Plan (DECC, 2013) included a number of illustrative deployment and generation scenarios for use of biomass for electricity, which have been used to derive the electricity component of Figure 10. However, these scenarios are for illustration only and are not exhaustive.

[21] Heat projections to 2020 are illustrative only as budget and policy projections are currently only agreed up to the end of 2015/16.

[22] Using Ofgem (2012) data, and assuming pellets have 7 wt% moisture, and wood chips, energy crops and agricultural residues have 25 wt% moisture.

[23] 2010 figure of 45.9 M m^3, equivalent to 21.4 Modt/y assuming wood specific gravity of 0.467 odt/m^3 (average value for softwood and hardwood). Accounts for imports and exports.

Projection for Biomass Electricity in Other Countries

39. Between 2006 and 2012, the amount of electricity generated from biomass globally increased from 209 TWh/y to 373 TWh/y (IEA, 2013), equivalent to solid biomass requirements of approximately 133 Modt/y[24] in 2006, and 238 Modt/y in 2012. International trade of wood for energy also increased during this time, mainly in the form of wood pellets consumed in the EU, reaching 300 PJ in 2010 (~16 Modt) (Lamers *et al.*, 2014). The International Energy Agency projects that globally, the use of biomass for electricity will continue to increase, generating 463 TWh of electricity by 2015 (~ 295 Modt/y) and 560 TWh by 2018 (~ 357 Modt/y) (IEA, 2013). International trade in wood for energy is therefore also likely to continue to increase; in particular, it has been reported that Belgium, the Netherlands and Denmark are expected to increase the quantity of pellets they import for bioenergy in the future (Lamers *et al.*, 2014).

Feedstocks for Biomass Electricity

40. The 2.9 million oven dry tonnes of biomass used for electricity generation in the UK in 2011 were in the form of imported wood pellets (mainly from North America forestry), domestic wood chips (from UK forests), residues such as olive meal and straw (from UK and other countries) and energy crops such as Short Rotation Coppice (SRC) Willow and Miscanthus (from the UK) (Figure 11).

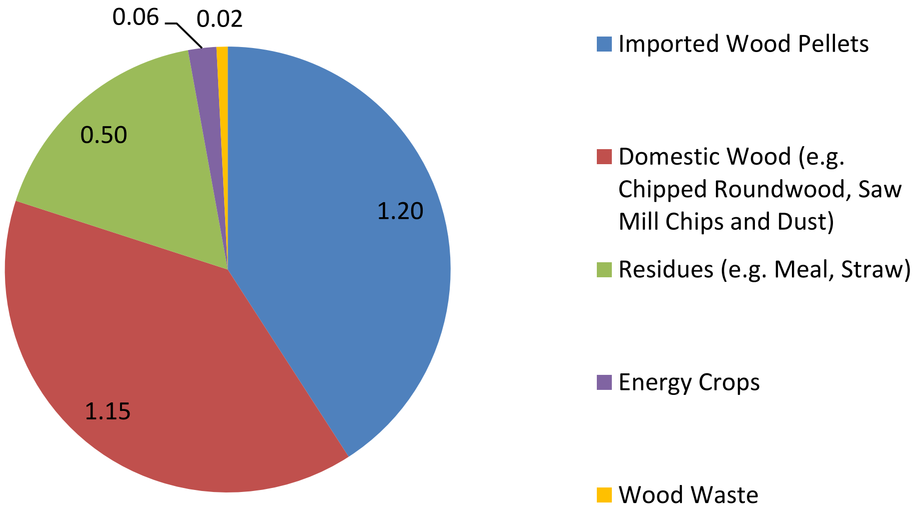

Figure 11. 2011-2012 solid biomass feedstocks, in million oven dry tonnes per year (Ofgem, 2012), assuming (i) pellets contain 7 wt% moisture, (ii) wood chips, energy crops and agricultural residues contain 25 wt% moisture.

41. The total wood harvest from UK forests for all uses (products, pulp and paper, fencing, wood fuel) is approximately 5.3 Modt/y[25] (Watson and Jarot, 2013). The Forestry Commission aims to increase harvest from English woodlands, so that another 1 Modt/y will be available for wood fuel (most likely for heat production) by 2020 (Forestry Commission England, 2007). It is therefore clear that the UK could not satisfy the projected 2020 solid biomass requirement of 12.9 to 23.5 Modt/y using biomass from UK forests alone. This point is emphasised by considering the forest area that would be required to provide the projected upper UK solid biomass

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[24] Assuming global average conversion efficiency of biomass to electricity of 30% (based on Lower Heating Value), and Lower Heating Value of dry biomass of 5.23 MWh/odt.

[25] 2012 figure of 10.6 M green tonnes, equivalent to 5.3 Modt assuming 50 wt% moisture.

requirement in 2020; the productivity of a typical managed UK coniferous forest is approximately 3.7 odt/ha/y, therefore the harvest of 23.5 Modt/y of wood corresponds to the whole harvest from 6.4 Mha of coniferous forest; or 20% of the whole harvest from 31.8 Mha. For comparison, the total UK forest area is 3 Mha[26], and the total UK land area is 24 Mha (Forestry Commission, 2014a).

42. It is possible that more agricultural residues and perennial energy crops could be used as solid biomass feedstocks by 2020 (DECC, 2013c). However, industry indicates that the majority of the biomass feedstocks used for electricity generation in the UK in 2020 are likely to be in the form of imported woody pellets, mainly from North American forests (NNFCC, 2013). The North American pellet industry is therefore expanding rapidly: in February 2014, the production capacity of operational pellet plants in the USA was 10.1 Mt pellets/y (~ 9.4 Modt/y[27]); a further capacity of 6.1 Mt pellets/y (~ 5.7 Modt/y) was planned or under construction. In Canada, the operational pellet production capacity at that time was 3.3 Mt pellets/y (~ 3.1 Modt/y) and a further capacity of 2.4 Mt pellets/y (~ 2.2 Modt/y) was planned or under construction (Biomass Magazine, 2014). In February 2014, the total operational and planned capacity in North America was therefore 22.0 Mt pellets/y (20.5 Modt/y). As the UK is not the only country importing pellets from North America for energy (IEA Bioenery, 2011; Lamers *et al*., 2014), it is conceivable that more pellet plants than those already planned may be built before 2020.

Traditional North American Forestry

43. North American forests are traditionally used for the production of wood for sawn timber (used in construction), veneer products, particleboard, fibreboard, paper products, and wood fuel. Saw logs are harvested to produce sawn timber, wood panels and veneer products used for construction; pulpwood and residues from saw log processing are used for the production of particleboard, fibreboard, paper products and wood fuel[28]. Table 4 shows how the wood harvested from North American forests is traditionally used, with the largest wood user being the paper industry.

Table 4. Proportions of total North American wood harvest used for sawn timber, paper, wood panels and wood fuel, between 2006 and 2011 (using wood product data from FAOSTAT, 2013, and specific wood densities from USDA, 2009a).

Final Wood Use	Proportion of total wood harvest (wt%)
Sawn Timber	19 - 25%
Paper	49 - 55%
Wood Based Panels[29]	15 - 17%
Wood Fuel	9 - 11%

44. Forests can be managed in different ways to produce different product distributions, depending on the desired proportion of saw logs and pulpwood. The rotation length

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[26] Consisting of both coniferous and broadleaf long-rotation forests; in the UK, broadleaf long-rotation forests generally have lower productivities than coniferous long-rotation forests.
[27] Assuming 7 wt% moisture content.
[28] See Table 2 for glossary.
[29] Includes fibreboard, particleboard, veneer sheets and plywood.

(time between harvests of a stand of trees), thinning practice, fertilisation, and tree regeneration method (*e.g.* planted or natural regeneration) all affect the final yield of wood and the proportion of saw logs and pulpwood produced.

45. Figure 12 shows how North American roundwood removals varied between 1970 and 2011 (FAOSTAT, 2013). Total North American harvest in 2012 was ~ 210 Modt/y, therefore the potential UK solid biomass requirement for electricity in 2020 of 9.0 to 16.0 Modt/y represents ~ 4.3 to 7.6% of this total harvest, and the total UK solid biomass requirement of 12.9 to 23.5 Modt/y represents 6.1 to 11.2%. Between 2005 and 2011 there was a sharp reduction in North American wood harvest, owing to the impacts of the recession on the housing markets and, to a lesser extent, a declining paper product market. This led to the saw log harvest reducing by ~ 73 Modt/y during this time horizon, and the pulpwood harvest reducing by ~ 14 Modt/y.

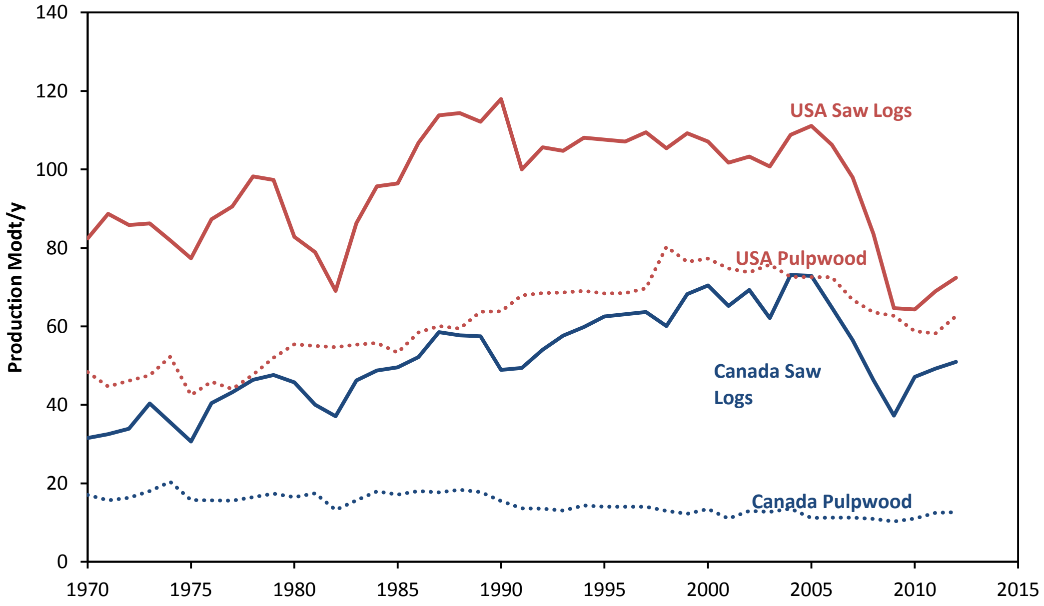

Figure 12. North American industrial volumetric roundwood removals between 1970 and 2012 (FAOSTAT, 2013), converted to oven-dry mass using average specific densities of 0.411 kg/m^3 for softwood and 0.523 kg/m^3 for hardwood, taken from United States Department for Agriculture (USDA, 2009a).

46. Wood consumption patterns vary depending on the specific region and wood type (softwood or hardwoods). For example, Figure 13 shows how softwood consumption in the Southern coastal states of the USA changed between 1990 and 2009; although the consumption of pine saw logs followed the same pattern as national data (Figure 12), pine pulpwood consumption increased during this period.

47. Traditional wood demand in the USA is starting to increase again as housing markets recover and demand for exports (*e.g.* to China) increases (Floyd, 2013); for example, from late 2012 through the first quarter of 2014, more than 4 billion ft^2 (0.37 billion m^2) of idled OSB manufacturing capacity was restarted, and RISI (2014) predicts that demand will “catch back up with and even surpass supply growth in the medium term”. It is predicted that by 2020, the wood removal from USA forests for traditional wood industries will be at least back to pre-recession levels, and after this, wood harvest will continue to increase (Forisk, 2011; Ince and Nepal, 2012; FAO and UNECE, 2012). The US Department for Agriculture has projected that the 2060 USA wood harvest will be nearly double that of 2010, with increased production of saw logs and veneer logs (for construction), and pulpwood (for paper products and composite products such as OSB). Although paper product consumption in the USA

is expected to continue to decrease, wood pulp production is projected to increase up to 2030 owing to growth in exports (Ince and Nepal, 2012).

48. Canadian wood harvest is projected to increase to pre-recession levels by 2015, then stay fairly stable or decline slowly up to 2030, with an increase in the harvest of wood for paper products and wood based panels being roughly cancelled out by a decrease in the harvest of wood for sawn timber (FAO and UNECE, 2012). It is important to emphasise that caution should be made when using such projections, as they are based on economic assumptions about the future, which are uncertain.

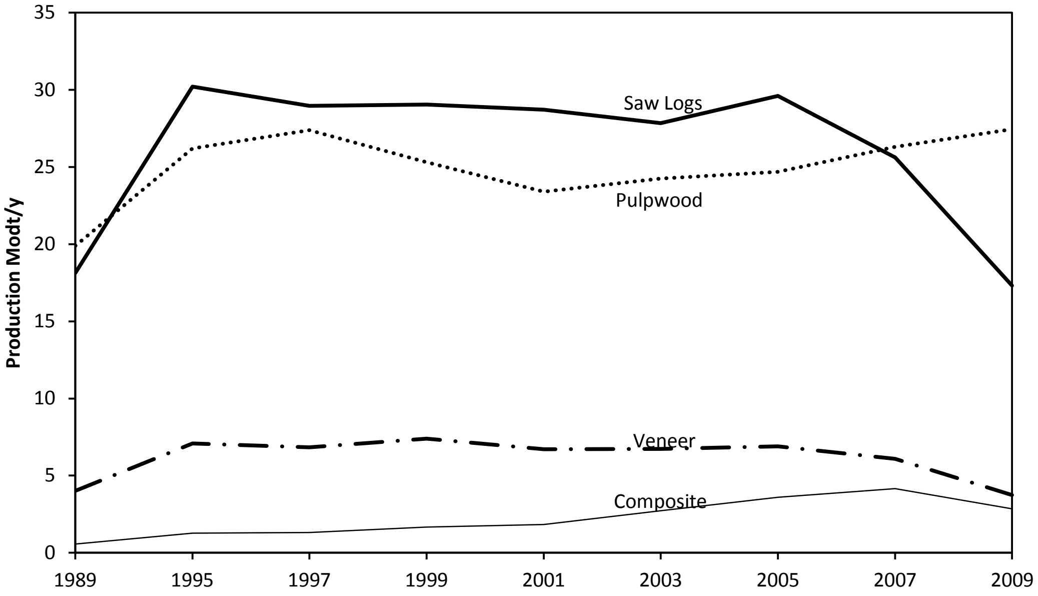

Figure 13. South USA Coastal States industrial pine wood removals between 1990 and 2009 (Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, Texas, Virginia). Volumetric consumption from USDA (2012a); assuming specific gravity of Loblolly pine (0.469 odt/m^3) to convert to Modt/y (Smith *et al*., 2006).

North American Forest Inventories

49. Since 1952, US forests have been growing faster than they have been harvested, causing the inventory of wood, and hence carbon, to increase. For example, between 1953 and 1997, the US growing stock volume increased from 17,430 to 23,650 Mm^3, despite the rate of removal increasing from 336 to 453 Mm^3/y (USDA, 2001). In 2006, privately owned US forests (representing 56% of US forest land, and 92% of harvested wood output; Smith *et al*., 2010) were growing at a rate ~ 30% greater than they were being harvested (*e.g.* Growth:Drain ratio of 1.3), and public forests were growing at a rate ~ 430% greater than harvest (*e.g.* Growth:Drain ratio of 5.3) (US DOE, 2011).

50. This increase in inventory in US forests is a result of a number of factors, including:

- The existence of publically owned natural forests, that produce little timber and therefore have large Growth:Drain ratios (Smith *et al*., 2010). The area of reserved forest doubled between 1953 and 1997 (USDA, 2001).
- Tree planting and conservation efforts in the 1970s and 1980s (US Environmental Protection Agency, 2013).
- The movement of agricultural land from the East to the Mid-West since the 1950s, resulting in marginal agricultural land in the East reverting to forests (Smith *et al*.,

2010; Fernholz *et al*., 2013; USDA, 2012). Overall, the total US forest land area increased by 4% between 1987 and 2007 (Smith *et al*., 2010).

- The age distribution of US forests. Significant areas of forest had not yet reached their equilibrium carbon storage in 2010, and were therefore continuing to grow. However, the new forests which have been established on the previous agricultural land in the East are now approaching maturity, therefore growth is slowing down (USDA, 2012).
- Increased wood recycling and increasingly efficient wood processing techniques, reducing the wastage of wood. US saw-mills have reduced the amount of wood incinerated as a waste from 41 - 45% in 1940 to less than 1% in 2005 (Fernholz *et al*., 2013).
- Increased productivities, and hence wood outputs from intensively-managed plantations, reducing pressure on other forests (Fernholz *et al*., 2013; US Environmental Protection Agency, 2013).
- Decreased harvest during the recession (Ince and Nepal, 2012).
- A diverse wood industry resulting in it being economically competitive for private land owners to grow trees (Fernholz *et al*., 2013).

51. This increased forest inventory has been an important carbon sink in the US LULUCF (Land Use Change, Land Use Change, and Forestry) inventory; in 2011, the CO_2 removed from the atmosphere from the LULUCF sector offset about 14% of total US greenhouse gas emissions (US Environmental Protection Agency, 2014). The US Department of Agriculture has projected that the future US forest inventory will continue to increase up to 2060 (Ince and Nepal, 2012); however, this, or the extent of the increase of the inventory, will depend on future harvest rates (including harvest for wood energy) and future land use change patterns (Ince and Nepal, 2012; USDA, 2012).

52. In Canada, the story is different, as erratic patterns of natural disturbances such as wildfires and insect breakouts tends to mask underlying patterns. Between 2005 and 2010, the forest inventory reduced by an average of 23 Mt carbon each year (equivalent to 46 Modt/y of biomass) (FAO, 2010). This reduction was predominantly caused by the mountain pine beetle reducing stored carbon in forests in Pacific Canada.

North American Wood Pellets

53. In 2010, the vast majority of pellet plants relied on saw-mill residues as feedstock; however, in several countries, demand for wood pellets was already outstripping the supply (IEA Bioenergy, 2011). Furthermore, large-scale pellet consumers such as power plants require medium and long term supply agreements with well-defined volumes and prices; the IEA (2010) have reported that this growing need for feedstock price and volume stability conflicts with the volatile supply situation of the residue stream of the saw-milling industry. The IEA therefore claim that the pellet industry aims to use other feedstocks in the future, such as forest residues, dead wood from natural disturbance events, and industrial roundwood (IEA Bioenergy, 2011). Other publications also recognise this, including a report by the USDA on North America's Wood Pellet industry, which states that roundwood and beetle-killed trees are the most likely primary future feedstocks, owing to their availability in large

volumes (USDA, 2009). In 2012, the Wood Pellet Association of Canada also reported that forest residues and ‘whole tree chipping’ are being used to a greater degree for pellet manufacture, for the same reasons (Wood Pellet Association of Canada, 2012).

54. In South USA, the majority of pellets are produced from roundwood, and wood residues are used to dry the biomass prior to pelletisation (Forest2Market, 2013). As well as providing a more reliable supply chain than saw-mill residues, the use of this feedstock ensures the production of pellets of consistent quality (IEA Bioenergy, 2011; USDA, 2009; Wood Pellet Association of Canada, 2012). Figure 14 shows the world’s largest pellet facility (producing 750,000 t pellets per year), run by Georgia Biomass and owned by RWE Innogy, which uses roundwood for the production of their pellets.

Figure 14. Aerial view of Georgia Biomass plant at Waycross, Georgia, South USA (Georgia Biomass, 2014). Copyright Georgia Biomass, reproduced with permission.

55. Saw logs have a greater economic value than the pulpwood, as can be seen in Figure 15, which shows how the stumpage price of each classification of softwood roundwood in the South USA has changed since 1980[30]. Owing to this price differential, saw logs are generally used for high value wood products (*e.g.* flooring, window frames), and the lower value pulpwood is used for the production of lower value commodities, such as wood pellets, paper products and particleboard (Forisk, 2011a). Forked trees and large logs that are big enough to be saw logs, but have too many defects to be graded as saw logs, are also used to produce these lower value commodities. Figure 15 shows that the value of each wood product can vary significantly over time, depending on the market conditions; for example, the value of pine sawn timber in South USA decreased after 2008, owing to a reduction in demand caused by the collapse of the US house-building sector (Ince and Nepal, 2012), but the value of pulpwood increased.

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[30] See Table 2 for glossary of terms.

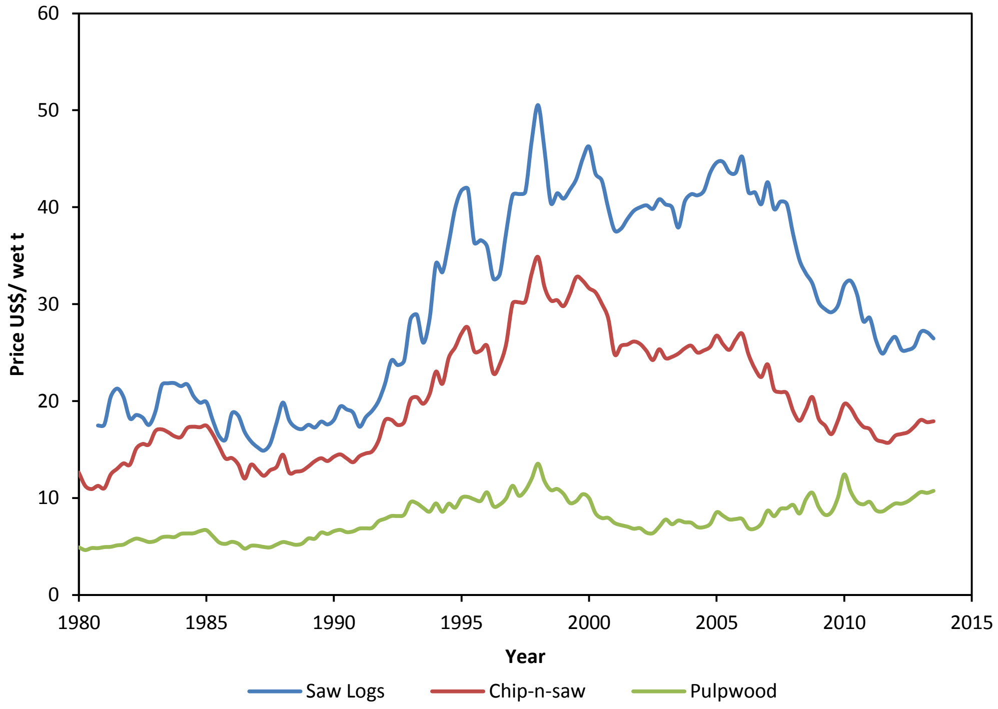

Figure 15. South USA average stumpage prices of pine saw logs, chip-n-saw and pulpwood. Units in US $/metric green tonne (~ 50 wt% water). Data obtained from Timber Mart-South, 2014.

56. Figure 16 shows estimations of the key prices in 2013 contributing to the cost of producing pellets in South USA from pine pulpwood, and shipping to the UK for electricity generation. The pelletisation and transport contribute the most to the overall cost of pellet production, with pelletising representing 40% of the total cost in Figure 16, and shipping representing 23%; the stumpage cost of softwood pulpwood represents a smaller proportion of the overall cost of production (~ 13% for in Figure 16). Pellet price indices, which started to be published in 2008, indicate that pellet prices have been stable historically. However, it is estimated that only 5 to 7% of traded pellets prices are public, therefore these price indices may not accurately reflect settlement prices (Bloomberg New Energy Finance, 2013). DECC therefore uses fuel price estimates that are based on both published indices and direct contract prices derived from discussions with suppliers and generators[31]. Bloomberg project that the price of pellets is likely to increase in the future, owing to increased competition for the raw material, and increasing shipping costs (Bloomberg New Energy Finance, 2013).

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[31] DECC's price assumptions can be found in our 2013 Electricity Generation Cost Report. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf.

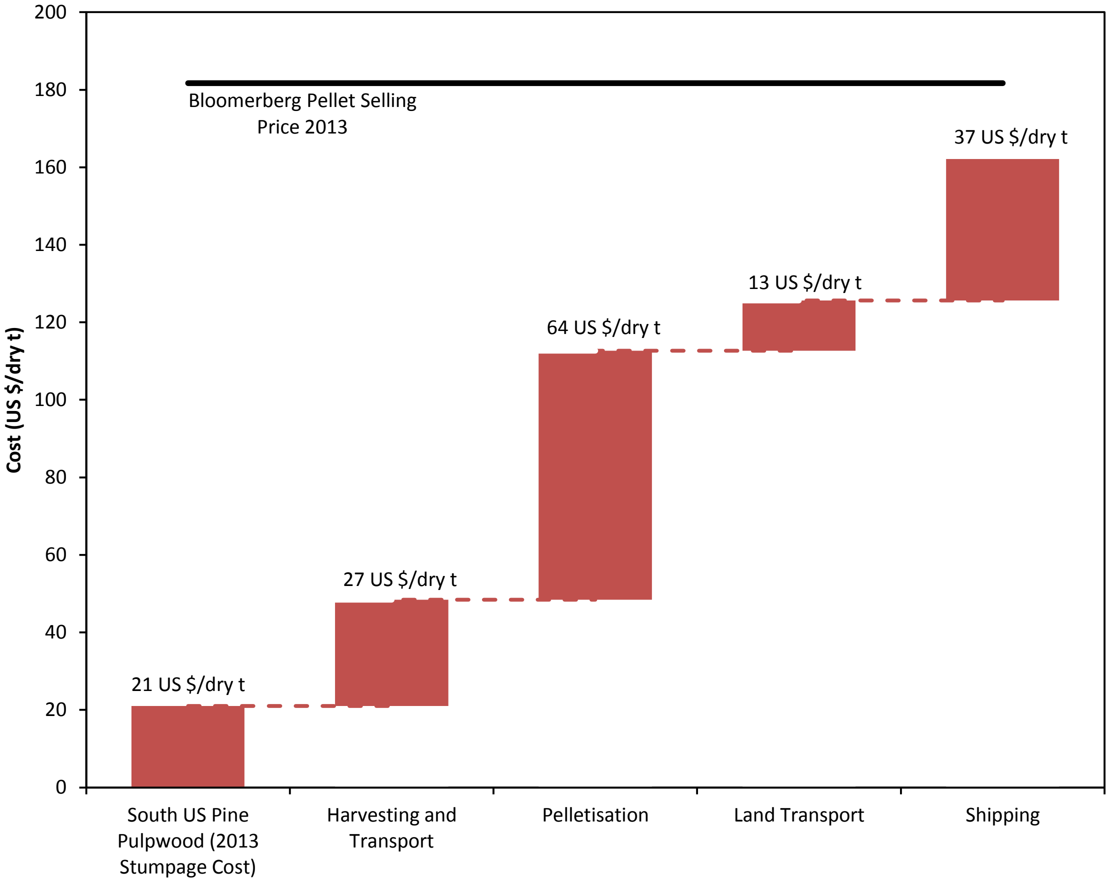

Figure 16. Example 2013 prices for pellets produced from softwood pulpwood, shipped from South USA to UK (assumed 7150 km) and used in biomass power plants. Sources: South USA pine pulpwood stumpage cost from Figure 15 ($10.5/green t); harvesting and transport, pelletising, land transport, and shipping estimated 2013 costs from Bloomberg New Energy Finance (2013). Pellets assumed to have a moisture content of 7 wt%.

Potential Impacts of Increased Demand for Wood for Energy

57. The bioenergy industry have stated that the value of wood used for the production of wood pellets for bioenergy is too low to cause any changes to management practices (AEBIOM *et al.*, 2013), and that the roundwood used for bioenergy is pulpwood that would be harvested anyway as part of the management practice used to produce of saw logs for construction (*e.g.* in thinning operations). It is claimed that owing to a depressed pulp and paper market, this pulpwood would have no other use; this would mean the use of the wood for bioenergy would not cause any indirect effects[32], such as indirect land use change.

58. However, others (*e.g.* Walker *et al.*, 2010; Abt *et al.* 2012) have reported that an increased demand of pulpwood for bioenergy could result in a higher economic value, which could affect the management practices of forests, or cause the displacement of wood products which use the same raw material. In Germany, it has been reported that since the installation of bioenergy systems (mainly CHP and biomass boilers), the value per tonne of woody biomass used for bioenergy has increased to 60% - 70% of the value of saw logs (Schulze *et al.*, 2012). It is,

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[32] Indirect effects: If wood used for pellet production would otherwise have been used for the production of a different commodity, the displaced commodity would have to be produced by another method (*e.g.* from wood harvested elsewhere, or using non-wood alternatives), which would have associated resource costs and GHG emissions.

however, important to note that the North American and German wood product industries are different, and therefore the price responses to an increased demand for wood for bioenergy would also be different. Abt *et al.* (2012) modelled the impact of increased demand for domestic biomass on pulpwood prices in South USA (Alabama, Florida and Georgia); for a future woody biomass demand of ~ 14 Modt/y (on top of ~ 47.5 Modt/y demand from traditional products), they projected that the pulpwood price would increase to between 130% and 200% of 2007 prices by 2037 (based on the assumption that wood supply and demand is price inelastic). In South USA, where many new pellet facilities that use pulpwood as a feedstock are being established, it has been reported that the demand for pine pulpwood from OSB and pellet manufacture increased between Quarter 2 of 2012 and 2013, contributing to a 10% increase in the stumpage price of pine pulpwood (Forest2Market, 2013). Hardwood pulpwood prices in the region are also on an upwards trend (Forest2Market, 2013; Forest2Market, 2013a; Timber Mart-South, 2014).

59. There are several potential effects on forests of high pulpwood prices. Abt and Abt (2013) reported that a high demand for wood pulp for energy in South USA could result in (i) an increased rate of harvest of existing forests (ii) the displacement of wood used for non-bioenergy wood products, and (iii) the establishment of more intensively-managed plantations. In the past, new pine plantations in the South USA have been established on both productive naturally-regenerated timberland and agricultural land (Wear and Greis, 2002). Walker *et al.* (2010) considered the impact of increased biomass stumpage prices on harvest levels in forests in Massachusetts, and reported similar potential effects as Abt and Abt. They predicted that an increase in the price of wood for energy from the price at the time of $US 1-2/green short ton ($US 2.2 to 4.4/dry t) to up to $US 20/green short ton ($US 44/dry t) could result in (i) more forests being harvested, (ii) the displacement of wood used for traditional wood products, and (iii) the intensity of harvest operations increasing.

60. Another potential impact is that the management practices of current forestland could change in order to produce more pulpwood. Henderson and Munn (2012) reported that if the pulpwood stumpage price of Loblolly pine plantations in South USA were to increase to 44 to 84% of the saw log price (currently this value is ~ 30%), pulpwood only regimes would become financially preferable to the current mixed-product regimes; it is important to note that saw log prices are projected to increase in the region as the construction market picks up, therefore this scenario represents a case where the pulpwood price also increases but at a substantially greater rate than saw log prices. The relative stumpage price of pulpwood and saw logs is not the only factor determining how foresters manage pine plantations in South USA; the stability and resilience of the product market is also highly important, therefore for pulpwood only plantations to be viable, the pulpwood market (*e.g.* for paper, OSB and bioenergy) would require long-term stability.

61. It has also been projected that the increased demand for wood for energy could result in less forest being converted to other uses, such as agricultural land, in the future. For example, in 2012 the US Forest Service estimated how US forest area and inventory would change between 2010 and 2060, considering IPCC 2007 assumptions and projections of global population growth, economic growth, bioenergy use and climate (USDA, 2012)[33]. Two of the scenarios investigated assumed the same economic and population assumptions, but varied future demand for biomass for bioenergy, with one scenario assuming the high IPCC 2007 projected

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[33] It is important to note that this analysis was based on IPCC 2007 economic projections, and did not account for the collapse in US housing construction after the recession, or the expansion of unconventional oil and gas production *via* hydraulic fracturing and horizontal drilling, which would affect the US forest inventory and demand for wood for energy.

increase in global bioenergy use (named RPA-A1B), and the other assuming bioenergy use based on historical use in all countries (RPA-A1B HFW). The scenario with the higher demand for bioenergy (RPA-A1B) resulted in a larger area of US forest in all analysed years (2010 to 2060), as a result of less land being converted to other uses[34]. However, the high bioenergy scenario (RPA-A1B) also resulted in a significantly lower overall US forest inventory (hence carbon stock) than the low bioenergy scenario (RPA-A1B HFW), as a result of the increased harvest for bioenergy[35].

62. We can also learn about the implications of increased prices of pulpwood by considering what happened in the past, when demand for wood for pulp and paper increased in South USA in the 1990s (see box 1).

Box 1. Case Study: Response to increased demand for pulp and paper in the 1990s

In the 1990s, the demand for wood as a raw material for the production of paper increased in South USA, owing to an overall increase in demand in the USA coinciding with declining production in the West USA. As demand grew, resources became limited, and therefore wood was used more efficiently. However, producers were not able to increase output as fast as the demand increased, therefore the price for the paper feedstock increased (by ~15% between 1990 and 1998 for softwood and 100% for hardwood). This led to increased investment in forest productivity; intensively-managed plantations were established that used genetically selected[36] trees and were managed using advanced silvilcultural techniques (*e.g.* thinning, fertilisation and vegetation management). These intensively-managed plantations were established on agricultural land, as well as on naturally-regenerated forests, and less-productive plantations. Hardwood forests were also harvested to a greater extent, and whole-tree chipping was introduced in areas not previously subject to harvesting (Wear and Greis, 2002).

63. In summary, a higher value for pulpwood for pellets and other uses (*e.g.* paper products and OSB) could lead to:

- an increase in the rate of harvest of existing forests, lowering the average age of trees (Abt and Abt, 2013; Walker *et al.*, 2010; Schulze *et al.*, 2012; Weir and Greis, 2000; Holtsmark, 2012);
- changes in the management practice of current forests (other than rate of harvest) to produce more wood for bioenergy (Walker *et al.*, 2010; Henderson and Munn, 2012);
- the conversion of naturally-regenerated forests to intensively-managed, genetically-selected plantations, which are highly productive (Abt *et al.*, 2012; Evans *et al.*, 2013; Davis *et al.*, 2012; USDA, 2012; Zhang and Polyakov, 2010);
- the establishment of new plantations on current agricultural land (Abt *et al.*, 2012; Davis *et al.*, 2012; Zhang and Polyakov, 2010; Sedjo *et al.*, 2013);
- the use of pulpwood for bioenergy, causing the displacement of non-bioenergy wood uses (Sedjo *et al.*, 2013., Abt and Abt, 2013; Abt *et al.*, 2012); and

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[34] Figure 34 in USDA (2012).

[35] Figure 41 in USDA (2012).

[36] *Via* selective breeding, not genetic modification.

- the prevention of some productive forests being converted to other uses, such as agricultural land (USDA, 2012; Abt *et al*., 2012).

Greenhouse Gas Intensity of Bioenergy

64. Under the Climate Change Act of 2008, the UK must reduce its GHG emissions by at least 80% on 1990 levels. It was reported in the UK Government's 2011 Carbon Plan that to achieve this, the electrical grid GHG intensity should reduce to between 50 and 100 kg CO_2e/MWh by 2030 (H M Government, 2011). As biomass electricity is projected to provide a significant proportion of the UK's primary energy, it is therefore important that biomass policies deliver energy with GHG intensities consistent with these decarbonisation targets. This is reflected in Principle 1 of the UK Government's 2012 UK Bioenergy Strategy: "Policies that support bioenergy should deliver genuine carbon reductions that help meet UK carbon emissions objectives to 2050 and beyond (DECC, DfT and DEFRA, 2012)."

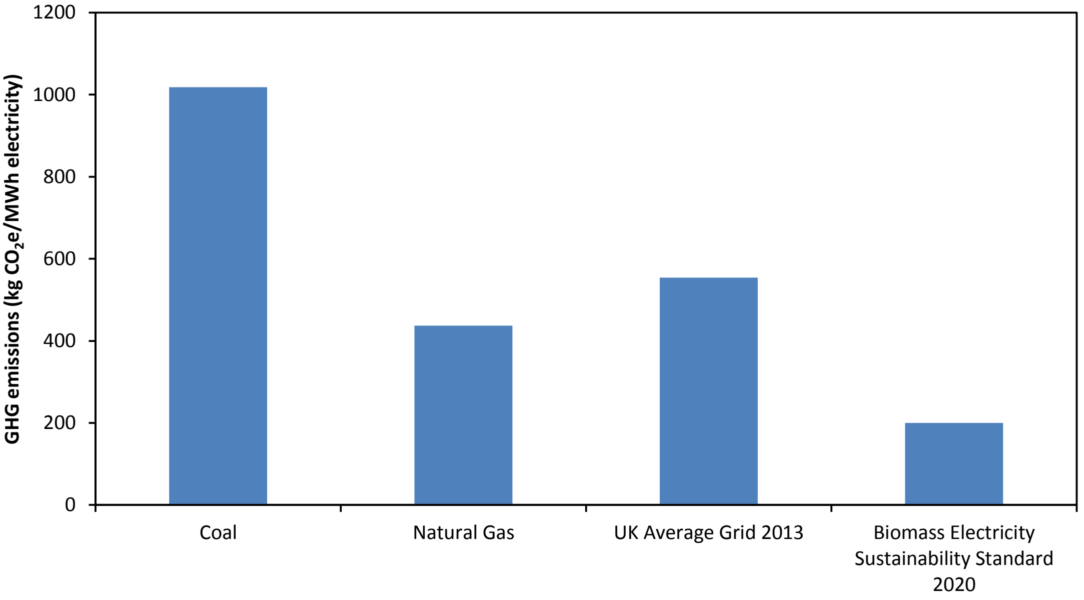

Figure 17. Electricity from coal: assumes average UK fleet efficiency of 35.7% based on Higher Heating Value (HHV) of coal (DUKES, 2013), and total GHG emissions based on coal HHV of 0.363 kg CO_2/kWh primary energy (DEFRA, 2013). Natural Gas: assumes average UK fleet efficiency of 48.5% based on HHV of natural gas (DUKES, 2013), and total GHG emissions based on natural gas HHV of 0.212 kg CO_2/kWh primary energy (DEFRA, 2013). UK Average Grid: data from (DEFRA, 2013). Total emissions include those emitted at the point of generation, as well as those emitted prior to the point of generation, including those from extracting and transforming the primary energy source into the energy carrier, and distributing the fuel; emissions from the production of vehicles, machinery or infrastructure are not included.

65. DECC recently published sustainability criteria for biomass feedstocks supported under the Renewable Obligation (RO), stating that electricity from biomass which is subsidised by the RO must be proven to generate electricity with a maximum GHG emission intensity of 285 kg CO_2e/MWh[37] from April 2014[38], and 200 kg CO_2e/MWh from April 2020 (DECC, 2013a). Figure 17 shows how 200 kg CO_2e/MWh compares to the Life Cycle emissions associated with electricity from coal, natural gas, and the UK average electricity grid GHG intensity.

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[37] The unit kg CO_2e/MWh is equivalent to g CO_2e/kWh.

[38] Apart from new, dedicated biomass power plants, which must meet 240 kg CO_2e/MWh.

66. To meet the sustainability criteria, the GHG intensity of biomass electricity must be calculated using the LCA methodology recommended by the European Commission in their 2010 report on biomass sustainability (European Commission, 2010), which is based on the LCA methodology set out in Annex V of the EU Renewable Energy Directive (2009/28/EC). Electricity generators can use the UK Solid and Gaseous Biomass Carbon Calculator to report their bioenergy GHG emissions, in accordance with this LCA methodology.

67. The LCA methodology of the Renewable Energy Directive (2009/28/EC) accounts for emissions from:

- cultivation;
- harvesting;
- direct land use change where the land use has changed category since 2008, *e.g.* from annual crop land to forest, grassland to annual crop land;
- soil organic carbon (SOC) accumulation from improved management;
- processing;
- transport and distribution;
- the final energy generating process;
- carbon capture and geological storage; and,
- carbon capture and replacement[39].

68. However, the following factors are not considered in the Renewable Energy Directive (2009/28/EC) LCA methodology:

- Carbon debt: when a stand of trees in a forest is harvested all at once and replanted (or left to regenerate), it takes time (possibly several decades) for the trees to re-grow to their pre-harvest mass. Until that time, the amount of carbon stored on the stand is lower than it was before harvest. If the wood removed from the land is combusted, the net reduction in carbon stored on the land would cause an equivalent temporary increase in carbon in the atmosphere. This term considers carbon impacts at the stand level rather than at the overall forest level (see page 48 for the difference between stand and forest level).
- Changes in average forest carbon stock: the average carbon stored in a forest consisting of multiple stands can change over time if, for example, forest management practices change (*e.g.* harvest rates, silvicultural regimes, or tree species change). This term considers carbon impacts at the overall forest level, rather than stand level.
- Foregone carbon sequestration: if the harvest of trees in a forest stops or reduces, the forest would likely continue to grow and reach a new equilibrium carbon stock. If this is the alternative (or counterfactual) to continuing to harvest a forest, the foregone carbon sequestration is the sequestration which has been prevented by the continued harvesting. This term considers carbon impacts at the overall forest level, rather than stand level.

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[39] Defined by European Commission as emissions avoided through the capture of CO_2 of which the carbon originates from biomass and which is used to replace fossil-derived CO_2 used in commercial products and services.

- Indirect impacts: If land used for bioenergy would otherwise have been used for the production of a different commodity, the displaced commodity may be produced by another method (*e.g.* from wood harvested elsewhere, or using non-biomass alternatives), which would have associated resource costs and GHG emissions.

69. It is well known that deforestation and degradation of forests can result in significant CO_2 emissions to the atmosphere; as a result the UK is committed to the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD)[40]. However, recent reports have shown that the factors listed above (paragraph 68) are also important as they can have significant impacts on the total GHG intensities of some types of biomass feedstocks (Agostini *et al.*, 2013; European Environment Agency, 2011; Mitchell *et al.*, 2012; Guest *et al.*, 2013; Repo *et al.*, 2010; Baral and Malins, 2014; Daigneault *et al.*, 2012).

70. Baral and Malins (2014) stated that for harvesting cycles longer than 10 years, the impact of temporary biogenic emissions can be significant and therefore should not be ignored. Abt *et al.* (2012) reported that if increased demand for pulpwood in South USA were to cause new pine plantations to be established on agricultural land, the total amount of carbon stored in forests in the region would increase compared to the counterfactual (potential indirect impacts were not considered in this study[41]). Repo *et al.* (2014) showed that increasing bioenergy production from forest harvest residues in Europe would decrease organic material stored at the harvest site, which could reduce the carbon stock and sink of forests. Although the reduction was found to be small compared to the size of the overall carbon stocks, it was found to be significant in comparison to the amount of energy produced from the residues[42].

71. It is clear that these impacts need to be considered for complete LCA analysis. As the function of the UK Solid and Gaseous Biomass Carbon Calculator is to provide a regulatory method which can be used for the purposes of compliance monitoring against the Renewable Energy Directive LCA methodology, it is not intended for research purposes and therefore not designed to be used to investigate the impact of the factors listed above. DECC has therefore developed the Biomass Emissions And Counterfactual (BEAC) model for this purpose.

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[40] A financial value is created for the carbon stored in forests in developing countries, offering incentives for these countries to reduce emissions from forested lands.

[41] See glossary for definition of indirect impacts.

[42] forest harvest residues would need to be continued for 60 - 80 years to achieve a 60% carbon dioxide (CO_2) emission reduction in heat and power generation compared to the fossil fuels it replaces in most European countries (Repo *et al.*, 2014).

Methodology

Construction of Scenarios

72. Scenarios have been constructed to represent North American woody feedstocks that are currently used for the production of pellets (*e.g.* pellets from saw-mill residues, dead trees from natural disturbances, and pulpwood), as well as potential future scenarios which might come to pass if the demand for biomass were to increase significantly in the future (*e.g.* pellets from wood derived from new, dedicated plantations). Peer-reviewed literature has been used to construct these scenarios, as well as discussions with key stakeholders. We have included not only scenarios judged plausible and desirable, but also some scenarios that might be judged implausible or undesirable, so as to illustrate negative consequences that policies should ensure are avoided. Care should therefore be taken in interpreting the outputs from this study since the scenarios and counterfactuals modelled are not equally realistic; environmental, economic and social factors will all play a part in determining which of these scenarios could play out in the future.

73. The BEAC model allows the user to investigate the GHG impacts of bioenergy scenarios that cause a change in the amount of wood products used for construction, resulting in a change in the amount of non-wood alternative products used for construction. For example, if wood used for bioenergy would otherwise have been used to produce particleboard, the user of BEAC can consider the GHG impact of replacing the particleboard with a non-wood material (for example, concrete breeze blocks).

74. In North America, the majority of houses are built from wood products, with 90 - 94% of one- and two-family house constructions being built from wood in the USA, and 76 - 85% of those in Canada (Lippke *et al.*, 2011). Using non-wood alternatives for housing construction in North America would require a fundamental shift in building design and cultural acceptance; it was therefore considered unlikely that the amount of non-wood products used for house construction in North America would change as a result of wood demand for bioenergy.

75. Such scenarios have therefore not been reported in this study. Instead, it is more likely that increased demand for wood for bioenergy would result in more wood being harvested for bioenergy, therefore scenarios representing this outcome have been considered. For these scenarios, it has been assumed that the additional wood, in comparison to the counterfactual, is used for bioenergy, and that there is no difference in the amount of wood used for non-bioenergy uses between the bioenergy scenario and its counterfactual scenario. This is similar to the approach taken by Walker *et al.*, 2010.

76. The scenarios are grouped by the wood that is turned into pellets as follows:

- forest residues without an alternative market;
- additional roundwood harvest from naturally-regenerated timberland;
- roundwood (*e.g* pulpwood) from existing plantations;

- wood for bioenergy displacing non-bioenergy uses, causing additional wood to be imported;
- additional wood harvest from establishing new plantations (energy crops and intensively-managed pine) on naturally-regenerated timberland in South USA;
- additional wood harvest from establishing new plantations (energy crops and intensively-managed pine) on abandoned agricultural land.

77. Counterfactual land uses have been chosen for each scenario, representing what the land would be used for if it were not used to generate the bioenergy feedstocks. For example, if wood pellets are generated from forest residues that do not have an alternative market, the counterfactuals include:

- leaving the woody residues to decay in the forest after harvest;
- removing the residues from the forest and burning them at the roadside.

78. A full list of the scenarios is shown below in Table 5. All scenarios are specific to wood produced in North America. However, as biomass is globally traded, the additional use of North American wood for bioenergy could impact the demand for imported wood (*e.g.* wood imported by the USA from Canada or South America), which is reflected in Scenarios 19 to 21.

Table 5. Scenarios for UK Bioelectricity from North American Wood Pellets.

Scenario number	Feedstock used for pellets	Counterfactual scenario	Page number for section
Woody Residues			
Saw-mill Residues			*55*
1	(a) Saw-mill residues in South USA; no drying. (b) Saw-mill residues in Pacific Canada; no drying.	Burn as a waste (no energy recovery).	
2	(a) Saw-mill residues in South USA; dry from 25 wt% to 10 wt% moisture. (b) Saw-mill residues in Pacific Canada; dry from 25 wt% to 10 wt% moisture.	Burn as a waste (no energy recovery).	
3	(a) Saw-mill residues in South USA; dry from 50 wt% to 10 wt% moisture. (b) Saw-mill residues in Pacific Canada; dry from 50 wt% to 10 wt% moisture.	Burn as a waste (no energy recovery).	
Forest Residues			*61*
4	(a) Coarse forest residues, removed from forests in South USA, continuously over the time horizon. (b) Coarse forest residues, removed from forests in Pacific Canada, continuously over the time horizon.	Leave all residues in the forest.	
5	(a) Fine forest residues, removed from forests in South USA, continuously over the time horizon. (b) Fine forest residues, removed from forests in Pacific Canada, continuously over the time horizon.	Leave all residues in the forest.	
6	(a) Coarse forest residues, removed from forests in South USA, for 15 years only (then residues are left in the forest	Leave all residues in the forest.	

Scenario number	Feedstock used for pellets	Counterfactual scenario	Page number for section
	again). For example when analysed over a time horizon of 40 years, this involves the removal of residues for the first 15 years, then leaving the residues in the forest for the last 25 years of the time horizon. (b) Coarse forest residues, removed from forests in Pacific Canada, for 15 years only (then residues are left in the forest again).		
7	(a) Fine forest residues, removed from forests in South USA, for 15 years only (then residues are left in the forest again). (b) Fine forest residues, removed from forests in Pacific Canada, for 15 years only (then residues are left in the forest again).	Leave all residues in the forest.	
8	(a) Forest residues (both coarse and fine), removed from forests in South USA, continuously over the time horizon. (b) Forest residues (coarse and fine), removed from forests in Pacific Canada, continuously over the time horizon.	Burn the residues at the roadside as a waste.	
Dead Trees from Natural Disturbances			*70*
9	Salvaged dead trees, which have been killed by the mountain pine beetle in Pacific Canada.	(a) Leave in the forest. (b) Remove and burn at the roadside.	
Roundwood and Energy Crops			
Increased harvest of Naturally-Regenerated Forests			*77*
10	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated hardwood forest in East Canada (a) from every 100 years to every 50 years, (b) from every 100 years to every 80 years.	Continue harvesting the forest every 100 years.	
11	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated conifer forest in Pacific Canada from every 70 years to every 50 years.	Continue harvesting the forest every 70 years.	
12	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated conifer forest in boreal Interior-West Canada (a) from every 100 years to every 50 years, (b) from every 100 years to every 80 years.	Continue harvesting the forest every 100 years.	
13	(a) Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated hardwood forest in South USA from every 70 years to every 60 years.	(a) Continue harvesting the forest every 70 years.	
	(b) Additional wood (in comparison to the	(b) Reduce the rate of harvest to	

Scenario number	Feedstock used for pellets	Counterfactual scenario	Page number for section
	counterfactual) generated by continuing harvesting a naturally-regenerated hardwood forest in South USA every 70 years	every 80 years.	
Existing Intensively-managed Plantations			*87*
14	Additional wood (in comparison to the counterfactual) from intensively-managed pine plantation, in South USA. (a) Continue harvesting every 25 years, (b) increased demand for pulpwood results in the rotation length reducing to 20 years.	Reducing the frequency of harvest to every 35 years.	
15	Same as Scenario 14.	Converted over 50 years to an even-aged naturally-regenerated pine forest that is harvested every 50 years.	
16	Same as Scenario 14.	Converted over 25 years to a naturally-regenerated pine forest that is left to continuously sequester carbon, rather than harvested.	
17	Same as Scenario 14.	Converted over 25 years to agricultural land (*e.g.* cotton plantation).	
18	Additional wood (in comparison to the counterfactual) from increasing the management intensity (and hence yield) of a pine plantation in South USA that is harvested every 25 years (*e.g.* adopting optimal thinning practices and initial planting densities; Will *et al.*, 2006).	Continue previous management regime (medium-intensity management practices, harvested every 25 years).	
Displacing Non-Bioenergy Wood Uses			*97*
19	Pulpwood from South USA, causing indirect impact of Eucalyptus plantation replacing Brazilian rainforest.	Pulpwood used for non-bioenergy purposes.	
20	Pulpwood from South USA, causing indirect impact of Eucalyptus plantation replacing Brazilian abandoned degraded pasture land, which would otherwise revert to tropical savannah (IEA, 2011).	Pulpwood used for non-bioenergy purposes.	
21	Pulpwood from South USA, causing indirect impact of increasing the harvest rate of naturally-regenerated coniferous forest in Pacific Canada, from every 70 years to every 50 years.	Pulpwood used for non-bioenergy purposes.	
New Plantations Replacing Naturally-regenerated Forests in South USA			*103*
22	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated coniferous forest in South USA that is harvested every 50 years, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years.	Continue harvesting the forest every 50 years, and leaving to regenerate naturally.	
23	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated coniferous forest in South USA that is harvested every 50 years, to	Continue harvesting the forest every 50 years, and leaving to regenerate naturally.	

Scenario number	Feedstock used for pellets	Counterfactual scenario	Page number for section
	an SRC hardwood plantation that is coppiced every 3 years. Conversion takes (a) 3 years, (b) 50 years.		
24	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated hardwood forest in South USA that is harvested every 70 years, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years.	Continue harvesting the forest every 70 years, and leaving to regenerate naturally.	
25	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated hardwood forest in South USA that is harvested every 70 years, to an SRC hardwood plantation that is coppiced every 3 years. Conversion takes (a) 3 years, (b) 70 years.	Continue harvesting the forest every 70 years, and leaving to regenerate naturally.	
New Plantations on Abandoned Agricultural Land			*113*
26	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land in USA that was previously annually ploughed, to an SRC hardwood plantation that is coppiced every 3 years. Assumed exported to UK from South USA. SRC yields of: (a) 5 odt/ha/y (b) 10 odt/ha/y (c) 15 odt/ha/y (d) 30 odt/ha/y.	Abandoned agricultural land left to revert to sub-tropical, moist, deciduous forest.	
27	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land in USA that was previously annually ploughed, to an SRC hardwood plantation that is coppiced every 3 years. Assumed exported to UK from Northeast USA. SRC yields of: (a) 5 odt/ha/y (b) 10 odt/ha/y (c) 15 odt/ha/y (d) 30 odt/ha/y.	Abandoned agricultural land left to revert to temperate grassland.	
28	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land that was previously annually ploughed, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years. Assumed exported to UK from South USA.	Abandoned agricultural land left to revert to sub-tropical, moist, deciduous forest.	
29	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land that was previously annually ploughed, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years. Assumed exported to UK from Northeast USA.	Abandoned agricultural land left to revert to temperate grassland.	

Evaluation of Scenarios

79. A literature review has been conducted to estimate the likely available resource of each feedstock by 2020, and DECC's Biomass Emissions And Counterfactual (BEAC) Model has been used to estimate the GHG intensity and Energy Input Requirement (EIR) of each scenario.

80. The overall GHG intensity and EIR of the bioenergy scenarios have been estimated by accounting for the emissions and energy associated with the following:

- Land carbon stock changes over time in above- and below-ground biomass, as well as soils.
- Crop or tree establishment and maintenance (*e.g.* machinery diesel, fertiliser, pesticide).
- Biomass harvest (*e.g.* machinery diesel).
- Transport of biomass (*e.g.* road, rail or shipping).
- Pre-treatment operations (*e.g.* pelletisation, drying).
- Final processing (*e.g.* generation of electricity).

81. Emissions associated with, and energy requirement of, the *production* of vehicles, machinery and infrastructure are not included in the model.

GHG Intensity

82. The GHG intensity of bioenergy is defined as:

$$\text{GHG intensity} = \frac{\text{Life Cycle GHG emissions (kg } CO_2 \text{ equivalent)}}{\text{Delivered Electricity (MWh)}}$$

83. The GHG intensity of bioenergy pathways can change significantly over time, therefore BEAC allows the user to investigate the GHG intensity of different scenarios over three different time horizons: 20, 40 and 100 years.

84. Unless otherwise stated, the GHG emissions were calculated by assuming that biomass is harvested from the land continually over the entire time horizon. We used the difference in GHG emissions and energy output between the bioenergy and counterfactual scenarios to evaluate the average emissions per unit of delivered energy over the time horizon; these calculations therefore required evaluation of the following factors for both the bioenergy and counterfactual scenarios (i) the land carbon stock at the end of the time horizon, (ii) the total energy output over the entire time horizon, and (iii) the supply chain emissions released over the entire time horizon.

85. The Global Warming Potential (GWP) of non-CO_2 greenhouse gases were taken as the 100 year IPCC 2007 values in all cases (25 kg CO_2e/kg CH_4 and 298 kg CO_2e/kg N_2O). BEAC is open-source (open government license) and users who are interested to explore other weightings of non-CO_2 gases can do so.

86. The carbon stock changes of forests were calculated using the data specific to North American forests provided by the United States Department for Agriculture (USDA) (Smith *et al.*, 2006) and the C-SORT model developed by UK-based Forest Research. The USDA data provides information on how the harvested wood output, and carbon stocks in the trees, understory, dead wood, forest floor and soil, change over time after the clearcut harvest and re-growth of forests in different forest types of

North America. The C-SORT model allows the user to define the tree species, yield class (measure of the growth rate of the tree), soil type, planting density, and time between harvest, to estimate how the carbon stock changes over time in a modelled forest, as well as the amount of saw logs, pulpwood and forest residues that are produced. The C-SORT model therefore requires assumptions to be made about a typical forest in a region in order to model the carbon output and biomass production (for the relevant scenarios, these assumptions are provided in the Annex).

87. Calculations to determine the effect of harvesting biomass for bioenergy can be performed using a 'stand-level' or a 'landscape- or forest-level' approach. If the purpose of the calculation is to determine the impact over time associated with harvesting an area of land all at once (*e.g.* a stand of forest), calculations would be performed using the 'stand-approach' (*e.g.* studies by Cherubini *et al.*, 2013; Walker *et al.*, 2010). Figure 18 illustrates the change in non-soil carbon stocks that can occur on an area of land in South USA which is planted with Loblolly trees, and harvested, every 25 years; calculations would be performed by determining the change of carbon stock on the land over the time horizon which the calculations are being performed over.

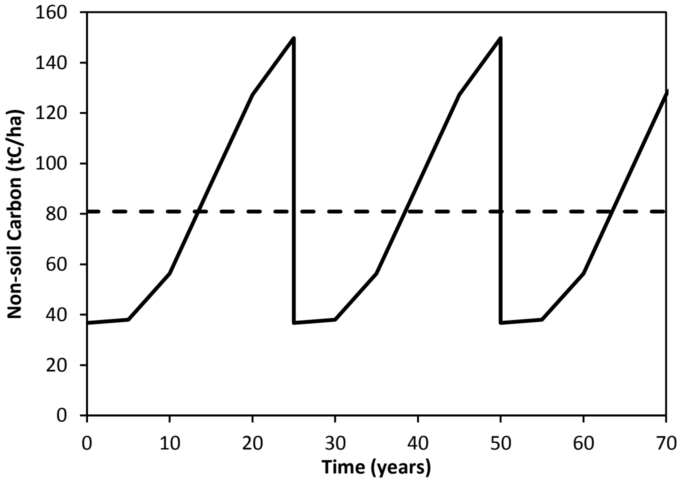

Figure 18. The non-soil carbon stock of a stand of Loblolly trees in South USA that are intensively-managed and clear-felled every 25 years (data from Smith *et al.*, 2006).

88. However, in North American and European forests that adhere to Sustainable Forest Management practices, it is often the case that not all the stands are felled at the same time; this ensures that a steady supply of wood is available. In these cases, the forests consist of a mix of unplanted, newly-planted, immature and mature stands. Hence, at the scale of a forest or landscape, if the management practice of the forest does not change and the forest consists of stands with a uniform age distribution (referred to as even-aged), losses of carbon stocks due to harvesting may be counterbalanced by sequestration in the remaining stands which are still growing. In this case, the forest's carbon stock stays at an average value, shown as the dotted line in Figure 18. If the management practice changes, *e.g.* the time between harvest changes, the tree species changes, or harvesting practices are stopped, this average carbon stock will change. When calculating the carbon stock of forests consisting of multiple-stands, harvested at different times, the 'landscape- or forest-level' approach is used, whereby the average carbon stored in all the stands is calculated (*e.g.* Forest Research and North Energy, 2012; Biomass Energy Resource Centre, 2012; Mitchell *et al.*, 2012). As a steady supply of wood for bioenergy is required, and the UK Bioenergy Sustainability Criteria requires the wood to be supplied from

'sustainably-managed forests', where stands are generally harvested on a rotational basis, calculations have been performed at the landscape-level.

89. By fully accounting for carbon stock changes in forests, accounting for the GHG intensity of the land counterfactual, and considering the GHG intensities over different time horizons, BEAC addresses the impacts described on page 41 that are not accounted for by the EU Renewable Energy Directive LCA methodology.

Energy Input Requirement

90. The Energy Input Requirement of bioenergy is defined as:

$$\text{Energy Input Requirement} = \frac{\text{Energy Input (MWh)}}{\text{Delivered Electricity (MWh)}}$$

91. The EIR calculation is used to estimate the amount of energy, other than bioenergy, required to deliver 1 MWh of electricity. The EIR is essentially the inverse of the standard metric 'EROI', the energy return on energy invested, and is a measure of how much useful energy is spent to deliver a unit of electricity; a lower EIR means that on a net basis, more energy is available from a given source (for further information on EROI see Murphy and Hall; 2010; Weissbach *et al.*, 2013; Raugei *et al.*, 2012 and Kubiszewski *et al.*, 2010). The primary energy of the biomass is not included as an energy input in the calculation, just as the energy in the wind or sunshine is not included in the Energy Input Requirement for those technologies.

92. The EIR has been calculated using two different methods; Figure 19 shows the terms used in the calculations. First, the EIR is reported on an energy-carrier input basis, and calculated as:

$$\text{EIR}_{\text{energy carrier basis}} = \frac{E_{EC}}{E_D}$$

93. Here, the energy input is considered to be energy carriers which are ready for final use, *e.g.* electricity, diesel, natural gas, fuel oil. This means that 1 MWh of electricity is treated to be equivalent to 1 MWh of diesel. However, other studies often extend the boundary when calculating the energy inputs, using primary energy inputs rather than the energy carrier inputs (*e.g.* Raugei *et al.*, 2012; Kubiszewski *et al.*, 2010) therefore the EIR for the bioenergy scenarios has also been calculated on this basis, to allow comparison with other studies:

$$\text{EIR}_{\text{primary energy basis}} = \frac{E_{PE}}{E_D}$$

94. The energy required to produce chemicals, *e.g.* fertilisers, are included; most data were available in the form of primary energy requirement, rather than high-value energy carrier requirement. However, as these chemicals are often made from natural gas and oil (with ratios of energy carrier to primary energy close to 1), it was considered appropriate to use these values as approximations for both the energy carrier, and primary energy input values.

95. It is important to note that owing to lack of data, the EIR values for the biomass technologies do not include infrastructure energy requirements. The conversion of coal to biomass fired power stations does not involve significant infrastructure requirements, therefore would not impact the EIR values significantly; however, future work to estimate the energy input associated with pelletising infrastructure would be useful.

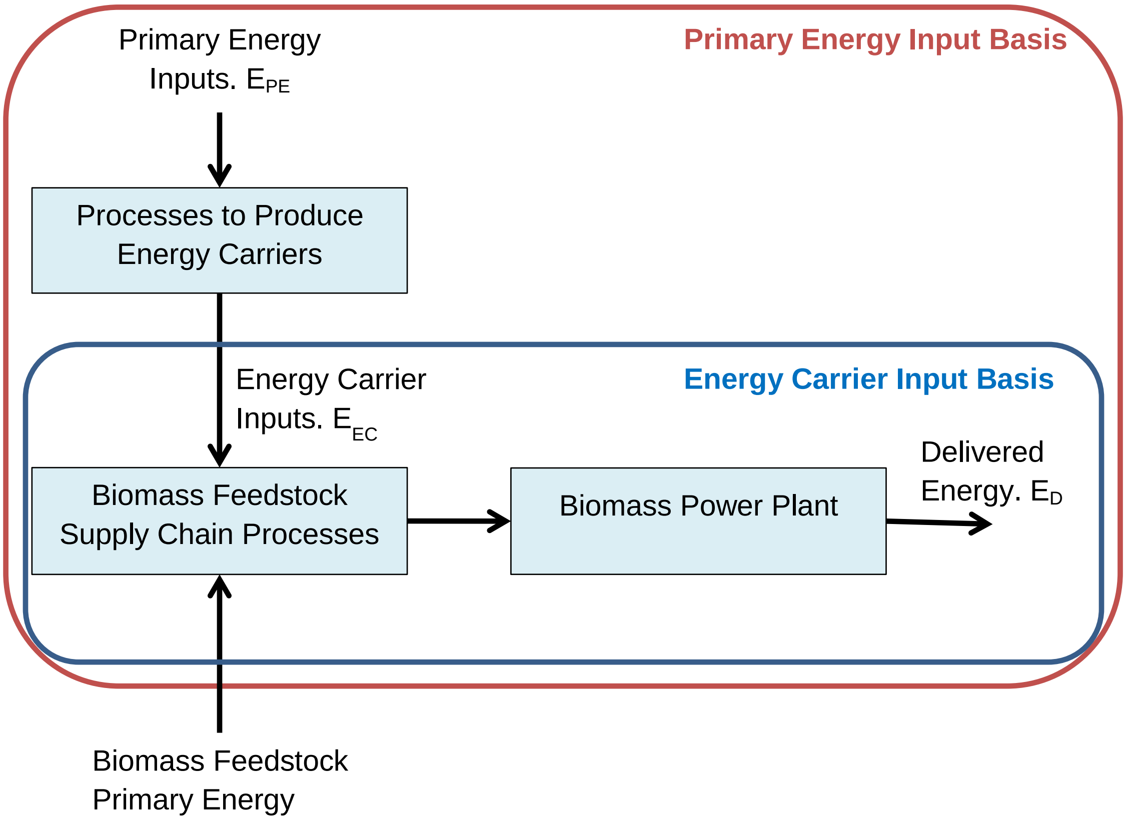

Figure 19. Diagram of terms included in Energy Input Requirement (EIR) calculations.

Consideration of Metrics for Comparing Technologies

96. As well as GHG intensity and EIR, other metrics are important to consider when comparing different technologies. For example, neither of these metrics accounts for the intermittency and flexibility of the energy generation; biomass has advantages over other renewables such as solar and wind in this regard. The cost of the generated energy, and environmental impacts other than global warming, such as mining, air pollution and biodiversity implications, are also not considered.

Display of Results in BEAC

97. The set scenarios in BEAC show the GHG intensities and EIRs associated with electricity generation; however, the tool can also be used to investigate the GHG intensities of other energy services, such as electricity generation with Carbon Capture and Storage, heat from biomass boilers, and the production of transport fuels *via* the Fischer-Tropsch process[43].

98. The results are displayed in 3 headline bar charts in BEAC, with the first comparing the total GHG intensity of the scenario to key comparators (as illustrated in Figure 20), the second showing the GHG intensity for each component of the life cycle (Figure 21), and the third showing the EIR of the scenario (Figure 22). The LCA stages shown in BEAC (Figure 21) are described in detail in Table 6.

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[43] The production of liquid fuel from the gasification of biomass, followed by catalytic processing of the syn gas.

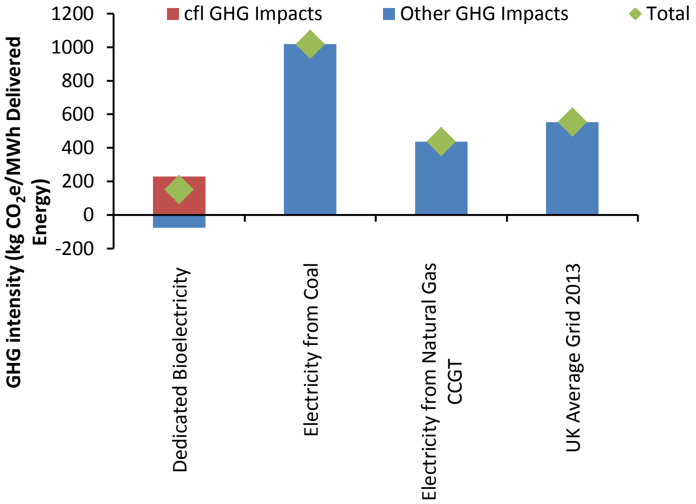


Figure 20. Example headline graph in BEAC (type 1), showing the total GHG intensities for a biomass electricity scenario and key comparators. cfl: counterfactual.

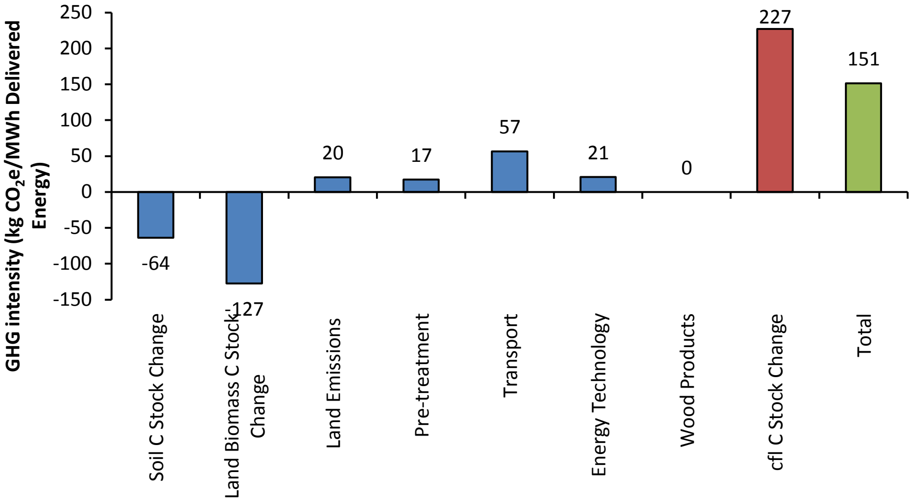


Figure 21. Example headline graph in BEAC (type 2), showing the GHG intensity of each stage of the life cycle for a biomass electricity scenario. cfl: counterfactual.

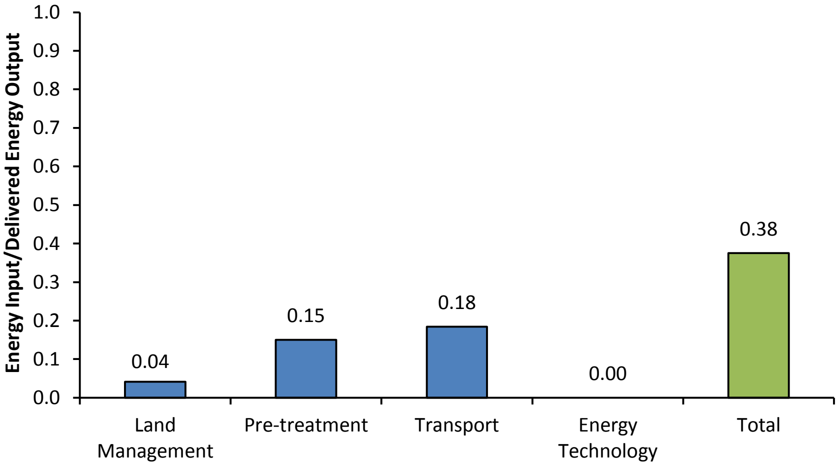


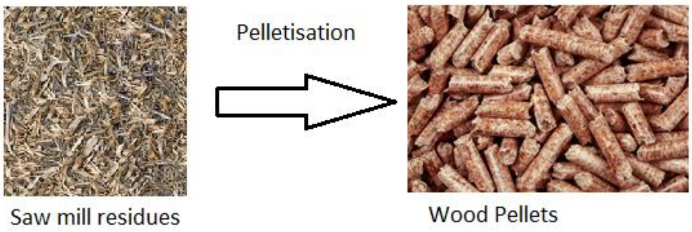
Figure 22. Example headline graph in BEAC (type 3), showing the EIR of each stage of the life cycle for a biomass electricity scenario.

Table 6. Description of the LCA stages shown in Figure 21.

Label in Figure 21	Details:
Soils C Stock Change	Change in the amount of carbon stored in soils for the bioenergy scenario over the time horizon.
Land Biomass C Stock Change	Change in the amount of carbon stored in above- and below-ground biomass for the bioenergy scenario.
Land Emissions	Difference between the bioenergy scenario and counterfactual for the following: • natural GHG emissions flux (*e.g.* methane production from tropical peat forests); • GHG emissions from crop/tree establishment, fertiliser and pesticide production and use, irrigation and harvest; • GHG emissions from biomass combustion on the land (*e.g.* roadside burning of residues).
Pre-treatment	The treatment of biomass before its final use for energy. Includes drying, chipping, and pelletising.
Transport	The transport of biomass by road, rail and ship: • from the farm/forest to the pellet facility; • from the pellet facility to the port; • from the country of origin to the UK port; • from the UK port to the location of final use.
Energy Technology	The GHG emissions associated with the final energy technology, *e.g.* combustion for energy and/or heat, production of ethanol etc.
cfl C Stock Change	Change in the amount of carbon stored in soils, and above- and below-ground biomass for the counterfactual scenario.

Results: Woody Residues

Saw-Mill Residues: Scenarios 1 to 3



99. Saw-mill residues are produced as by-products of primary[44] and secondary processing mills[45]. These residues are already used for many purposes: coarse saw-mill residues (chips, slabs and edgings) are feedstocks for the production of paper and particleboard, and also used for onsite energy generation at wood processing mills; fine residues (saw dust, wood flour, shavings and bark) are mainly used for particleboard, pellets, and onsite energy generation (FAO, 2013; Rotherham, 2009).

Scenarios: Saw-Mill Residues

100. In this section, the resource availability and GHG intensity associated with bioenergy from saw-mill residues that are not required for alternative uses, and would otherwise be burned as a waste, is considered (as shown in Table 7). Another scenario, which could be considered in future studies, is using saw-mill residues for bioenergy that would otherwise be sent to landfill.

101. If a greater amount of saw-mill residue is used for bioenergy in the future than this, and alternative uses of saw-mill residues are displaced, it is possible to cause ‘indirect GHG impacts’. The magnitude of such indirect GHG impacts is investigated in detail later in this report (Scenarios 19 to 21, starting on page 99).

102. The moisture content of saw-mill residues varies, meaning that the drying required before pelletisation will also vary; for example, sander dust has a moisture content between 2 and 10 wt%, whereas sawdust has a moisture content between 25 and 55 wt% (Cal Recycle, 2014). In this study, three drying requirements were considered: no drying, drying from 25 wt% to 10 wt% moisture, and drying from 50 wt% to 10 wt%.

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[44] Mills that convert roundwood into primary mill products such as lumber, plywood, and wood pulp.

[45] Mills that convert primary mill products into other products, such as pallets, furniture, and flooring.

Table 7. Scenarios modelled to represent using saw-mill residues for bioenergy.

Scenario number	Feedstock used for pellets	Counterfactual scenario
1	Saw-mill residues in South USA; no drying. Saw-mill residues in Pacific Canada; no drying.	Burn as a waste (no energy recovery).
2	Saw-mill residues in South USA; dry from 25 wt% to 10 wt% moisture. Saw-mill residues in Pacific Canada; dry from 25 wt% to 10 wt% moisture.	Burn as a waste (no energy recovery).
3	Saw-mill residues in South USA; dry from 50 wt% to 10 wt% moisture. Saw-mill residues in Pacific Canada; dry from 50 wt% to 10 wt% moisture.	Burn as a waste (no energy recovery).

Considerations for Scenario Plausibility: Saw-Mill Residues

103. In 2011, the majority of biomass pellets produced globally were made from saw-mill residues (IEA Bioenergy, 2011). In 2009, saw-mill residues represented 80 - 85% of the feedstocks used to manufacture pellets in British Columbia, with the remaining 15 - 20% being forest residues and diseased trees (AEBIOM *et al.*, 2013).

104. The IEA has reported that the pellet industry aims to further use feedstocks other than saw-mill residues in the future, such as roundwood and forest residues. This is because large-scale users of pellets require long-term supply arrangements (~ 10 year contracts) with well-defined volumes and prices, but the use of saw-mill residues for the production of pellets results in the pellet industry being directly linked to the construction industry, with the availability and price of feedstock being subject to trends and market dynamics of the wood industry (IEA Bioenergy, 2011).

Resource Availability: Saw-Mill Residues

105. In the USA, approximately 103 Modt of coarse and fine residues are produced from primary and secondary mills each year (US DOE, 2011), with ~ 87 Modt from primary mills, and 16 Modt from secondary mills. The majority is already used for a variety of purposes, as described above, including 31% (32 Modt/y) for onsite energy generation (*e.g.* energy used internally by the mills); only ~7 Modt/y is unused (US DOE, 2011). By 2020, it is predicted that more wood will be processed in US saw-mills than at present, therefore more saw-mill residues will be produced, despite increases in saw-mill efficiencies resulting in less residue being produced per tonne of processed wood (US DOE, 2011). Ince and Nepal (2012) predicted an increase in the total amount of saw-mill residues available for any energy generation (including onsite energy) between 2010 and 2020 of ~ 25 Mm^3/y, equivalent to ~ 11 Modt/y. However, the U.S. Department of Energy predicts that demand for saw-mill residues will increase in the future, including an increase in use for onsite energy of 10 Modt/y (to 42 Modt/y) by 2030 (US DOE, 2011). For the purposes of this study, it was assumed that the upper value in the range of the quantity of unused saw-mill residues in the USA that may be available for increased pellet production by 2020 is equal to that predicted by the US Department of Energy, of 7 Modt/y; the low value

was assumed to be the ‘readily available’ resource estimated by Forisk (2011) of 1.7 Modt/y.

106. In Canada, the paper industry uses coarse saw-mill residues as their principal feedstock (Rotherham, 2009). Fine saw-mill residues are used for the production of wood pellets, particleboard and fuel (Bradley, 2010). Approximately 14 Modt of fine saw-mill residues were produced in 2011, all either combusted for internal energy use, or used for the production of wood pellets, composite wood products, animal bedding, landscape gardening, food flavouring and composting (Bradley, 2010). The reduction in the amount of saw logs going to saw-mills after the recession led to a reduction in the amount of saw-mill residues being available for wood pellet production, therefore many pellet facilities were forced to start using alternative feedstocks such as forest residues (Bradley, 2010). For the purpose of this report, it has been assumed that by 2020, the production of fine saw-mill residues will have recovered to pre-recession levels, when 21.2 Modt/y of saw-mill residues were being produced (Canadian Bioenergy Association, 2011). This would lead to an increased production of residues, compared to 2013, of approximately 5 Modt/y (Canadian Bioenergy Association, 2011). This approach assumes that demand from other uses remains constant, and that the saw-mills do not increase in efficiency. In reality, the demand for other products is likely to increase this decade, therefore the lower value in the range is assumed to be zero.

GHG Emission Intensity: Saw-Mill Residues

107. A summary of the GHG intensities of biomass electricity for BEAC Scenarios 1-3 is shown in Figure 23. These results have been calculated using the default key parameters (transport distances, transport fuel requirements, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station) in Table 29 of the Annex. Figure 23 shows that it is possible to produce electricity with significant GHG savings in comparison to electricity from natural gas or coal, when left-over saw-mill residues are used as the feedstock.

108. The GHG impacts from transport, pelletisation and methane emissions from incomplete wood combustion dominate the life cycle. The transport emissions are significantly higher for pellets shipped from Pacific Canada than those from South USA, owing to the greater transport distances involved. However, the Canadian electrical grid has a lower GHG intensity than the USA electrical grid, therefore the pre-treatment stage for Canadian pellets has a lower GHG intensity than South USA pellets (when the same method is used). Combusting the saw-mill residues in a large-scale electricity plant is likely to result in more complete combustion than the counterfactual process used to burn the residues as a waste, therefore the results show significant GHG savings from reduced methane emissions of using the residues for electricity generation, in comparison to the counterfactual[46].

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[46] Assuming that methane emissions from the large-scale combustion of wood pellets would be 30 kg CH_4/GJ HHV feedstock, and the emissions for the counterfactual of incinerating the residues would be similar to domestic-scale wood combustion at 300 kg CH_4/GJ HHV feedstock (US Environmental Protection Agency, 2008).

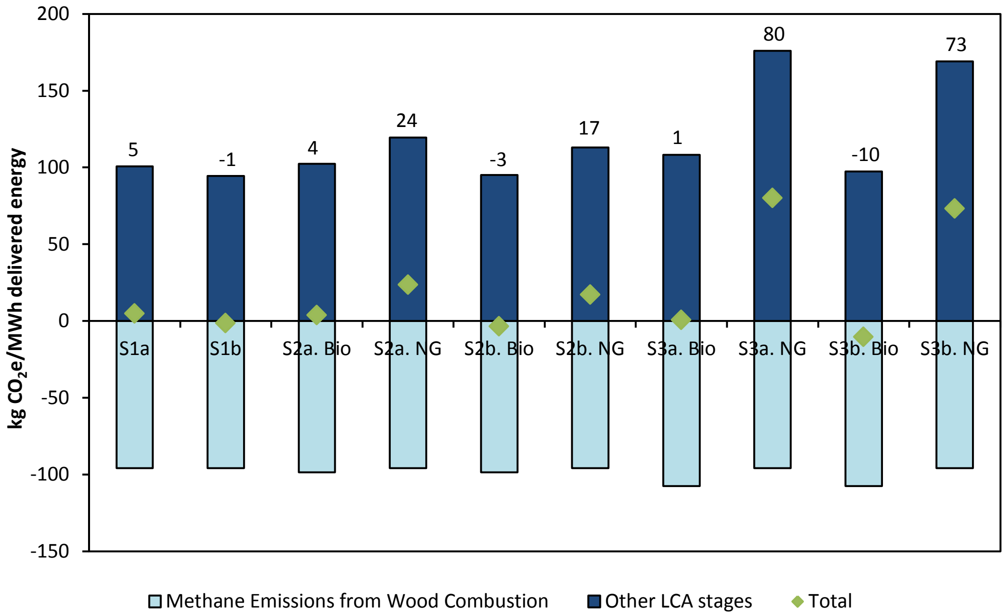

Figure 23. GHG intensity over time horizons of all time horizons, of electricity from 'waste' saw-mill residues in North America, and shipped to the UK, for BEAC Scenarios 1 - 3 (a and b), using default BEAC values for key parameters (see Table 29 in the Annex). Bio: dry using biomass; NG: dry using natural gas.

Energy Input Requirement: Saw-Mill Residues

109. A summary of the Energy Input Requirement of biomass electricity for these scenarios is shown in Figure 24 (energy carrier input basis). Results are shown for using biomass (default in BEAC), and natural gas as the fuel for drying. Currently pellets from South USA generally use biomass to dry the wood; however, in Canada, it has been reported that both natural gas and biomass are used as fuels for drying (Magelli *et al.*, 2009; Sikkema *et al.*, 2010).

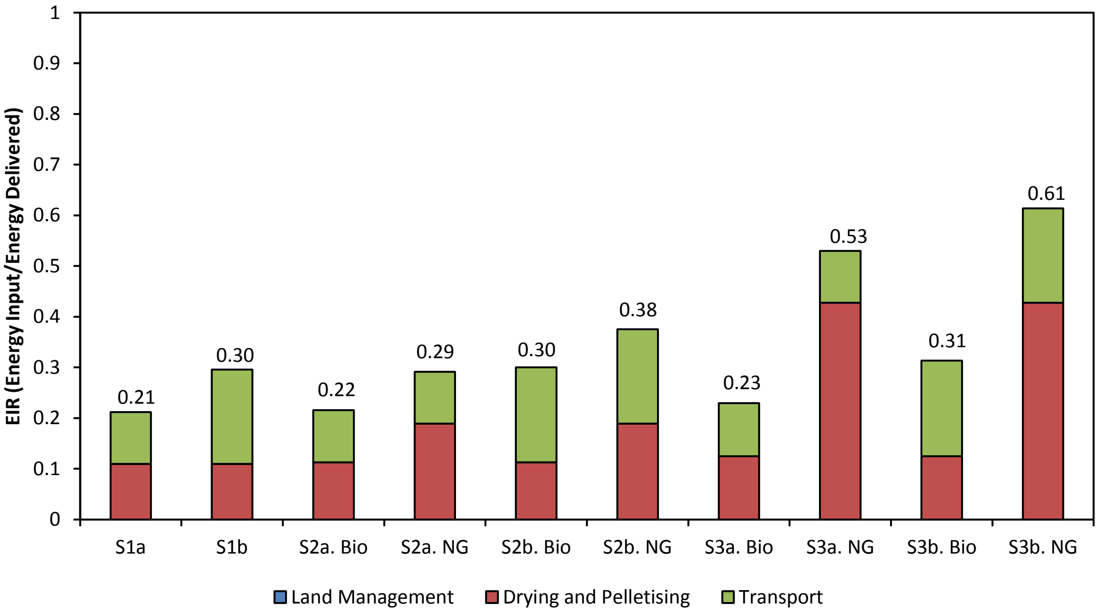

Figure 24. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from North American saw-mill residues, using default BEAC values for pelletising electrical requirement, transport, and electrical efficiency (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

110. The EIR range for electricity from North American biomass residues has been determined using low and high values of key parameters[47] (detailed in the Annex, Table 29) and is compared to other electricity generating technologies in Figure 25. Other studies often extend the boundary when calculating the energy inputs, using primary energy inputs rather than the energy carrier inputs, therefore the EIR for the bioenergy scenarios has also been calculated on this basis, to allow comparison with other studies. Biomass electricity was found to require greater energy inputs than electricity from nuclear, coal, natural gas, and wind power. It is important to note that owing to lack of data, the EIR values for the biomass technologies do not include infrastructure energy requirements, whereas the EIR values for the comparator technologies do. The conversion of coal to biomass fired power stations does not involve significant infrastructure requirements, therefore would not impact the EIR values significantly; however, future work to estimate the energy input associated with pelletising infrastructure would be useful so that EIR values for electricity from wood pellets can be directly compared with other technologies.

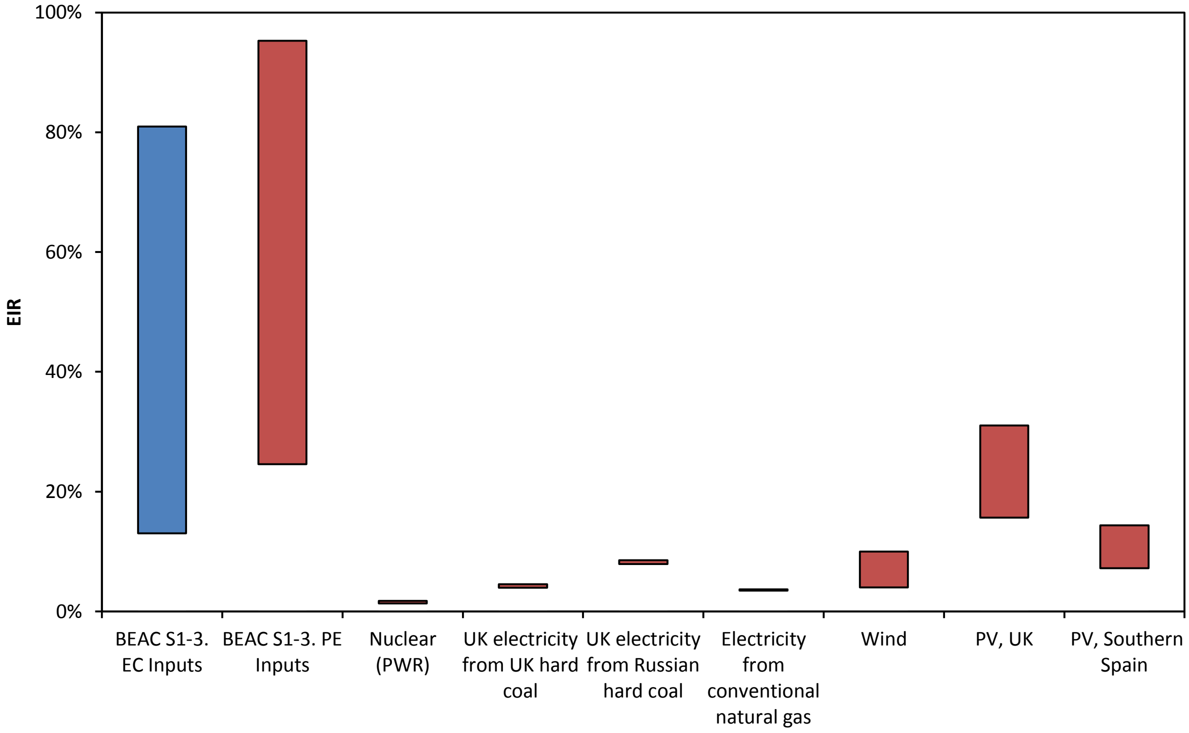

Figure 25. Energy Input Requirement (EIR) values for UK biomass electricity from North American saw-mill residues (ranges calculated using the BEAC model, by varying key parameters within the ranges given in Table 29), and other electricity generating technologies (ranges determined using published literature). EIR for bioenergy is calculated using energy carrier inputs (blue), and primary energy inputs (red). References: Nuclear (Pressurized Water Reactor, PWR): Weissbach *et al.*, 2013; World Nuclear Association, 2014. UK hard coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal 32 km by truck (UK Coal, 2014). Russian coal: data for extraction and electricity generation from Raugei *et al.*, 2012 and Weissbach *et al.*, 2013, and assuming additional energy required to transport coal by rail for 1200 km, ship 2800 km, and rail 122 km (EWS Energy, 2014). Natural gas: Weissbach *et al.*, 2013 (owing to limited literature data, only one data point was available, which uses US and German data). Wind: Kubiszewski *et al.*, 2010; Weissbach *et al.*, 2013. PV: data from Raugei *et al.*, 2012, assuming UK average irradiance of 925 kWh/m^2/y; low value is for ground-mounted CdTe panels, high value is for roof-mounted monocrystalline Si panels.

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[47] Key variables taken as pelletisation electricity requirement, transport distances, transport energy requirements, power station efficiency, and drying method.

Summary: Saw-mill Residues

111. The predicted resource availability of North American saw-mill residues, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 8.

Table 8. Potential resource of North American saw-mill residues by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[48] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020	GHG intensity[49]	EIR		Details
	Modt/y	kg CO_2e/MWh	MWh per MWh		
			EC basis	PE basis	
Saw-mill Residues	1.7 to 12.0	-17 to 121	0.13 to 0.81	0.25 to 0.95	**Min**: BEAC Scenario 1a. **Max**: BEAC Scenario 3a for GHG, 3b for EIR.

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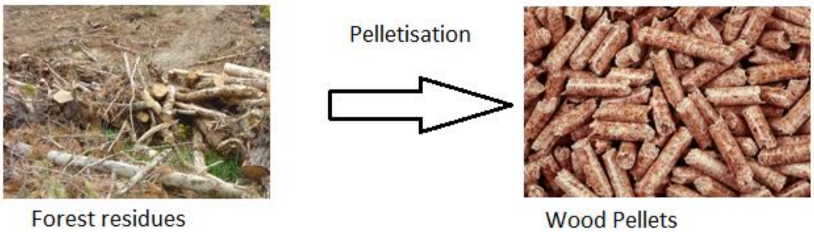
[48] EIR values are the same for 40 and 100 year time horizons.

[49] Over all time horizons.

Forest Residues: Scenarios 4 to 8



112. Forest logging residue is the woody material that is left over from traditional timber harvesting and forest management, such as tree tops and limbs, pre-commercial thinnings and non-merchantable trees. These residues are classified as either coarse (diameter > 0.1 m) or fine (diameter < 0.1 m) (Fritsche *et al.*, 2012). To cost-effectively extract these resources, entire trees are removed from the forest *via* whole-tree harvesting, rather than just the stem wood *via* stem-only harvesting (Biomass Energy Resource Centre, 2012). In Canada, whole-tree harvesting is the most common harvesting method, and the residue is often burned at the roadside to reduce the hazard of fire (Bradley, 2007; Lamers *et al.*, 2013). In the USA, the majority of wood residues are currently left in the forest (US DOE, 2011).

113. In the long term, there is concern that the introduction of residue removal could lead to a future nutrient imbalance, reduced forest productivity, and changes in species composition and diversity (Helmisaari and Vanguelova, 2012; Schulze *et al.*, 2012; Walker *et al.*, 2010). Indeed, dead wood is a central contributor to biodiversity in US forests, with red-back voles, salamanders, saproxylic insects, fungi, mosses and liverworts being particularly dependent on sufficient quantities and sizes of it being available (Walker *et al.*, 2010). Some institutions have therefore developed guidelines for harvesting woody biomass from forests; a report published by the Forest Guild, *An Assessment of Biomass Harvesting Guidelines*, reviewed biomass harvesting guidelines in Europe, USA, and Canada, and recommended (i) that harvesting of residues does not occur on nutrient limited sites, (ii) that on sites with operational soils, between 25 and 33% of the tops and limbs should be retained onsite where 1/3 of the basal area is being removed on 15 - 20 year cycles, and (iii) that for more frequent or intense operations, a greater retention of tops and limbs may be necessary (Walker *et al.*, 2010). Uncertainties remain about the long-term sustainability of the introduction of forest residue harvesting on different soil and forest types (Helmisaari and Vanguelova, 2012; Walker *et al.*, 2010; Repo *et al.*, 2014).

Scenarios: Forest Residues

114. The scenarios considered in this report are shown in Table 9. As a steady supply of wood for bioenergy is required, it was assumed that wood is removed annually over the entire time horizon. However, as a sensitivity, the annual removal of residues from the forest for only the first 15 years of the time horizon was also considered, assuming that the residues would remain on the forest floor after this (Scenarios 6 and 7).

Table 9. Scenarios modelled to represent using forest residues for bioenergy.

Scenario number	Feedstock used for pellets	Counterfactual scenario
4	(a) Coarse forest residues, removed from forests in South USA, continuously over the time horizon. (b) Coarse forest residues, removed from forests in Pacific Canada, continuously over the time horizon.	Leave all residues in the forest.
5	(a) Fine forest residues, removed from forests in South USA, continuously over the time horizon. (b) Fine forest residues, removed from forests in Pacific Canada, continuously over the time horizon.	Leave all residues in the forest.
6	(a) Coarse forest residues, removed from forests in South USA, for 15 years only (then residues are left in the forest again). For example when analysed over a time horizon of 40 years, this involves the removal of residues for the first 15 years, then leaving the residues in the forest for the last 25 years of the time horizon. (b) Coarse forest residues, removed from forests in Pacific Canada, for 15 years only (then residues are left in the forest again).	Leave all residues in the forest.
7	(a) Fine forest residues, removed from forests in South USA, for 15 years only (then residues are left in the forest again). (b) Fine forest residues, removed from forests in Pacific Canada, for 15 years only (then residues are left in the forest again).	Leave all residues in the forest.
8	(a) Forest residues (both coarse and fine), removed from forests in South USA, continuously over the time horizon. (b) Forest residues (coarse and fine), removed from forests in Pacific Canada, continuously over the time horizon.	Burn the residues at the roadside as a waste.

Considerations for Scenario Plausibility: Forest Residues

115. To date, the use of forest-floor residues for the production of pellets has been limited, owing to high transport costs, but the pellet industry report that these resources are expected to be used to a greater extent in the future for pellet manufacture (AEBIOM *et al.*, 2013). However, users of wood pellets often require homogeneity and predictability of combustion characteristics, and high contents of bark and non-

combustible elements, such as alkali metals, can cause problems of slagging, fouling and corrosion in boilers. The bark and ash content can be high in pellets produced from forest residues (Marinescu and Bush, 2013), therefore some electricity stations require pellets produced from other biomass, with low bark contents (*e.g.* roundwood).

116. It is also important to note that power stations in North America are also starting to use these forest residues in chip form for electricity generation, which could limit the availability for export (Biomass Energy Resource Centre, 2012; Bradley, 2010; Shore, 2013); the US Department of Energy projects that forest fuel-wood consumption will increase from 38 Modt/y in 2010 to 96 Modt/y in 2022 (US DOE, 2011).

Resource Availability: Forest Residues

117. Table 10 shows estimates from the literature of the potential resource availability of North American forest residues.

Table 10. Resource availability of forest logging residues from North American forests.

Country	Resource description	Resource availability	Reference
USA	Forest residues, which could be collected after conventional harvesting techniques. Assuming that a minimum of 30 wt% should be left in the forest to prevent soil degradation and loss of habitats. Includes pre-commercial thinnings.	13.0 to 47.0 Modt/y, depending on the biomass economic value.	US DOE, 2011
USA	Forest residues, potentially available from fire-treatment processes[50].	14.0 to 35.0 Modt/y, depending on the biomass economic value.	US DOE, 2011
USA	Forest residues from the conversion of forest to other uses.	4.4 to 12.0 Modt/y	US DOE, 2011
USA	Forest residues currently left in the forest, assuming 35% should remain in the forest. Residues from fuel treatment were taken as zero in this study, as they reported 'wood flows from fuel treatments are minimal and, based on existing research, costly and unproven to date.'	28.0 Modt/y	Forisk, 2011
Canada	Currently burned as a waste to prevent fires.	22.0 Modt/y	Bradley, 2010
Canadian managed forests which are south of 60˚ N latitude[51].	Assuming that 50 wt% should be left in the forest to prevent soil degradation and loss of habitats.	20.0 ± 0.6 Modt/y	Dymond *et al.* 2010

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[50] Using the DOE, 2011 data, it would be double counting to assume that the estimates of the availabilities of residues from both conventional harvesting, and fire treatments, would be available. In reality, a split between these two techniques of residue collection would be employed.

[51] Forests in the three northern territories lack significant industrial forestry sectors.

118. In this report, the range of resource available by 2020 from residues that would otherwise be left in the forest was estimated from the amount of US forest residues that are currently left in the forest following conventional harvest[52]. This was taken from the US Department of Energy (2011), using their assumption that 50% of available forest residues would be collected following conventional harvest (resulting in a range of 6.5 to 23.5 Modt/y) and 50% of available forest residues would be collected during fire-treatment processes.

119. The range of resource available from residues that would otherwise be burned at the roadside was assumed to be the sum of the amount available from fire-treatments of US and Canadian forests, and biomass from clearing of US forests for other land uses, estimated to be 23.8 to 51.5 Modt/y (as shown below in Table 11).

Table 11. Assumed resource availability in 2020 of forest residues that would otherwise be burned as a waste.

Details	Resource Availability (Modt/y)	Reference
Residues from fire-treatment of US forests	0.0 to 17.5	Lower: Forisk, 2011 Upper: US DOE, 2011[53]
Residues from Canadian forests	19.4 to 22.0	Lower: Dymond *et al.*, 2010 Upper: Bradley, 2010
Residues from clearing of US forests	4.4 to 12.0	Lower: US DOE, 2011 Upper: US DOE, 2011
TOTAL	23.8 to 51.5	

GHG Emission Intensity: Forest Residues

Forest residues which would otherwise be left in the forest

120. We assume that, when left on the forest floor, residues decay following an exponential profile, with the time constant depending on the location and size of the debris; residues decay fastest in warm, moist conditions, and fine residues (those with diameters < 0.1 m) decay quicker than coarse residues (diameters > 0.1 m). The decay constants assumed for fine and coarse forest residues in South USA and Pacific Canada are shown below in Table 12.

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[52] In reality, there would be further residues (that would otherwise be left in the forest) available from Canadian forests. However, to determine the ranges of resource availability, owing to the lack of available data it was assumed here that the majority of Canadian residues would otherwise be burned at the roadside.

[53] Assuming 50% of available forest residues would be collected fire treatment processes.

Table 12. Decay constants assumed in BEAC for fine and coarse forest residues in South USA and Pacific Canada.

		Assumed decay constant (y^{-1})	Reference
South USA	Fine residues	0.185	Mattson *et al.*, 1987
	Coarse residues	0.083	Mattson *et al.*, 1987
Pacific Canada	Fine residues	0.097	Vavrova *et al.*, 2009
	Coarse residues	0.028	Chambers *et al.*, 2000

121. Mattson *et al.* (1987) reported the decay constants for coarse and fine woody debris in South USA to be 0.083 and 0.185 y^{-1}, respectively. This means that 20 years after the harvest of forest residues from one stand of forest in the South USA, ~19% of the initial carbon in the coarse residues would still have remained in the stand if it were not removed for bioenergy, and 2.5% of the carbon in the fine residues would have remained in the stand. After 100 years, only negligible amounts of either coarse or fine woody residues would have remained in the stand. For a forest consisting of multiple stands, where the residues are removed every year from a different stand, after 20 years ~ 47% of the initial carbon in the coarse residues would still have remained in the forest if it were not removed for bioenergy, and ~ 25% of the fine residues. After 100 years, ~ 12% of the coarse residues would have remained in the forest, and ~ 5% of the fine residues.

122. Following discussions with leading scientists of forestry and soils (Schlesinger, 2014; Harmon, 2014) it was assumed that methane emissions from dead wood in the North American forests are likely negligible, even in wetland forests (Anderson-Teixeira and DeLucia, 2011; Biomass Energy Resource Centre, 2012; IPCC, 2006). It was also assumed that the removal of residues from the forest floor does not affect the growth rate of the trees, although uncertainties remain about potential negative (*e.g.* reduced growth rate from nutrient loss; Helmisaari and Vanguelova, 2012) or positive (*e.g.* quicker re-establishment of trees by removing debris) impacts from the introduction of forest residue harvesting. Further work is therefore required in this area.

Forest Residues which would otherwise be burned at the roadside

123. In some forests in North America, removing residues from forests may reduce the frequency of wildfires (*e.g.* overstocked forests) (US DOE, 2011; Mitchell and Gallagher, 2007). For the purpose of this report, it has been assumed that the residues that affect the frequency of fires are those that have been removed from forests during fire-treatment procedures, and that these would otherwise be burned as a waste if the demand for bioenergy were not there. In this case, the residues are already harvested from the forest and combusted, therefore their use for bioenergy does not cause a carbon stock reduction in the forest.

124. However, if the fire-treatment procedures would only occur if the demand for bioenergy were there, the GHG intensity would be different as the appropriate counterfactual would be leaving the residues in the forest (with increased fire frequency), rather than burning as a waste. In this case, the GHG emissions associated with the removal of the residue would be determined by comparing the carbon stock of the forest that has had the residues removed and is exposed to less frequent fires, to the carbon stock of the forest that has the residues left in the forest and is exposed to more frequent fires. Mitchell *et al.* (2009) sought to answer this

question for forests in the Pacific Northwest USA, and concluded that although fuel reduction treatments in the region consistently reduced fire severity, to reduce the amount of carbon that is lost from a forest during a wildfire, a much greater amount of carbon must be removed during fire-treatment, since most of the carbon stored in forest biomass remains unconsumed, even by high-severity wildfires. In contrast, Hurteau and North (2010) investigated the effect of fuel treatments on carbon stocks in the dry, temperate forests of Sierra Nevada, and concluded that while there is an initial carbon stock reduction associated with fuel treatments in the region, treated forests can quickly (within several years) recover carbon stocks, if treatments involve understorey thinning, rather than the removal of large, fire-resistant, overstorey trees.

125. A summary of the GHG intensities of biomass electricity for BEAC Scenarios 4-8 is shown in Figure 26. These results have been calculated using the default key parameters[54] (details in Table 29), including the assumption that biomass is used to dry the wood prior to pelletisation. When stored outside for several months, the moisture content of forest residues reduces from ~ 50 wt% to ~ 25 wt%, owing to the drying effect of wind, sun and spontaneous internal heating due to bacteriological action on the materials in the interior of the pile (FAO, 2013). It was therefore assumed that the residues are dried at the pellet plant from 25 wt% to 10 wt% moisture, prior to pelletisation. The GHG intensity is shown to vary significantly between these scenarios, with the highest values for electricity from coarse forest residues that would otherwise have been left to decay in a forest in Pacific Canada (Scenario 4b), and the lowest values for electricity from forest residues that would otherwise be burned at the roadside in Pacific Canada (Scenario 8b).

126. For forest residues that would otherwise be left in the forest (Scenarios 4 to 7), the GHG intensity associated with the biomass electricity depends on the location, residue type, time horizon which the GHG intensity is analysed over, and time for which the residues are removed. This variation is caused by differences in the reduction in carbon stock in the forest for each scenario. Removing coarse woody debris for energy generates electricity with a larger GHG intensity than removing fine woody debris, owing to the lower decomposition rates of the larger material. The GHG intensities of Scenarios 4 to 7 decrease with time after the collection of the harvest residues commences, as a result of greater decomposition at older harvest sites.

127. Comparing the results for BEAC Scenarios 4 and 6, it can be seen that if the time horizon during which the residues are removed from the forest is shortened (*e.g.* only removed for the first 15 years of the time horizon for Scenario 6, rather than continuous removal over the entire time horizon of 40 or 100 years, for Scenario 4) the GHG intensity over the time horizon will reduce (this is provided the time horizon which the GHG intensity is analysed over is greater than the time which the residues are removed for). Again, this is because the residues would decompose over time if left in the forest; owing to the exponential decay profile of the residues, the removal of residues in the years closest to the end of the time horizon result in the greatest carbon stock reduction in comparison to the counterfactual of leaving the residues in the forest. This means, if the residues are left in the forest towards the end of the time horizon, the average GHG intensity (over the entire time horizon) of the electricity generated from the residues removed earlier in the time horizon would reduce.

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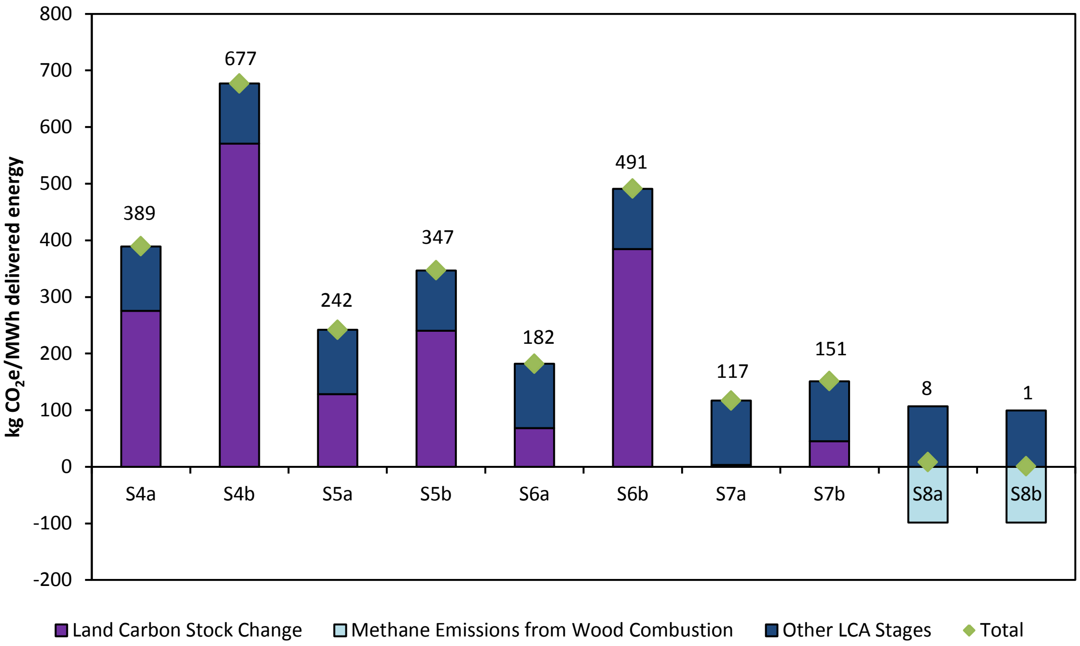
[54] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

40 year time horizon



100 year time horizon

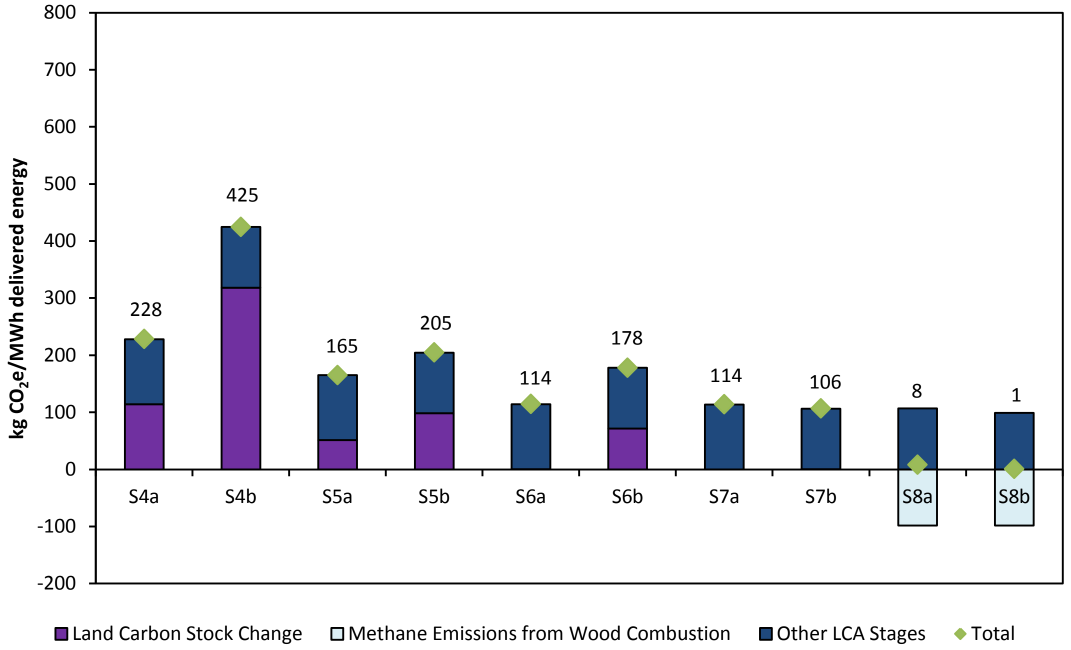


Figure 26. GHG intensity over time horizons of 40 and 100 years of electricity from pelletised forest residues, from forests in South USA and Pacific Canada, and shipped to the UK, for BEAC Scenarios 4 to 8. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

128. These results for the continuous removal of the residues from forests in Pacific Canada (BEAC Scenarios 4b and 5b) are comparable with those reported by Repo *et al.* (2010) for the GHG intensity of bioenergy from average sized branches (diameter of 0.02 m, therefore classified as fine residues) and stumps (diameter of 0.26 m, therefore classified as coarse residues) from boreal forests in Finland. Repo *et al.* (2010) found that the carbon stock reduction per unit energy from the removal of the fine residues from the forests for bioenergy was 340 kg CO_2e/MWh primary energy (equivalent to 944 kg CO_2e/MWh delivered electrical energy, assuming 36% efficiency) when the practice was first introduced, and decreased to 70 kg

CO_2e/MWh primary energy (equivalent to 194 CO_2e/MWh delivered electrical energy) over a time horizon of 100 years, as a result of decomposition of the harvest residues for the counterfactual scenario. For coarse residues, the GHG intensity reduced from 340 to 160 kg CO_2e/MWh primary energy (equivalent to 944 to 444 CO_2e/MWh delivered electrical energy, assuming 36% efficiency) over this time horizon.

129. The GHG intensities of electricity from pellets made from forest residues which would otherwise be burned at the roadside (Scenario 8) are similar to those associated with the pellets from saw-mill residues (page 57), and show significant GHG savings in comparison to fossil-derived electricity.

Energy Input Requirement: Forest Residues

130. A summary of the Energy Input Requirement of biomass electricity for these scenarios is shown in Figure 27 (energy carrier input basis; see page 50 for description).

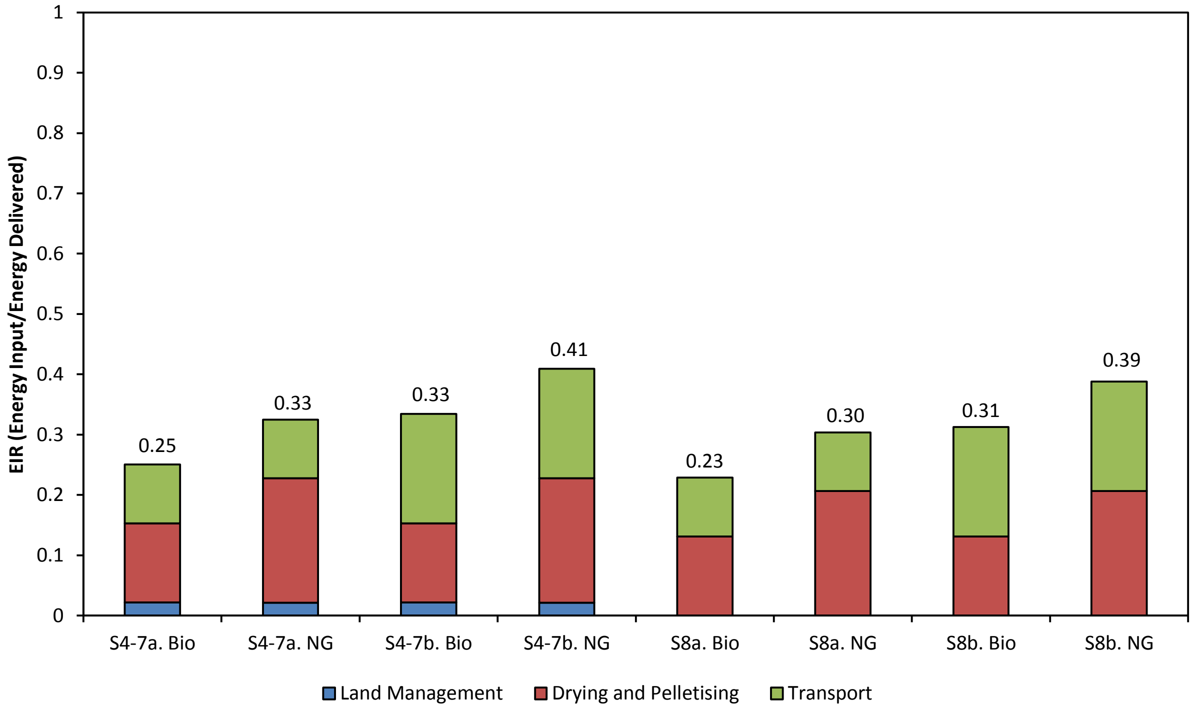


Figure 27. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from North American forest residues, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: Forest Residues

131. The predicted resource availability of North American forest residues, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 13.

Table 13. Potential resource of North American forest residues by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[55] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020	GHG intensity		EIR		Details
	Modt/y	kg CO_2e/MWh		MWh per MWh		
		40 years	100 years	EC basis	PE basis	
Residues collected from forests	6.5 to 23.5	82 to 826	80 to 536	0.17 to 0.56	0.29 to 0.68	**Min**: BEAC Scenario 7a. **Max**: BEAC Scenario 4b.
Residues collected from roadside	23.8 to 51.5	-14 to 58	-14 to 58	0.15 to 0.54	0.27 to 0.65	**Min**: BEAC Scenario 8a. **Max**: BEAC Scenario 8b for EIR, 8a for GHG.

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[55] EIR values are the same for 40 and 100 year time horizons.

Dead Wood from Natural Disturbances: Scenario 9

132. Standing dead trees, resulting from natural disturbances such as insects, fire and disease, are potential feedstock for bioenergy. For example, since the late 1990s, it has been estimated that over 710 million m^3 of Lodgepole pine has been infected by mountain pine beetles in British Columbia, equivalent to ~ 312 Modt (assuming a density of 0.44 odt/m^3) (Lamers *et al.*, 2013). The British Columbian Government has therefore been promoting 'salvage-logging' and the use of this wood for traditional lumber, pulp and bioenergy (IEA Bioenergy, 2011), as well as the burning of infected trees, to help reduce the rate of spread of the beetle (British Columbian Government, 2014). These dead trees are one of the major feedstocks currently used by pellet manufacturers in Canada; in 2011, approximately 30% of the feedstocks used to produce wood pellets in Canada used this wood as the feedstock (IEA Bioenergy, 2011), equivalent to ~ 0.6 Modt/y.

Scenarios: Deadwood from Natural Disturbances

133. The scenarios considered in this report are shown in Table 14.

Table 14. Scenarios modelled to represent using dead trees for bioenergy.

Scenario Number	Feedstock used for pellets	Counterfactual scenario
9	Salvaged dead trees, which have been killed by the mountain pine beetle in Pacific Canada.	(a) Leave in the forest (b) Remove and burn at the roadside

Considerations for Scenario Plausibility: Deadwood from Natural Disturbances

134. As mentioned previously, trees which have been killed from natural disturbances are already used as a feedstock for biomass pellets (*e.g.* beetle-killed trees in Pacific Canada). There are likely to be significant quantities of this resource available in the future (as detailed below). However, a significant issue associated with this feedstock is the inconsistency of the annualised volumes within a designated landscape, and high costs associated with the recovery and utilisation of such biomass. There is considerable variation in the area affected annually, especially from pests, and the severity of the damage (US DOE, 2011). In some cases, it may therefore not be economical to build facilities that require substantial capital and long payoff periods specifically to use dead trees, given the potential lack of long-term feedstock and high harvesting costs (Stennes and McBeath, 2006; Lloyd *et al.*, 2014).

Resource Availability: Deadwood from Natural Disturbances

135. The International Energy Agency predict that the amount of dead wood, killed by mountain pine beetles, which is used for pellet production in Canada will increase steadily up to 2020, reaching approximately 1.7 Modt/y by 2020 (IEA Bioenergy, 2011). However, this is considerably lower than the technical potential, which has been estimated by Dymond *et al.* (2010) to be 17.4 Modt/y between 2005 and 2020, assuming 50% should be left in the forest to prevent soil degradation and loss of habitats. Dymond *et al.* (2010) also estimated that a further 6.0 Modt/y could be retrieved from salvage logging trees between 2005 and 2020 in the boreal shield region of Canada from trees that have been diseased by Spruce worm, and that the total availability of insect-killed wood from Canada during this time horizon will be 30.7 Modt/y. On top of this, Dymond *et al*. (2010) estimated a further 19.9 Modt/y of fire-killed wood could be available from Canadian forests between 2005 and 2020,

assuming 50% should be left in the forest. However, it is important to note that some of the dead trees are likely to be in stands which are too remote, or on a terrain that is unharvestable. There are also problems with harvesting trees that have been dead for several years, as the stem can break during harvest, making the process dangerous and difficult (Canadian Biomass Magazine, 2013; Wood Business, 2013)

136. For the USA, the estimated availability of forest residues from fire-treatments calculated by the US DOE (2011) (described in the section "Forest Residues: Scenarios 4 to 8", starting on page 61) includes dead trees and therefore has not been considered here (to avoid double counting).

137. For the purpose of this report, a range of 1.7 to 50.6 Modt/y was assumed to be the potential availability of feedstocks from North American dead wood from natural disturbances in 2020.

GHG Emission Intensity: Deadwood from Natural Disturbances

Dead trees that would otherwise be left in the forest

138. It was assumed the dead trees would be harvested, after which the land would undergo natural regeneration. If the dead trees had not been harvested, the trees would have decayed in the forest with an assumed decay constant of 0.028 y^{-1} for Pacific Canada[56] (Chambers *et al.*, 2000), whilst the land naturally-regenerated. It was assumed that the increase in the forest carbon stock by natural regeneration would occur at the same rate in both cases. In reality, future stand development and natural disturbances might be different for a harvested stand of dead trees, and a stand which has been left untreated. For example, Collins *et al.* (2011) studied the regeneration pattern of Lodgepole pine stands affected by mountain pine beetles after the trees had been harvested, and in dead stands which had been left untreated. They predicted that stands that had been treated to remove the dead trees would be dominated by Lodgepole pine in the future, whereas stands that had not been treated would be dominated by Subalpine fir trees which grew better in shaded environments. The modelling of the future growth of the regenerated stands showed that stands which had been untreated would reach the pre-beetle attack tree basal area after 80 years, whilst it would take 105 years for the harvested stands to reach this level (Collins *et al.*, 2011). It is also possible that stands which have undergone salvage logging may be less susceptible to future fires, which can also affect the carbon stored in the forest. Further research should be undertaken to investigate the difference in future carbon stocks in stands which have been treated to remove dead trees, and those which have been left untreated, accounting for different species compositions, and different future natural disturbances.

Dead Trees that would otherwise be burned at the roadside

139. If the counterfactual to using diseased trees for bioenergy were burning at the roadside, the GHG intensity would be similar to that estimated for forest residues that would otherwise be burned as waste (see page 65).

140. A summary of the GHG intensities of biomass electricity for BEAC Scenarios 9a and 9b are shown in Figure 28. These results have been calculated using the default key parameters[57] (details in Table 29), including the assumption that biomass is used to dry the wood prior to pelletisation. Whereas the moisture content of wood, at the time

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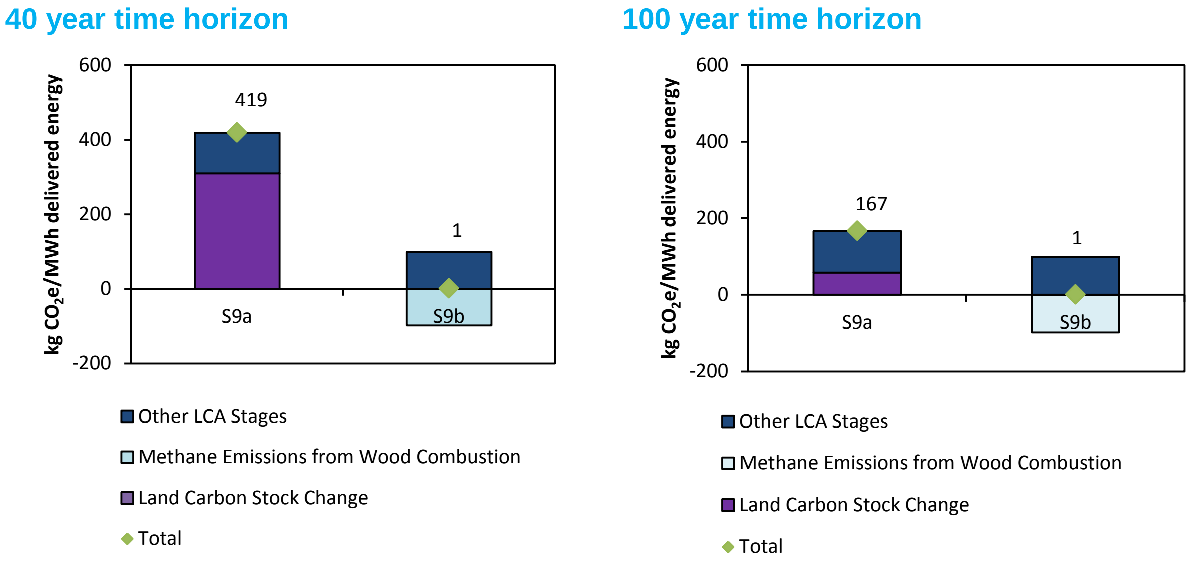
[56] Decay rate for dead trees in Pacific Northwest. The BEAC tool could be used to investigate other decay rates, for example, if data specific to beetle-killed trees were available.

[57] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

of logging, is usually ~ 50 to 55 wt% (FAO, 2013), dead wood generally has a lower moisture content of ~ 25 wt% (USFS, 2013). It was therefore assumed that the wood is dried at the pellet plant from 25 wt% to 10 wt% moisture, prior to pelletisation.


40 year time horizon

100 year time horizon

Figure 28. GHG intensity over time horizons of 40 and 100 years of electricity from pelletised dead trees, from forests in Pacific Canada, and shipped to the UK (BEAC Scenario 9). Default BEAC values have been used for key parameters (see Table 29 in the Annex).

Energy Input Requirement: Deadwood from Natural Disturbances

141. Figure 29 shows the EIR (energy carrier input basis; see page 50 for description) for UK electricity from dead trees originating from Pacific Canada, using different drying methods (drying from 25 wt% to 10 wt% moisture using biomass or natural gas) and assuming different counterfactuals. If the wood would otherwise have been left in the forest, the EIR is higher than if it would otherwise have been burned at the roadside. This is because extracting the trees, whether for energy or for burning at the roadside, requires additional diesel fuel than leaving in the forest.

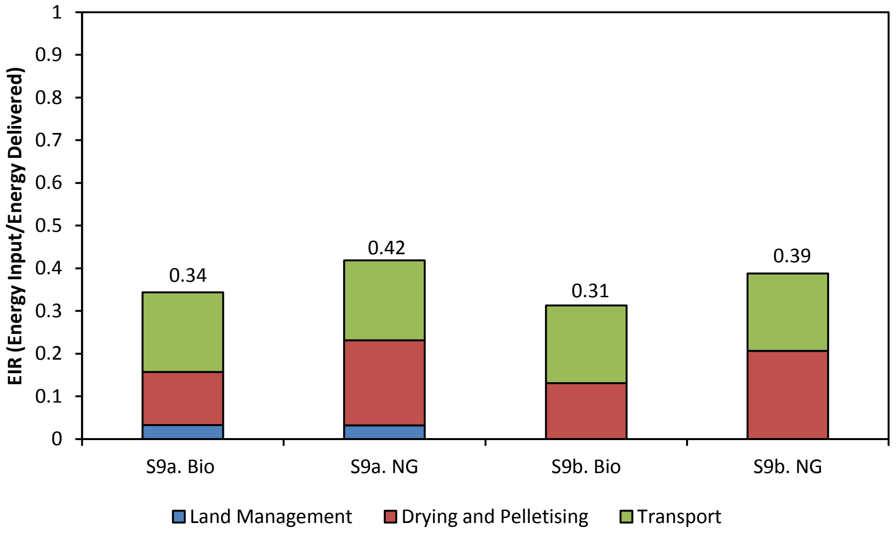


Figure 29. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from dead trees on the Pacific North American coast, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: Dead Wood from Natural Disturbances

142. The predicted resource availability of North American dead trees, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 15.

Table 15. Potential resource of North American dead wood by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[58] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020	GHG intensity		EIR		Details
	Modt/y	kg CO_2e/MWh		MWh per MWh		
		40 years	100 years	EC basis	PE basis	
Dead wood from natural disturbances	1.7 to 50.6	-7 to 531	-7 to 241	0.22 to 0.58	0.26 to 0.69	**Min**: BEAC Scenario 9b. **Max**: BEAC Scenario 9a.

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[58] EIR values are the same for 40 and 100 year time horizons.

Summary: Woody Residues for 2020

143. The projected resource of North American woody residues that may be available by 2020, along with their GHG intensities when used for dedicated electricity generation in the UK, are summarised in Figure 30 and Figure 31, for time horizons of 40 and 100 years, respectively. The projected resource is plotted against the Energy Input Requirement (EIR) in Figure 32.

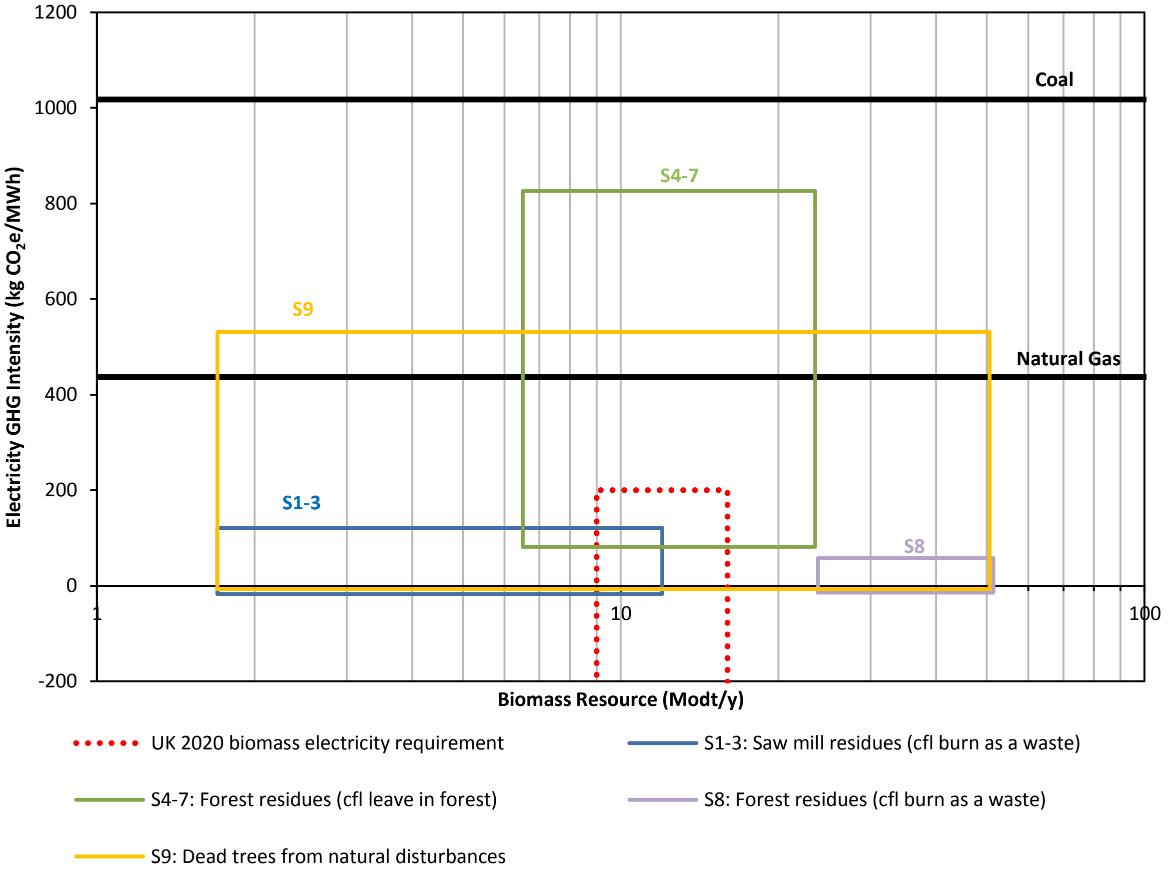


Figure 30. Summary of resource of North American woody residues that may be available by 2020, and their GHG intensity over 40 years. cfl: counterfactual.

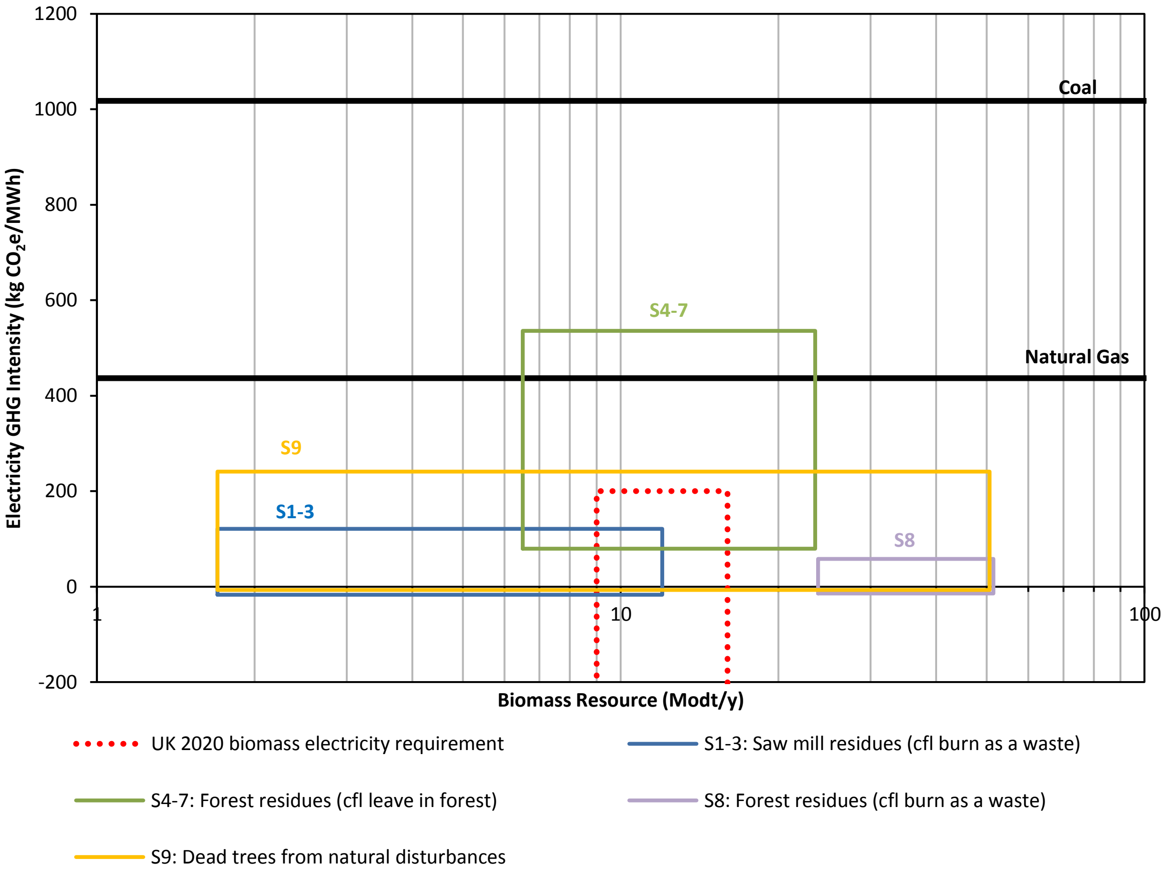


Figure 31. Summary of resource of North American woody residues that may be available by 2020, and their GHG intensity over 100 years. cfl: counterfactual.

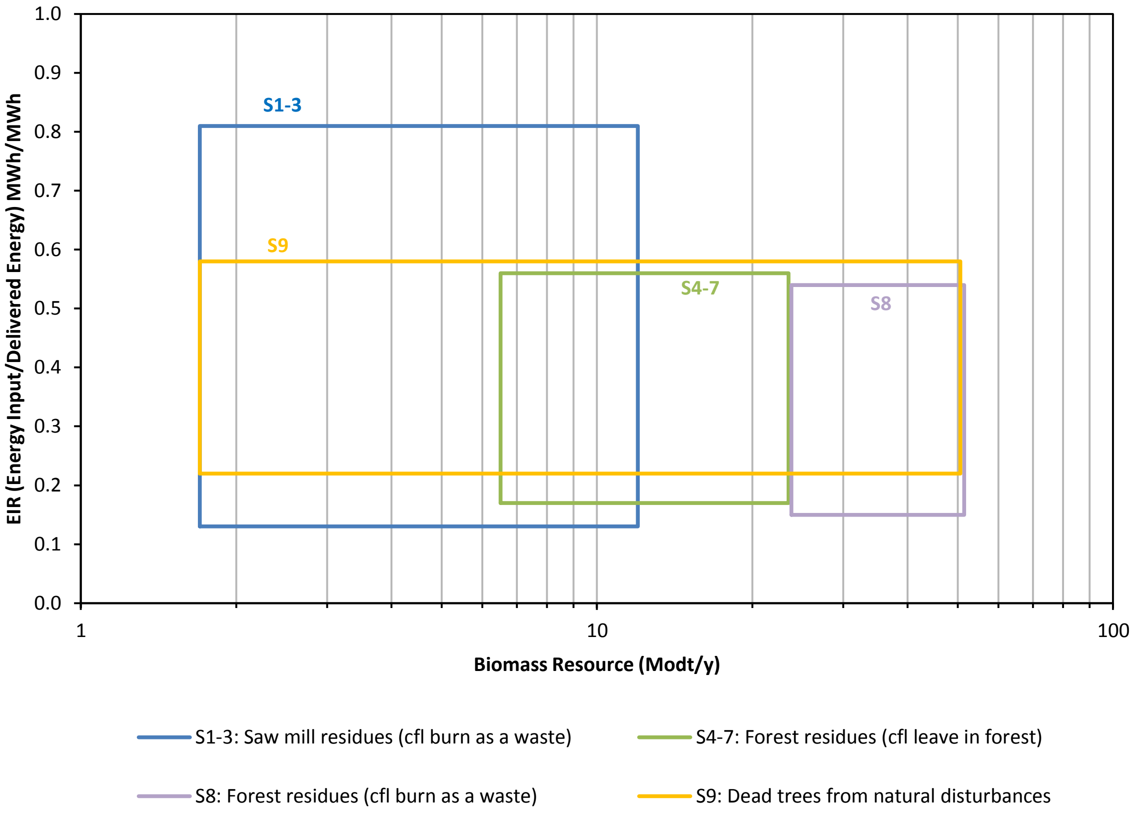
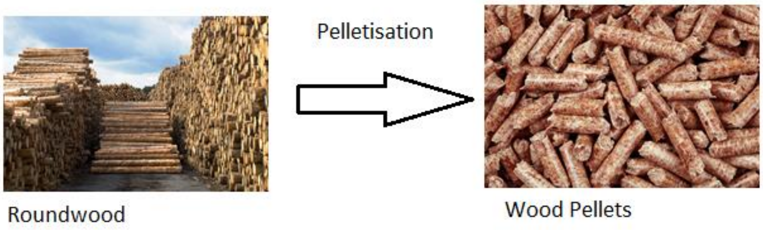


Figure 32. Summary of resource of North American woody residues that may be available by 2020, and their Energy Input Requirement (for both time horizons, 40 and 100 years). The EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. cfl: counterfactual.

Results: Roundwood and Energy Crops

Increased Harvest of Naturally-Regenerated Timberland: Scenarios 10-13



144. In North America, most productive forests are of natural origin; these forests regenerate naturally through seeding, root suckers, or stump sprouts from existing trees, and generally achieve lower growth rates than intensively-managed plantation forests, therefore are harvested over longer rotations (typically 50 to 100 years; Smith *et al.*, 2006). Figure 33 shows that in the USA, there are approximately 187 million hectares of productive, naturally-regenerated timberland, representing 88% of all productive timberland, whilst in Canada, there are approximately 136 million hectares of naturally-regenerated timberland forests, representing 94% of all productive timberland.

145. Naturally-regenerated timberlands are already used to produce biomass pellets. For example, it has been reported that naturally-regenerated hardwood forests in South USA are currently used to produce feedstock for pellet manufacture (Evans *et al.*, 2013).

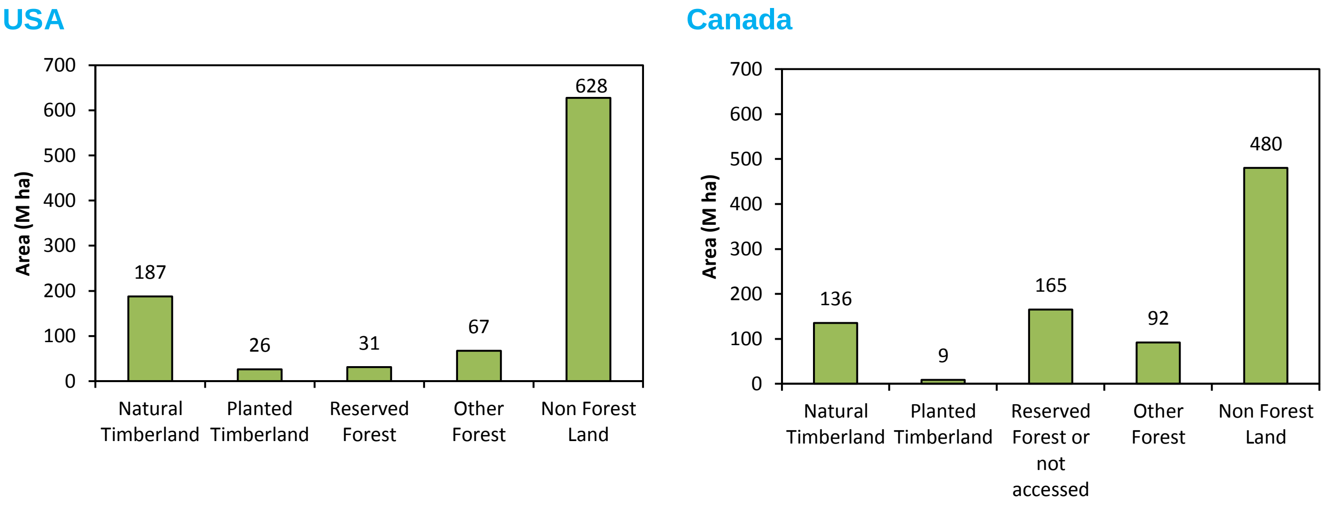


Figure 33. Land area by major class in the United States (Smith *et al.*, 2010) and Canada (FAO, 2010a).

Scenarios: Roundwood from Naturally-Regenerated Forests

146. As mentioned on page 37, a potential consequence of increased demand for wood for bioenergy could be that forests are harvested more frequently in comparison to the counterfactual, in order to extract more wood in the short-term (Abt and Abt, 2013; Walker *et al.*, 2010., Schulze *et al.*, 2012; Weir and Greis, 2000; Holtmark, 2012). The scenarios considered in this section of the report are therefore aimed at investigating the impact of increasing the rate of harvest of a naturally-regenerated forest, with the counterfactual being leaving the forest under the previous management regime. However, the impact of *continuing* to harvest a naturally-regenerated hardwood forest in the USA every 70 years, with the counterfactual being that the forest would be harvested *less* frequently, has also been considered (Scenario 13b). The scenarios which have been investigated are listed below in Table 16.

Table 16. Scenarios modelled to represent using roundwood from Naturally Regenerated forests for bioenergy feedstocks.

Scenario number	Feedstock used for pellets	Counterfactual scenario
10	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated hardwood forest in East Canada (a) from every 100 years to every 50 years, (b) from every 100 years to every 80 years. Rotation lengths of forests in boreal Canada range between 30 to 120 years, with typical rotation lengths being 80 to 100 years; rotation lengths less than 60 years are considered short, whilst rotation lengths greater than 100 years are considered long (Peng *et al.*, 2002). Scenario (a) therefore represents a case where the new rotation is considered short, and (b) represents a change where the new rotation is considered typical.	Continue harvesting the forest every 100 years.
11	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated conifer forest in Pacific Canada from every 70 years to every 50 years. These rotation lengths are typical to Douglas Fir in this region (Spittlehouse, 2003).	Continue harvesting the forest every 70 years.
12	Additional wood (in comparison to the counterfactual) generated by increasing the rate of harvest of a naturally-regenerated conifer forest in boreal Canada (a) from every 100 years to every 50 years, (b) from every 100 years to every 80 years. These rotation lengths are typical to Canadian boreal forests (Peng *et al.*, 2002).	Continue harvesting the forest every 100 years.
13	(a) Additional wood (in comparison to the counterfactual) generated by increasing the rate	(a) Continue harvesting the forest

Scenario number	Feedstock used for pellets	Counterfactual scenario
	of harvest of a naturally-regenerated hardwood forest in South USA from every 70 years to every 60 years.	every 70 years.
	(b) Additional wood (in comparison to the counterfactual) generated by continuing harvesting a naturally-regenerated hardwood forest in South USA every 70 years.	(b) Reduce the rate of harvest to every 80 years.

Considerations for Scenario Plausibility: Roundwood from Naturally-Regenerated Forests

147. As mentioned above, naturally-regenerated hardwood forests are already used to produce bioenergy feedstocks in South USA.

148. The demand for hardwood pulpwood in the region between 2008 and 2013, and the projected demand from 2014 to 2018, are shown in Figure 34. It can be seen that the demand for hardwood paper feedstocks declined between 2008 and 2009; this was caused by closures of paper mills (22 out of an initial 100 paper mills closed in the US South between 1990 and 2010; Forisk, 2014). However, since 2009, hardwood consumption for paper has remained stable, and is projected to remain stable over the next 5 years. The overall demand for hardwood pulpwood in the region is projected to increase by 5% over the next 5 years.

149. This additional demand for hardwood pulpwood for pellet production could result in a greater area of hardwood forest being harvested each year in the region in comparison to the counterfactual; in this case, BEAC Scenarios 13a and 13b would be relevant. If the pulpwood would be harvested anyway and treated as a logging residue, then the residue scenarios considered in the section “Forest Residues: Scenarios 4 to 8” (starting page 61) would be appropriate. However, in this region, hardwood pulpwood often represents ~ 50 to 60 vol% of the harvest from a stand of naturally-regenerated hardwood forest; it is currently not common practice to treat this amount of a harvest as a residue.

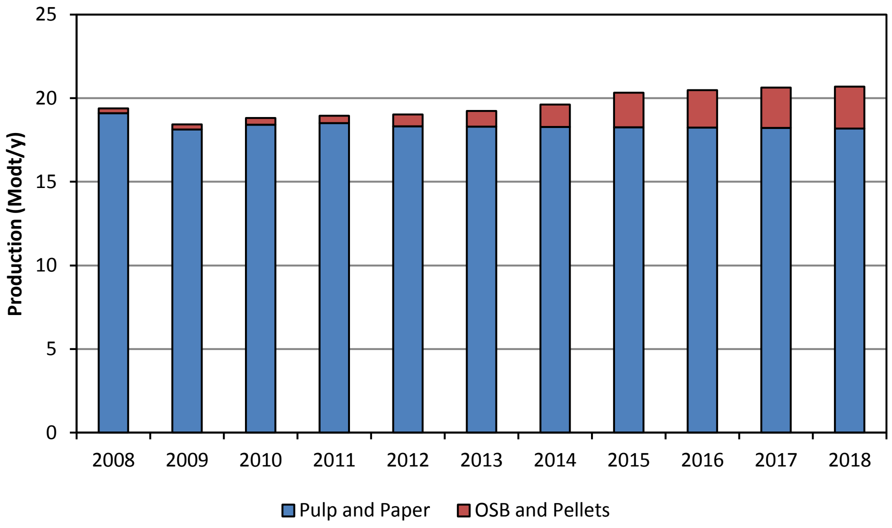


Figure 34. Hardwood pulpwood consumption in South USA from 2008 to 2013, and projected consumption between 2014 and 2018. Using green US ton consumption and projections from Forest2Market (2014), and assuming 50 wt% moisture. Includes the states of Texas, Oklahoma, Louisiana, Arkansas, Missouri, Mississippi, Alabama, Tennessee, Georgia, Florida, North Carolina, South Carolina and Virginia.

150. Discussions with the forestry industry indicate that smaller changes in the rotation length of naturally-regenerated forests (*e.g.* Scenarios 10b, 11, 12b and 13) are currently more likely than large reductions (*e.g.* Scenarios 10a and 12a, where rotation lengths are reduced from 100 years to 50 years). This is because such large reductions in rotation lengths can result in significant reductions in the amount of wood harvested that is large enough to be used in construction.

Resource Availability: Roundwood from Naturally-Regenerated Forests

151. The resource availability of additional biomass that could be harvested from naturally-regenerated timberlands by 2020 depends strongly on the change in the rate of harvest from these naturally-regenerated timberlands. For example, if the rate of harvest of broadleaf naturally-regenerated timberland in boreal Canada (BEAC Scenario 10) increased from every 100 years to every 50 years, the wood output of the forest would increase by ~ 84% over 40 years, and 57% over 100 years, whereas if the rate of harvest increased to every 80 years, the wood output would only increase by 23% over 40 years, and 20% over 100 years. By considering the change in wood outputs modelled in the BEAC scenarios, and reflecting the finding that large reductions in rotation length are currently not considered likely (*e.g.* Scenarios 10a and 12a, where rotation lengths are reduced from 100 years to 50 years), the range of potential increased wood outputs from increasing the harvest rate of naturally-regenerated forests was taken to be 11% to 26% over 40 years, and 4% to 12% over 100 years; the low value represents small changes in rotation length (*e.g.* Scenario 13, where rotation length is reduced from 70 to 60 years) and the high value represents larger changes (*e.g.* Scenarios 11, where the rotation length is reduced from 70 to 50 years). Currently North American naturally-regenerated timberland accounts for ~ 160 Modt/y[59] of wood production, therefore for the purpose of this report, it has been estimated that by reducing the rotation lengths, a further 17.6 to 41.6 Modt/y could be harvested over 40 years, and 6.4 to 19.2 Modt/y over 100 years.

GHG Emission Intensity: Roundwood from Naturally-Regenerated Forests

152. The main assumptions used to construct the BEAC scenarios are shown in Table 37 of the Annex. Decreasing the time between harvest causes each stand of forest to be harvested more frequently, therefore a greater area of forest is harvested each year. The result of this increased harvest is that the average non-soil carbon stored in the forest reduces, and the amount of biomass extracted increases (Peng *et al.*, 2002; Holtmark, 2012). As the trees are younger when harvested, the majority of additional biomass is in the form of pulpwood, as shown in Figure 35b.

153. For each scenario, it has been assumed that the additional wood created by the bioenergy scenario, in comparison to the counterfactual, is used for bioenergy, and any changes in carbon stock in the forest relative to the counterfactual are attributed to this wood output. As mentioned previously in the section “Construction of Scenarios” (page 43), it has been assumed that there is no difference in the amount of wood used for non-bioenergy uses between the bioenergy scenario and its counterfactual scenario, *e.g.* increased use of wood for bioenergy does not cause a change in the amount of wood harvested for non-energy uses. This approach has been taken by other studies, including that by Walker *et al.*, 2010.

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[59] Calculated from the total wood production from North America (~200 Modt/y; Figure 12), and assuming ~ 40 Modt/y of this is from plantations (value for South USA; Smith *et al.*, 2010).

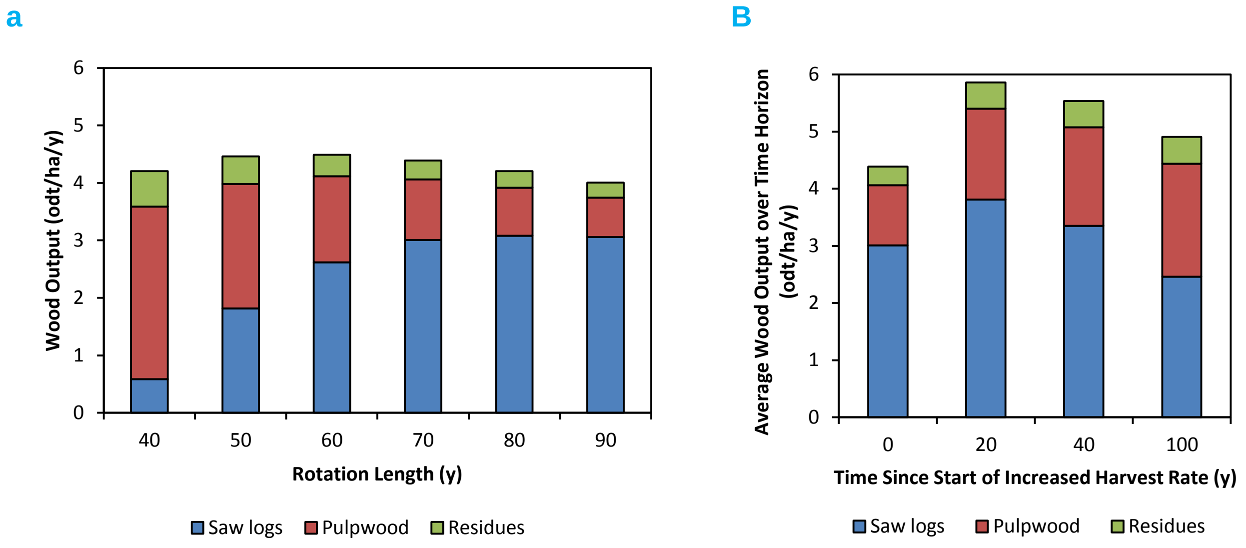

Figure 35. Wood output from a coniferous forest in Pacific Canada (BEAC Scenario 11) from the CSORT model. a: Wood output of even-aged forests with different rotation lengths. b: Average wood output before the rate of harvest increases from harvest every 70 years to every 50 years (labelled zero on x-axis), and after the harvest rate increases, over 20, 40 and 100 years.

154. The assumed carbon stored in a stand of forest at different ages is shown in Figure 36 for each scenario; these data were used to estimate the average amount of carbon stored in forests of different age distributions.

155. For each scenario and associated counterfactual, the wood output and non-soil carbon stored in the forest, calculated as averages over all stands, are shown in Figure 37. It was assumed for all scenarios that the forests were initially composed of an even-aged[60] distribution of stands, and that after the rate of harvest increases, that distribution of stands would be converted to another even-aged forest. For example, BEAC Scenario 11 involves increasing the rate of harvest of a coniferous forest in Pacific Canada from harvesting every 70 years to harvesting every 50 years; in this case, the area of forest harvested each year would increase by 40%, causing the initial wood output to increase. The average non-soil carbon stock would reduce, as shown in Figure 37, until a new equilibrium is reached, 50 years after the initial increased rate of harvest. At the start of this scenario, the forest has stands with uniform ages between 0 and 70 years old. After 50 years, the forest has stands with uniform ages between 0 and 50 years old.

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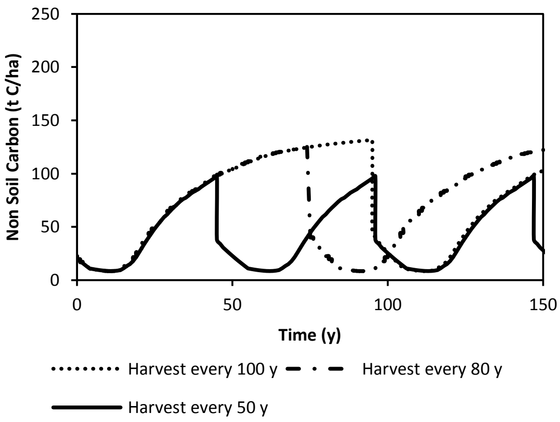
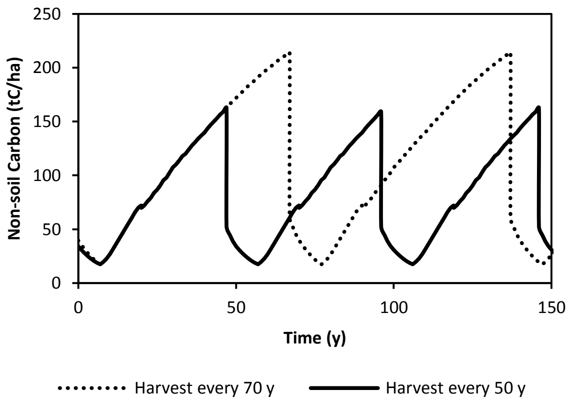
[60] A forest consisting of a number of stands of trees, with each stand being composed of trees of the same age, and the age distribution of stands in the forest being uniform.

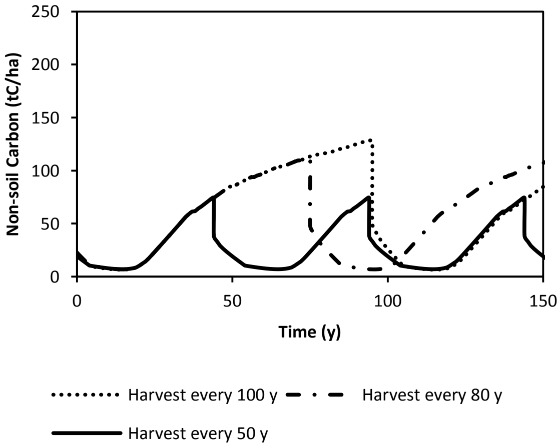
BEAC Scenario 10



BEAC Scenario 11



BEAC Scenario 12



BEAC Scenario 13

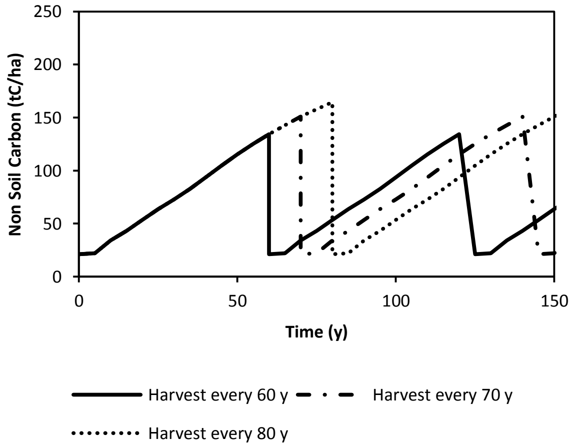


Figure 36. Non-soil carbon stock of stands of a forest at different ages, for BEAC Scenarios 10 to 13. Data sources: Forest Research C-SORT model for Scenarios 10, 11 and 12, and Smith *et al.* (2006) for Scenario 13.

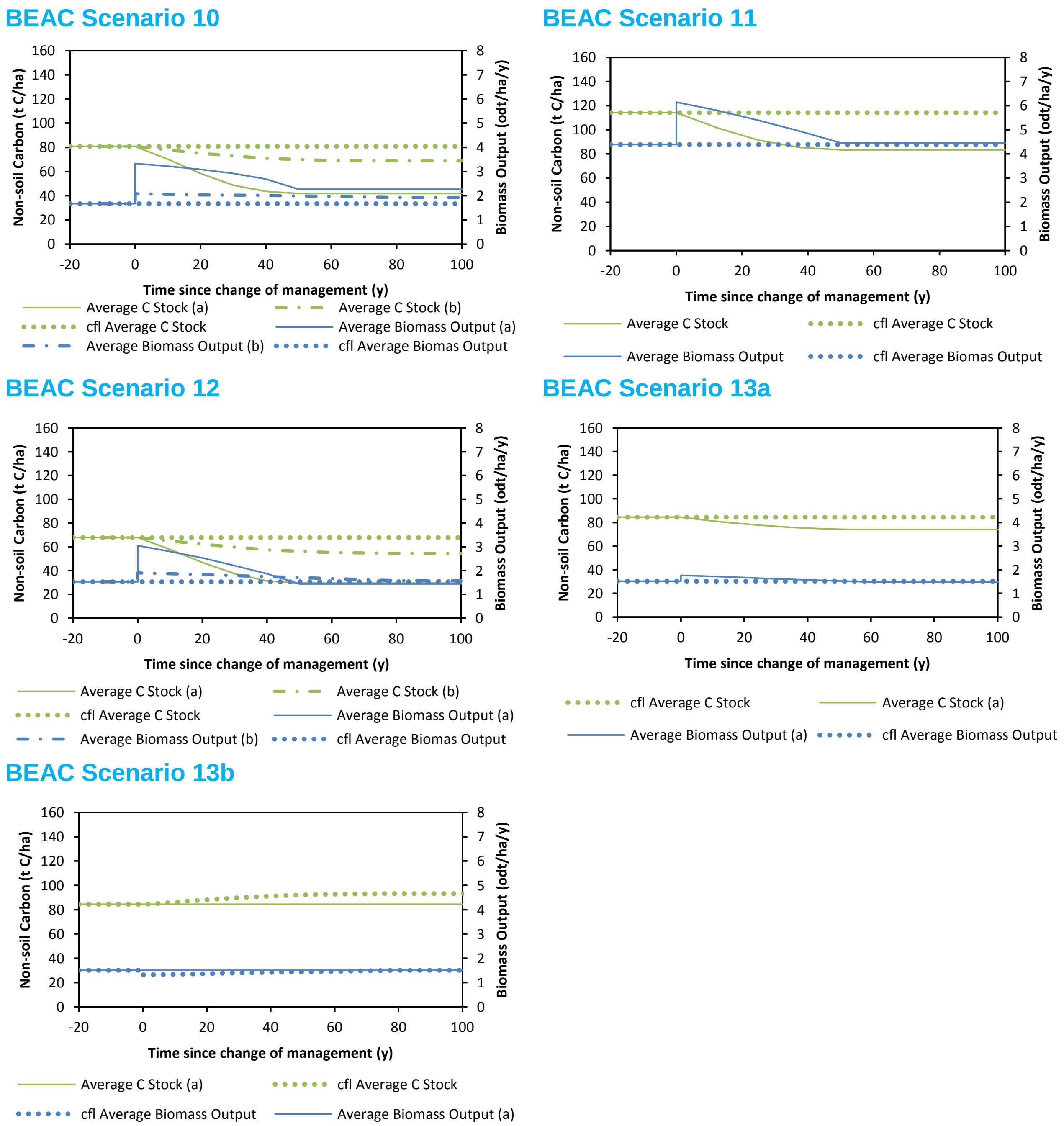


Figure 37. Total biomass output from, and non-soil carbon stored in, naturally-regenerated forests, calculated as average values over all stands in the forests, for BEAC Scenarios 10 to 13, using data from the Forest Research C-SORT model for Scenarios 10, 11 and 12, and Smith *et al.* (2006) for Scenario 13. cfl: counterfactual.

156. There is significant scientific debate around the effect of management practices on forest soil organic carbon (SOC). Large amounts of carbon are stored in deep mineral soils[61] of forests, but are often not considered in accounting for forest carbon fluxes because mineral soil carbon is commonly considered to be relatively stable (Buchholz *et al.*, 2013). Johnson and Curtis (2001) reviewed the literature on forest management and soil carbon, and concluded that the time since harvest did not affect the SOC content of forest soils. However, Peng *et al.* (2002) reported that shorter rotation lengths of boreal forests of Central Canada are associated with lower SOC contents. Bucholz *et al.* (2013) recently reported that SOC contents of mineral soils in northeastern US forests are often reduced by harvesting, therefore increased

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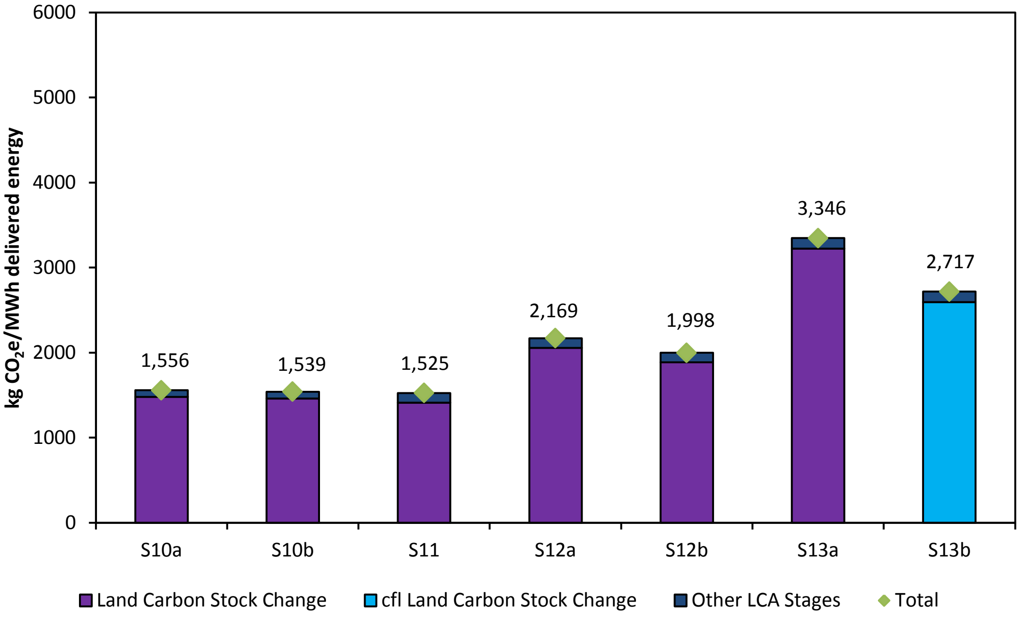
[61] See Table 2 for definition.

harvest rates may reduce the SOC content. Further work is required in this area. A conservative assumption was made in this study that SOC contents of mineral soils in forests are independent of harvest rate. This assumption was applied to all the BEAC scenarios considering management changes of forests in order to increase the biomass output.

A: 40 year time horizon



B: 100 year time horizon

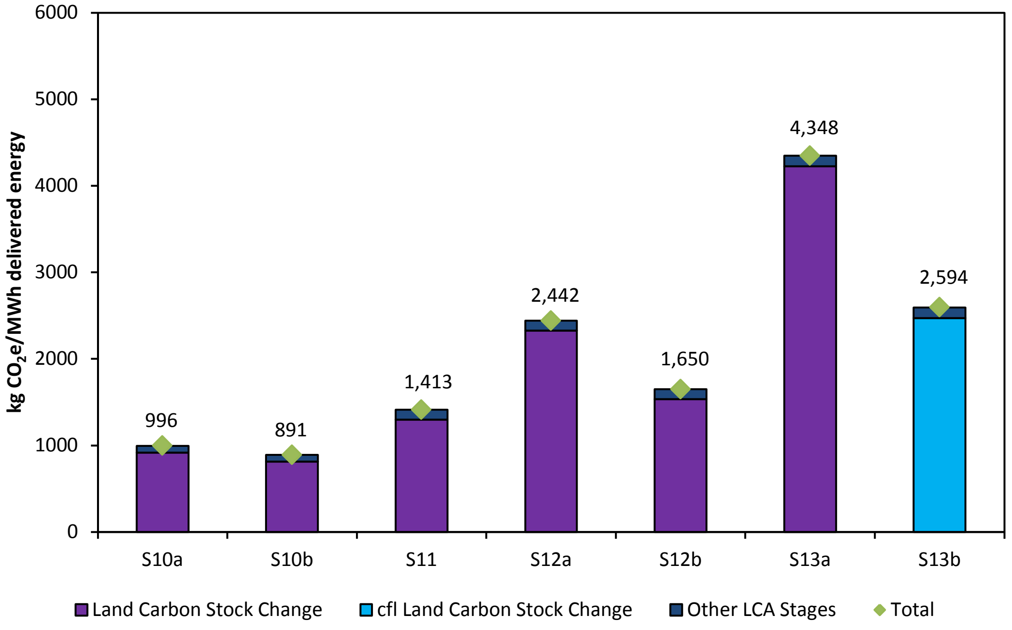


Figure 38. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from naturally-regenerated forestry in North America, and shipped to the UK, for BEAC Scenarios 10 - 13 (labelled S10 - S13). cfl: counterfactual. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

157. A summary of the GHG intensities of biomass electricity for these scenarios is shown in Figure 38. These results have been calculated using the default key parameters[62] (details in Table 29), including the assumption that biomass is used to dry the wood

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[62] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

prior to pelletisation. All of these scenarios have GHG intensities significantly greater than electricity from natural gas, over 20, 40 and 100 year time horizons.

158. The difference in GHG intensities between these scenarios depends on the growth curves, and hence wood yields, of the stands of trees over the assessed time horizons. For example, the final annual output of wood achieved once an Oak-Hickory stand in South USA (Scenario 13a) has been fully converted to an even-aged forest, harvested every 60 years, is slightly lower than the annual output associated of an even-aged forest, harvested every 70 years. However, for BEAC Scenario 11, reducing the time between harvests from 70 years to 50 years results in an overall increase in the final yield of wood, as shown in Figure 37. Thanks to the higher final yield achieved in Scenario 11, the carbon stock reduction per unit of wood output, caused by reducing the time between harvests, is lower than for Scenario 13a.

Energy Input Requirement: Roundwood from Naturally-Regenerated Forests

159. The Energy Input Requirements (energy carrier input basis; see page 50 for description) for BEAC Scenarios 10 to 13 are shown in Figure 39, assuming the wood is dried prior to pelletisation by using biomass (the default in BEAC), or using natural gas. The transport, drying and pelletising dominate the energy inputs. Pellets shipped from the East coast of North America (Scenarios 10 and 13) that have been produced using biomass to dry the wood prior to pelletising have the lowest EIR values, and pellets shipped from the Pacific coast (Scenarios 11 and 12) that have been produced using natural gas to dry the wood prior to pelletising have the highest EIR values.

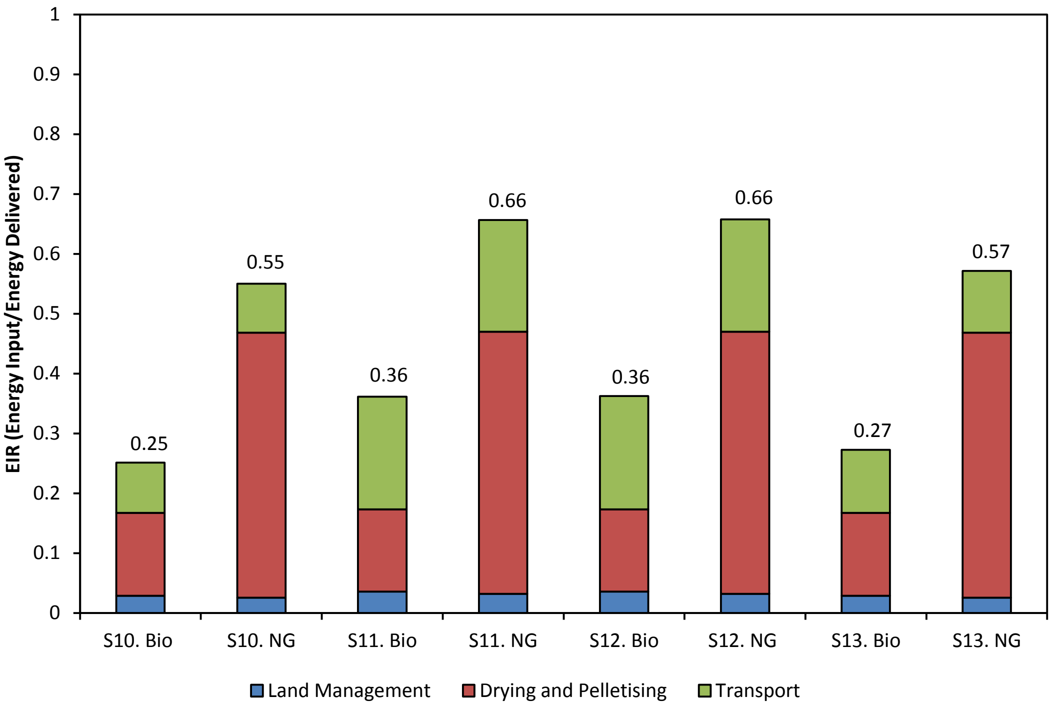

Figure 39. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from naturally-regenerated forests in North America, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: Roundwood from Naturally-Regenerated Forests

160. The predicted resource availability of North American wood from increased harvest of naturally-regenerated timberland, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 17.

Table 17. Potential resource of North American wood from increasing harvest rate of naturally-regenerated timberland by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[63] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020	**GHG intensity**		**EIR**		**Details**
	Modt/y	**kg CO_2e/MWh**		**MWh per MWh**		
		40 years	**100 years**	**EC basis**	**PE basis**	
Increased harvest of naturally-regenerated timberland	17.6 to 41.6 over 40 years 6.4 to 19.2 over 100 years	1270 to 3988	766 to 5174	0.16 to 0.88	0.19 to 1.03	**Min**: BEAC Scenario 11 for GHG over 40 y; BEAC Scenario 10b for GHG over 100 years.BEAC Scenario 10 for EIR. **Max**: BEAC Scenario 13a for GHG, BEAC Scenario 12 for EIR.

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[63] EIR values are the same for 40 and 100 year time horizons.

Roundwood from Existing Plantations: Scenarios 14 to 18

161. The majority of North American intensively-managed plantations are in South USA. Pulpwood from these plantations is already used to produce pellets (Evans *et al.*, 2013). This section therefore focuses on the impacts of using wood from South plantations for the production of wood pellets.

162. The total area of plantations in the USA is ~ 25 million hectares, representing 8% of all US forestland, or 12% of all productive timberland, with over 70% situated in the South (Table 18). These plantations are predominantly used to grow Loblolly pine (~ 62.5% by area), Slash pine (17% by area) and Douglas fir (15% by area).

Table 18. Pine plantations in the USA by area (Smith *et al.*, 2010).

Region	Area of Plantations (Million ha)
South USA	18
Pacific Coast USA	4.5
North USA	2.4
Rocky Mountain USA	0.4

163. Plantations are managed to achieve greater yields of wood than naturally-regenerated forests, using practices such as (Fox *et al.*, 2007):

- planting genetically improved[64] trees;
- mechanical site preparation to improve soil physical properties;
- herbicide application to control competing vegetation (*e.g.* naturally-regenerated trees and herbaceous vegetation);
- fertiliser application to improve soil fertility; and
- thinning to manage the stand density, and provide adequate growing space for the desired crop trees.

164. For example, the site preparation of intensively-managed pine plantations in the South USA often involves chopping, piling, burning, disking, bedding, herbicide application and planting (Dwivedi *et al.*, 2011); these plantations are also often thinned twice during the rotation, and fertilised with nitrogen and phosphorus every 6 to 8 years (North Carolina Forestry Service, 2012; Fox *et al.*, 2007a). Thanks to this intense management, these plantations typically achieve ~ 6 odt/ha/y of merchantable biomass over a 25 year rotation, whereas naturally-regenerated Loblolly forests in the same region produce less than 2 odt/ha/y over a 50 year rotation (Smith *et al.*, 2006).

165. Because plantations are generally harvested more frequently than naturally-regenerated timberland, the average carbon stock per unit area is often lower. For example, in 2007, plantations represented approximately 12% of the total productive forest area in the USA, but only 8% of the total forest growing-stock inventory (Smith *et al.*, 2010).

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[64] *Via* selective breeding, not genetic modification.

166. Intensively-managed plantations in South USA are used to produce saw logs, chip-n-saw and pulpwood. The thinnings, smaller diameter sections of the final harvested trees, and low-quality logs are used for pulpwood, and the larger, high-quality trees are used for chip-n-saw and saw logs.

Scenarios: Roundwood from Existing Plantations

167. There are a number of potential scenarios relevant to using pulpwood from existing plantations for the production of pellets for bioenergy, with the most appropriate scenario depending on the demand for the wood from other markets.

168. If the regional demand for roundwood were **low**, there may be some plantations from which a proportion of the wood could be harvested for bioenergy, without impacting other markets. The scenarios listed in Table 19 were modelled to represent potential implications of this situation.

Table 19. Scenarios modelled to represent using roundwood from existing plantations for bioenergy feedstocks, if the demand for pulpwood is low.

Scenario Number	Feedstock used for pellets	Counterfactual scenario
14	Additional wood (in comparison to the counterfactual) from intensively-managed pine plantation, in South USA. (a) Continue harvesting every 25 years. (b) Increased demand for pulpwood results in the rotation length reducing to 20 years.	Reducing the frequency of harvest. For example, an intensively-managed pine plantation in South USA that is harvested every 25 years, is harvested every 35 years instead (Carino and Biblis, 2002). Less biomass would be harvested, and more biomass would be stored in the above-ground biomass of the forest. This scenario was common after the recession, where fewer trees were cut, and the forest inventory increased (Floyd, 2013). This could also represent a scenario where initiatives encourage forest owners to extend their rotation length, in order to increase carbon storage (Carbon Canopy, 2014).
15	As above.	Managing the plantation less intensively. For example, an intensively-managed pine plantation in South USA that is harvested every 25 years, is converted over 50 years to an even-aged naturally-regenerated pine forest that is harvested every 50 years.
16	As above.	Harvesting the plantation, and then leaving the land to revert to a natural forest. For example, an intensively-managed pine plantation in South USA that is harvested every 25 years, is converted over 25 years to a naturally-regenerated pine forest that is left to continually sequester carbon, rather than harvested (Carbon Canopy, 2014).[65]
17	As above.	Convert the plantation to agricultural land (*e.g.* cotton field) (Abt *et al.*, 2012).

169. If the regional demand for roundwood for other uses were **high**, either more wood must be produced from the plantations, or the use of the wood for bioenergy would

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[65] This scenario could lead to increased natural disturbances, in comparison to the counterfactual. Owing to the large uncertainties involved, this hasn't been modelled, but should be considered in future studies.

cause non-bioenergy uses of wood to be displaced. The scenarios listed in Table 20 were modelled to represent the potential implications of this situation.

Table 20. Scenarios modelled to represent using roundwood from existing plantations for bioenergy feedstocks, if the demand for pulpwood is high.

Scenario number	Feedstock used for pellets	Counterfactual scenario
18	Additional demand for wood for bioenergy causes some plantations to be managed more intensively, causing an increased yield. For example, a plantation that is harvested every 25 years, and produces an average yield of wood 74% that of an intensively-managed plantation, is converted to an intensively-managed plantation by increasing the fertiliser input (assumed to increase from 1 to 3 mid-rotation fertilisation applications; Allen *et al.*, 2005), and improving silvicultural practices (*e.g.* adopting optimal thinning practices and initial planting densities; Will *et al.*, 2006).	Continue using medium-intensity management practices, and harvesting every 25 years.
19-21, covered in next section (p97)	Bioenergy displacing other wood users. If pulpwood is used for energy, other users (*e.g.* paper and OSB manufacturers) import the feedstock, or the wood products are imported.	Pulpwood used for other purposes.

170. Some areas of forests in North America are under threat of being converted to urban land (Fernholz *et al.*, 2013), and it has been suggested by some stakeholders that a counterfactual to using plantations for bioenergy is its conversion to urban land. However, as urban land uses are so valuable in comparison to agricultural land, we judge that such transitions are driven by different factors to those driving transitions between cropland and forestry, in particular population growth and household formation (Lubowski *et al.*, 2006; Heimlich and Hendersen, 2001). However, if this scenario were credible in the future, the GHG impact would be similar to BEAC Scenario 17 (both arable and urban land have low above-ground carbon stocks).

Considerations for Scenario Plausibility: Roundwood from Existing Plantations

171. As mentioned above, intensively managed pine plantations are already used to produce bioenergy feedstocks in South USA.

172. The removal of softwood pulpwood in South USA increased between the years 2000 and 2009 (Figure 13); competition for softwood pulpwood in the region is currently high, with prices increasing by 10% between Quarter 2 of 2012 and 2013 (Forest2Market, 2013), and 22% between the September/October periods of 2012 and 2013 (Forest2Market, 2013a). Furthermore, demand for softwood pulpwood is projected to increase further in the South in the coming years, owing to increased demand for OSB, packaging, fluff pulp and containerboard, as well as wood pellets; Forest2Market (2014) predict that total pine pulpwood demand will increase by 11% between 2014 and 2018 in South USA (Figure 40).

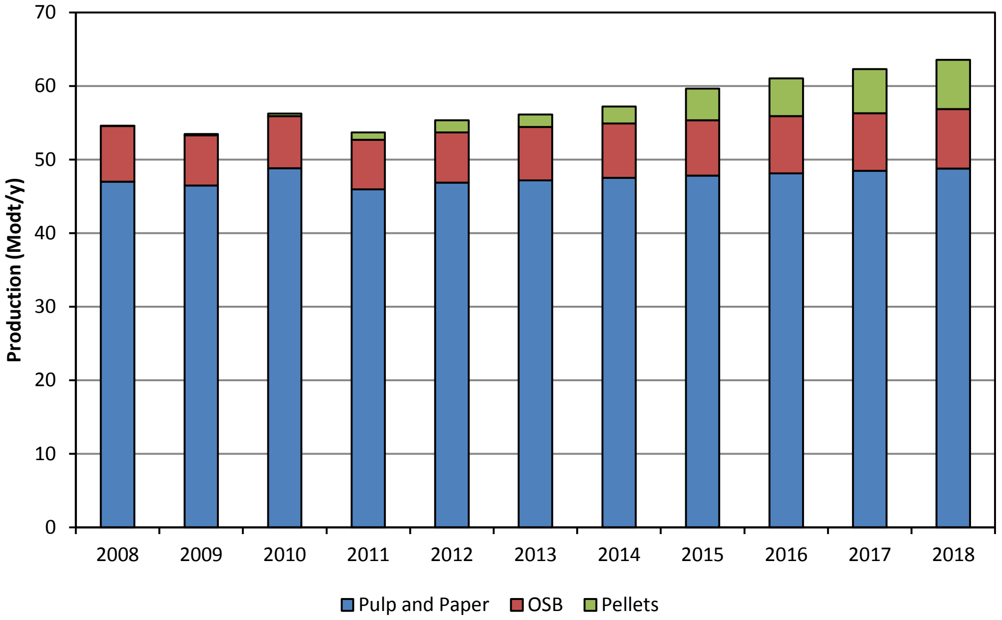


Figure 40. Softwood pulpwood consumption in South USA from 2008 to 2013, and projected consumption between 2014 and 2018. Using green US ton consumption from Forest2Market (2014), and assuming 50 wt% moisture. Includes the states of Texas, Oklahoma, Louisiana, Arkansas, Missouri, Mississippi, Alabama, Tennessee, Georgia, Florida, North Carolina, South Carolina and Virginia.

173. This indicates that counterfactuals relevant to a high demand for wood may be most likely (Scenario 18, and displacement scenarios 19 to 21, page 97). However, despite this, trends are regional, therefore there may be some cases where the counterfactuals relevant to a low demand for wood are the most appropriate. Furthermore, projections of further increases in demand are based on assumptions around future economic factors, and therefore may not materialise.

Resource Availability: Roundwood from Existing Plantations

174. Low demand for wood (BEAC Scenarios 14 to 17): In the coastal states of South USA (the location of the majority of intensively-managed pine plantations), total wood removal decreased by ~ 11 Modt/y during the recession (in the form of saw logs; Figure 13), therefore 11 Modt/y was taken as the high value in the range. The housing sector is starting to recover again (RISI, 2014), therefore the low value was taken to be zero, representing a case where the demand for wood for non-bioenergy purposes is high.

175. High demand for wood (BEAC Scenario 18): It was assumed that a yield increase of 35% may be possible if ‘medium-intensity’ plantations were managed more intensively (Allen *et al.*, 2005). There is little data on the proportion of plantations in the South USA which are currently not managed optimally, from the point of view of annual yield. Discussions with stakeholders indicated that it would be reasonable to assume that 50% of current plantations are currently not managed at maximum intensity. If the yield of 12.5 million hectares were to increase by 1.5 odt/ha/y, an additional 18.8 Modt/y could be achieved by this scenario. However, if the demand for wood for non-bioenergy purposes were to increase significantly in the future, higher yields might need to be achieved anyway to meet demand (even if demand for bioenergy were not there), therefore the low value of the range was taken to be zero.

176. The main assumptions used to construct the BEAC scenarios are provided in the Annex (Table 39). For each scenario, the difference in wood output between the bioenergy scenario, and the associated counterfactual, results in a difference in carbon stored in the forest. It has been assumed that the additional wood created by the bioenergy scenario, in comparison to the counterfactual, is used for bioenergy, and any changes in carbon stock in the forest relative to the counterfactual are attributed to this wood output. As mentioned previously, it has been assumed that there is no difference in the amount of wood used for non-bioenergy uses between the bioenergy scenario and its counterfactual scenario, *e.g.* increased use of wood for bioenergy does not cause a change in the amount of wood harvested for non-energy uses. These scenarios (14 to 18) therefore represent cases where the wood from the intensively-managed plantation is used for a mix of different products (*e.g.* construction products, paper, and bioenergy), apart from Scenario 16, where the counterfactual is to cease harvesting, in which case all the wood is used for bioenergy.

177. The assumed carbon stored in a stand of intensively-managed Loblolly, at different ages, is shown in Figure 41; this growth curve was used to estimate the average amount of carbon stored in forests of different age distributions. For all scenarios, it was assumed that the forest was initially composed of a uniform distribution of stands, between the ages of 0 and 25 years (*e.g.* an even-aged forest).

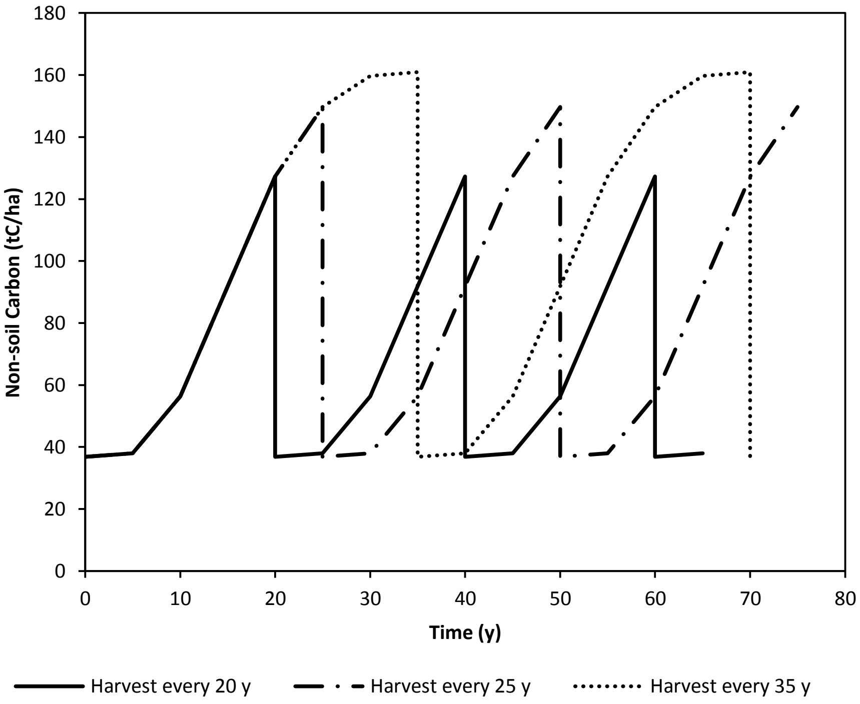
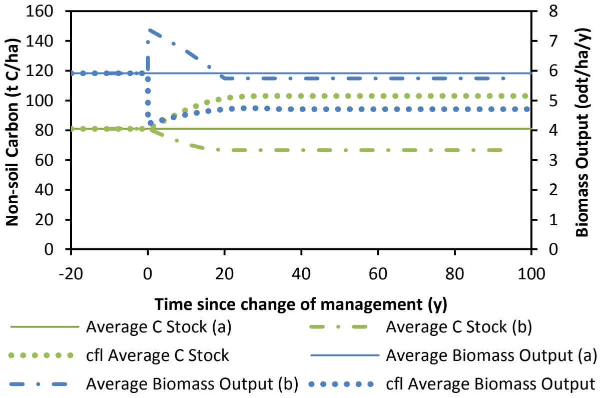
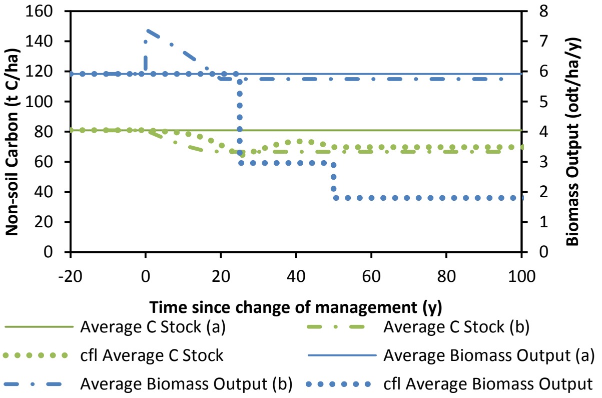
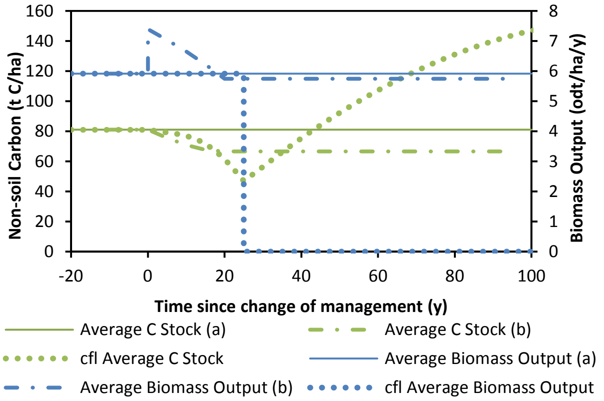


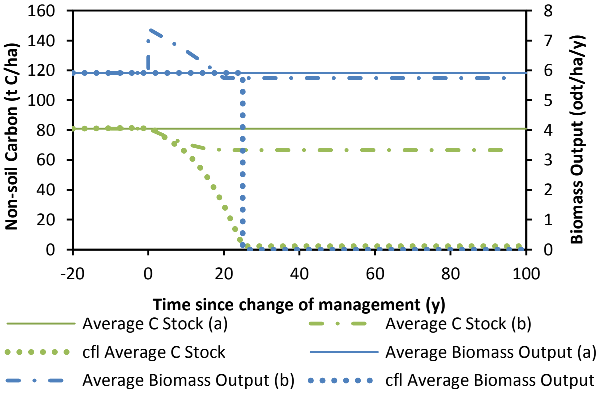
Figure 41. Non-soil carbon stock at different times, of a stand in an intensively-managed Loblolly pine plantation, located in South USA (Smith *et al.*, 2006).

178. For each scenario and associated counterfactual, the wood output and non-soil carbon stored in the forest, calculated as averages over all stands, are shown in Figure 42.


BEAC Scenario 14


BEAC Scenario 15


BEAC Scenario 16


BEAC Scenario 17

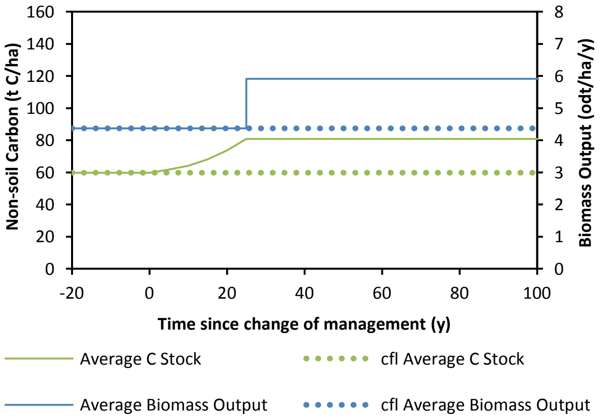

BEAC Scenario 18

Figure 42. Total biomass output from, and non-soil carbon stored in, a Loblolly plantation forest, calculated as average values over all stands in the forests, for BEAC Scenarios 14 to 18, using data from Smith *et al.*, 2006. cfl: counterfactual.

179. The summarised GHG results for these scenarios are shown in Figure 43. These results have been calculated using the default key parameters[66] (details in Table 29), including that biomass is used to dry the wood prior to pelletisation.

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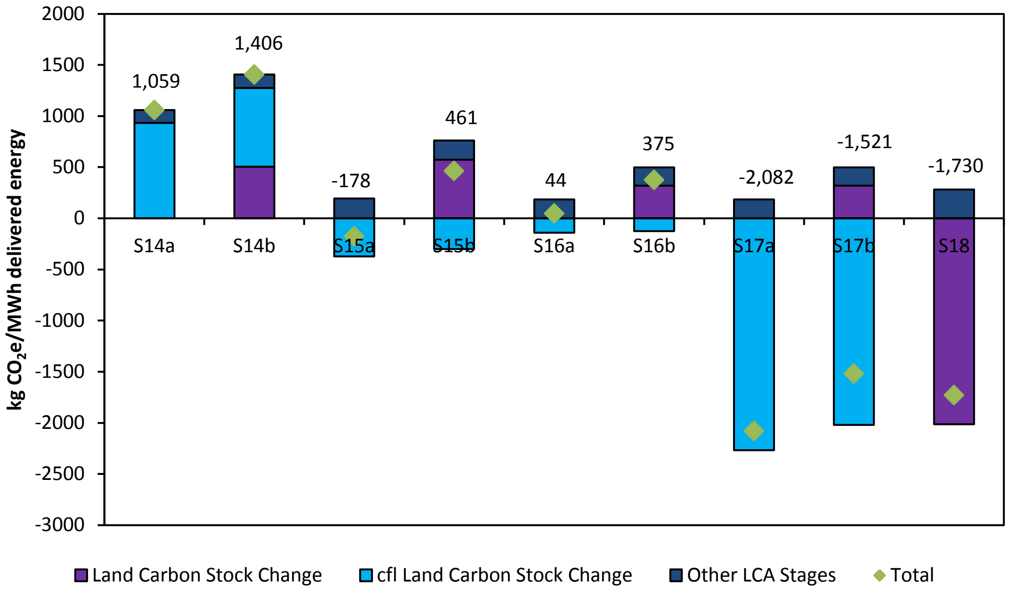
[66] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

A: 40 year time horizon



B: 100 year time horizon

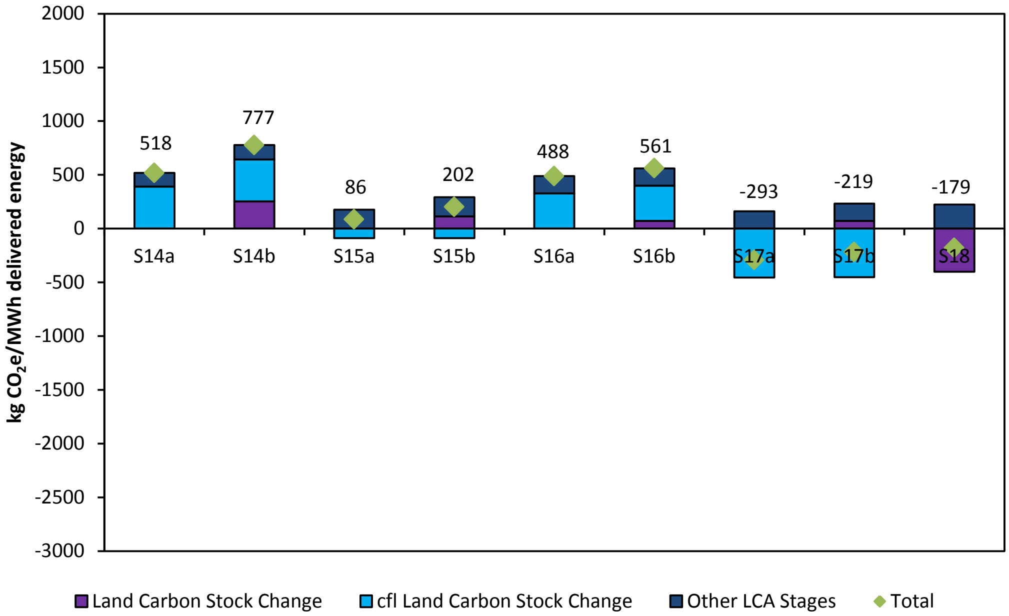


Figure 43. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from Loblolly Plantations in South USA and shipped to the UK, for BEAC Scenarios 14 to 18. cfl: counterfactual. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

180. The GHG impact of using plantations to produce bioenergy feedstocks can vary significantly, depending on the counterfactual land use, and the time between harvests. Overall, these results reflect that non-soil carbon stocks of forests are generally greatest if the forests are disturbed infrequently (*e.g.* by harvest or natural disturbances) and grow quickly. If the counterfactual to using a plantation for bioenergy were to involve longer rotation times and high (or the same) yields (*e.g.* Scenario 14), using the land for bioenergy would result in large GHG emissions; if the counterfactual were to involve shorter rotation times with lower yields, using the land for bioenergy would result in large GHG savings. Some scenarios involve a trade-off between these two factors (*e.g.* Scenarios 15 and 16).

181. If the plantation would otherwise have been harvested every 35 years, rather than every 25 years (Scenario 14a), the counterfactual scenario would have a greater carbon stock than the bioenergy scenario, and the foregone biomass growth would dominate the lifecycle GHG impacts. This causes the bioenergy to have a high GHG intensity, even when considered over a time horizon of 100 years (greater than electricity from natural gas).

182. However, the GHG impacts of bioenergy are lower if the forest would otherwise be left to regenerate naturally after harvest (Scenario 15 and 16). This is because naturally-regenerated forests, having lower growth rates than intensively-managed plantations, take longer to increase the carbon stored on the land after harvest. After 40 years, Figure 42 shows that keeping the forest as an intensively-managed plantation and harvesting every 25 years would result in more carbon being stored on the land than if the forest were either (i) converted over 50 years to a naturally-regenerated forest that is harvested every 50 years (BEAC Scenario 15a), or (ii) converted over 25 years to a naturally-regenerated pine forest, that is left to continually sequester carbon, rather than harvested (BEAC Scenario 16a). Scenarios 15a and 16a therefore show the produced bioenergy to have a low GHG impact over 40 years (-178, and 44 kg CO_2e/MWh electricity, respectively, using the default key parameters). When considered over a time horizon of 100 years, BEAC Scenario 15a still shows bioenergy to have a low GHG impact, as the carbon stock of the counterfactual land use would remain low over the time horizon (as the slow-growing, naturally-regenerated forest is assumed to be harvested every 50 years). However, if the forest would otherwise be left to continually sequester carbon (Scenario 16a), representing a case where a land owner is encouraged to increase the carbon stock of the land (Carbon Canopy, 2014), the counterfactual carbon stock at the end of the time horizon would be greater than an intensively-managed plantation (as shown in Figure 42), resulting in the GHG impact of the produced bioenergy being 488 kg CO_2e/MWh electricity (using the default key parameters), similar to electricity from natural gas.

183. Figure 43 also shows that if you assume the increased demand for small diameter pulpwood were to cause the time between harvests of the plantation to reduce from 25 to 20 years (Scenarios 14b, 15b, 16b, 17b), then the carbon stock of the land would reduce, increasing the GHG impact associated with the produced bioenergy when compared to maintaining the time between harvests at 25 years (Scenario 14a, 15a, 16a, 17a). Scenarios 14b, 15b and 16b result in GHG impacts greater than 350 kg CO_2e/MWh over 40 years, and greater than 200 kg CO_2e/MWh over 100 years.

184. Scenario 17 represents a case where the pine plantation would be converted to a cotton plantation, if the demand for wood for bioenergy were not there; in this case the GHG intensities associated with the bioelectricity are negative, as the carbon stored in pine plantations is significantly greater than cotton plantations. Although this scenario shows large GHG savings, it is important to note that if this land were used for bioenergy, rather than cotton, the cotton could instead be grown somewhere else, with indirect GHG implications (which have not been modelled).

185. Finally, the results of Scenario 18 show that if the demand for wood for energy caused medium-intensity plantations to be managed more intensively, causing the yield to increase by 35% (which would not happen otherwise), and the time between harvests stayed at 25 years, the produced bioenergy would have negative GHG intensities (electricity emission factors of -1730 and -179 kg CO_2e/MWh over time horizons of 40 and 100 years, respectively, using the default key parameters).

Energy Input Requirement: Roundwood from Existing Plantations

186. The Energy Input Requirements (energy carrier input basis; see page 50 for description) for BEAC Scenarios 14 to 18 over a time horizon of 40 years are shown in Figure 44, assuming the wood is dried prior to pelletisation using biomass (the default in BEAC), or using natural gas. Currently pellets from South USA generally use biomass to dry the wood, therefore the EIR typically varies between 0.28 and 0.48 MWh per MWh[67]. If natural gas were used to dry the pellets, the EIR would be significantly greater at 0.58 to 0.75 MWh per MWh[68]. The lowest value represents a case where the management practice (*e.g.* site preparation and fertilisation) of the plantation is the same for the bioenergy scenario, and the associated counterfactual (*e.g.* BEAC Scenario 14). The highest value represents a case where a plantation is more intensively-managed to increase the yield (*e.g.* BEAC Scenario 18); this increased energy requirement results from the assumption that intensive plantation management requires greater fertiliser and diesel inputs[69].

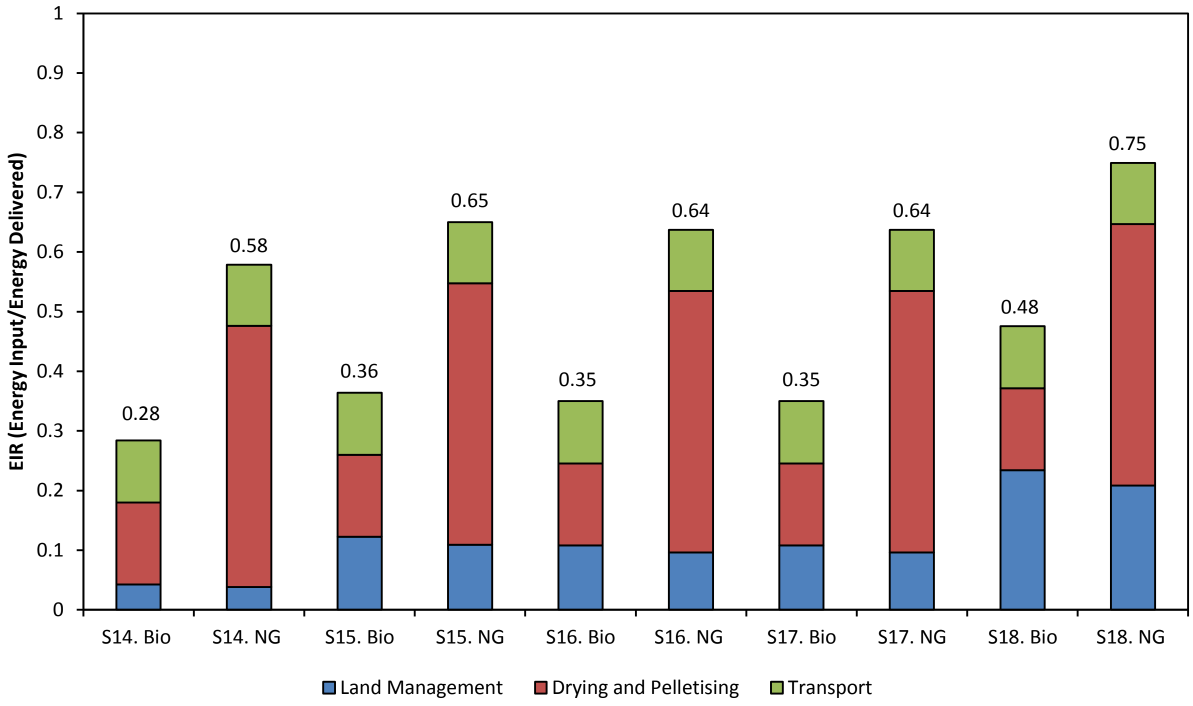


Figure 44. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from intensively-managed pine plantations in South USA, over a time horizon of 40 years, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

187. For BEAC Scenario 18, the EIR is lower when considered over 100 years, rather than 40 years (0.40 MWh per MWh over 100 years, compared to 0.48 MWh per MWh over 40 years, using the default BEAC assumptions). This is because this scenario involves converting an even-aged, non-intensively managed plantation to an even-aged, intensively-managed plantation over 25 years; this means that the increased biomass output is not realised until a stand of the newly-managed plantation is harvested (Figure 42). Therefore, there is a delay between the time when the energy

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[67] Using the default key parameters.

[68] Using the default key parameters.

[69] Assumed intensively-managed plantations employ site preparation techniques of chopping, piling, burning, disking, bedding, herbicide application and planting. Medium-intensity management assumed to employ burning, bedding, herbicide application and planting.

input to the forest increases (*via* more intense management), and the time when the increased biomass output is harvested from the forest.

Summary: Roundwood from Existing Plantations

188. The predicted resource availability of North American wood from existing plantations, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 21.

Table 21. Potential resource of North American wood from existing plantations by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[70] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

Scenario	**cfl**	**Resource in 2020 Modt/y**	**GHG intensity kg CO_2e/MWh**		**EIR MWh per MWh**		**Details**
			40 years	**100 years**	**EC Basis**	**PE Basis**	
Existing intensively-managed plantations (low demand for wood)[71]	Harvest less frequently	0 to 11.0	886 to 1692	435 to 949	0.19 to 0.77	0.32 to 1.18	**Min**: BEAC Scenario 14a **Max**: BEAC Scenario 14b
	Convert to naturally-regenerated forest	0 to 11.0	-182 to 515	52 to 712	0.26 to 0.83	0.40 to 1.24	**Min**: BEAC Scenario 15a **Max**: BEAC Scenario 16b
	Convert to agricultural land, without indirect impacts	0 to 11.0	-2504 to -1107	-386 to -78	0.25 to 0.83	0.38 to 1.24	**Min**: BEAC Scenario 17a **Max**: BEAC Scenario 17b
Pine plantation with increased yield (high demand for wood)		0 to 18.8	-2087 to -1272	-252 to -46	0.36 to 0.96[72]	0.5 to 1.37[73]	**Min**: BEAC Scenario 18 **Max**: BEAC Scenario 18

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[70] EIR values calculated over a time horizon of 40 years. There are minor changes to the EIR when considered over 100 years.

[71] Maximum resource for combination of all existing intensively-managed plantation scenarios equals 11 Modt/y.

[72] EIR range (EC basis) reduces to 0.29 - 0.88 when considered over 100 years.

[73] EIR range (PE basis) reduces to 0.43 - 1.28 over 100 years.

Wood for Bioenergy Displacing Non-Bioenergy Uses, Which Are Then Supplied by Imports: Scenarios 19 to 21

189. As described in the section “North American Wood Pellets” (page 34), currently the price differential between sawn timber and pulpwood (shown in Figure 15 for pine in South USA) causes high-quality sawn timber to be used for construction where markets are available, and therefore pellets are unlikely to be produced from wood that could be sold as sawn timber. However, pulpwood has several other uses competing with the production of pellets, including paper and OSB production (Forest2Market, 2013; Forisk, 2011a). If demand for pulpwood were to increase in the future, a potential scenario could be that pulpwood which would otherwise be used for non-bioenergy purposes is used for pellets instead (Sedjo *et al.*, 2013; Abt *et al.*, 2012; Abt and Abt, 2013). The displaced wood product might then instead be imported, causing additional demand and GHG consequences in another region of the world. For example, if thinnings from intensively-managed pine plantations were used as feedstock for the production of wood pellets for bioenergy, and the demand for pulpwood in the region were high, the thinnings may otherwise have been used as a feedstock for the production of paper products, leading to the paper products being imported instead.

190. Alternatively, the wood product could be replaced by a non-wood substitute; the BEAC tool allows the user to investigate such scenarios. For example, if wood used for bioenergy would otherwise have been used to produce OSB, the user of BEAC can consider the GHG impact of replacing the OSB with a non-wood material (for example, concrete breeze blocks). However, as mentioned on page 43, such scenarios have not been reported in this study. This is because, during the development of this report, many stakeholders expressed the view that using non-wood alternatives for housing construction in North America would require a fundamental shift in building design and cultural acceptance, therefore it was considered unlikely that the amount of non-wood products used for house construction in North America would change as a result of wood demand for bioenergy. Instead, it was considered more likely that increased demand for wood for bioenergy would result in more wood being harvested globally, therefore scenarios representing this outcome have been considered.

Scenarios: Bioenergy Displacing Non-Bioenergy Uses

191. In 2012 the USA was the second largest importer of wood products (*e.g.* wood panels, sawn wood, pulpwood and paper) in the world, with a significant proportion coming from Canada, Brazil, Chile, and China (Bandara and Vlosky, 2012). The potential indirect impacts of increased pellet production in the USA could therefore vary widely. The scenarios considered in this report are shown in Table 22; these were chosen to represent extreme cases (best and worse) in order to provide a range. However, there are many different potential scenarios which could play out as a result of increased imports to North America, therefore the potential indirect impacts are hard to estimate. It would be complex and difficult to model a realistic world scenario that would involve multiple source countries and forestry practices.

Table 22. Scenarios modelled to represent using pulpwood for bioenergy, causing indirect impacts.

Scenario number	Feedstock used for pellets	Counterfactual scenario
19	Pulpwood from South USA, causing indirect impact of Eucalyptus plantation replacing Brazilian rainforest.	Pulpwood used for non-bioenergy purposes.
20	Pulpwood from South USA, causing indirect impact of Eucalyptus plantation being established on Brazilian abandoned degraded pasture land, which would otherwise revert to tropical savannah (IEA, 2011).	As above.
21	Pulpwood from South USA, causing indirect impact of increasing the harvest rate of naturally-regenerated coniferous forest in Pacific Canada, from every 70 years to every 50 years.	As above.

192. The import of additional wood or wood products would result in additional transport. The assumed transport distances for BEAC Scenarios 19 and 20, and the associated counterfactual, is shown in Figure 45. These distances were also assumed for Scenario 21, apart from the shipping distance between ports in Pacific Canada and South East USA, which was taken to be 10500 km.

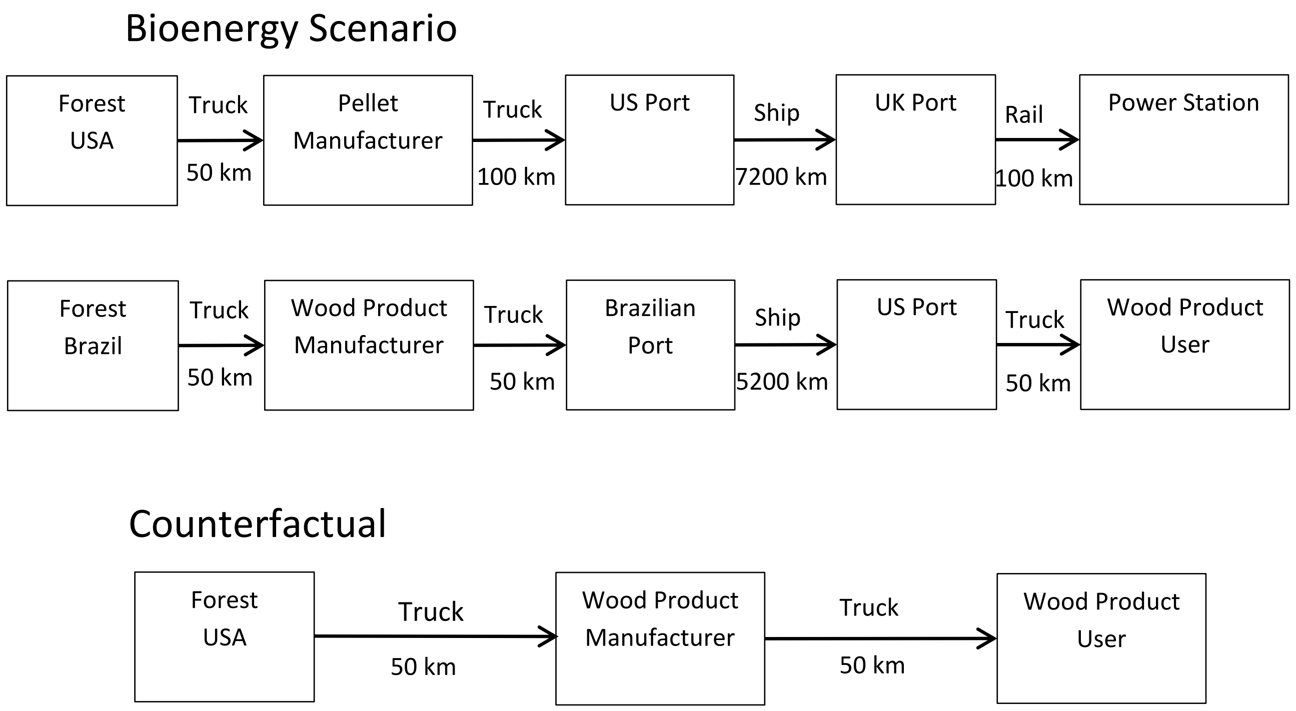

Figure 45. Illustration of transport involved for BEAC Scenarios 19 and 20.

193. Another potential scenario could be that without the demand for pulpwood for energy, harvested wood would be transported further for non-energy uses (*i.e.* in Figure 45, the distance between the US forest and wood product manufacturer in the counterfactual case would be greater than 50 km). As a sensitivity analysis, the impact of the distance between the US forest and the wood product manufacturer (for the counterfactual) on the GHG intensity of bioenergy for BEAC Scenarios 19-21 has therefore been investigated.

Considerations for Scenario Plausibility: Bioenergy Displacing Non-Bioenergy Uses

194. The pellet industry could displace other wood-using industries, if there were advantages to the forest owner from selling wood to the pellet industry over the other industries (*e.g.* if the pellet industry could pay more for the feedstock). Trends are regional and can change over time, and are therefore difficult to predict. It has been reported that currently, the capability of the pellet industry to pay for feedstock in the South USA is lower than non-bioenergy wood users such as the paper and panel industries (RISI, 2012). However, it has also been reported that the export pellet market in the South USA is more reliable and predictable than the paper market, owing to the use of long-term contracts by the pellet industry, and so in some cases, it can be more attractive for forest owners to sell their feedstock for pellets rather than paper (RISI, 2012). Looking further into the future, Sedjo *et al.* (2013) predicts that in the coming decades (up to 2060), increased demand for pulpwood for energy will result in pellet producers competing with other pulpwood industries, causing increased pulpwood imports to the USA.

Resource Availability: Bioenergy Displacing Non-Bioenergy Uses

195. The maximum amount of low quality wood (pulpwood, and saw-mill residues which are required for other purposes) that could be used for bioenergy, causing the displacement of a non-bioenergy use of the material, was taken to be the projected 2020 demand for paper, fibreboard and particleboard. It was assumed that the market for this raw material would recover to the 2006 pre-recession output (Ince and Nepal, 2012) of ~ 172 Modt/y (FAOSTAT, 2013). This value includes wood that will be required for pulp and paper, fibreboard and particleboard, and hence is used as an estimate of the amount of material that could be imported instead, if the material were not available in North America.

196. The lower limits for these amounts was set to zero, representing a case where the price paid for pulpwood by non-bioenergy industries is significantly greater than the pellet industry, hence the pellet industry does not successfully compete for feedstock.

GHG Emission Intensity: Bioenergy Displacing Non-Bioenergy Uses

197. The GHG intensities of the bioenergy for BEAC Scenarios 19-21 have been calculated by determining the effect of the increased land management and wood harvest required to produce the additional imported wood, and the additional transport involved. The summarised GHG results for these scenarios are shown in Figure 46. These results have been calculated using the default key parameters[74] (details in Table 29), including the assumption that biomass is used to dry the wood prior to pelletisation.

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[74] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

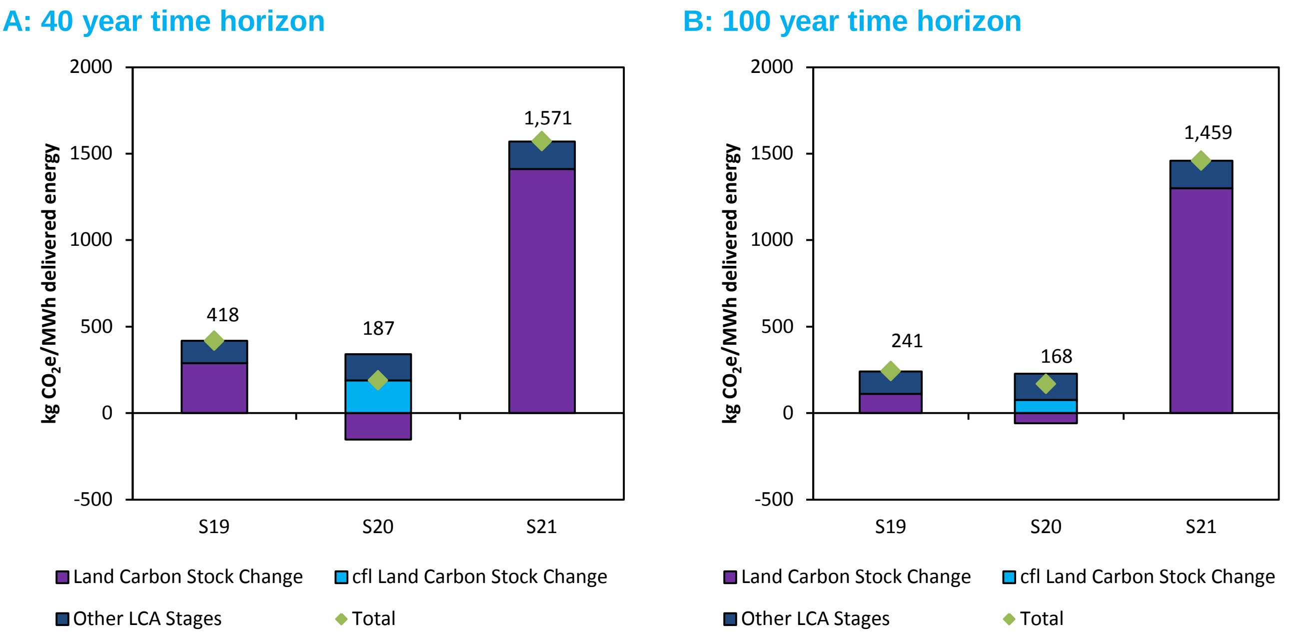

Figure 46. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from South USA and shipped to the UK, displacing non-bioenergy wood uses (BEAC Scenarios 19 to 21). cfl: counterfactual. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

198. Converting a tropical rainforest to a Eucalyptus plantation would result in a large reduction in the carbon stored in the land biomass, therefore Scenario 19 shows high GHG intensities, similar to electricity from natural gas, over 40 years. The emission intensity is lower when considered over 100 years, but still greater than 200 kg CO_2e/MWh. In contrast, converting pasture land to Eucalyptus plantations would result in an increase in carbon stock (although the carbon stock of the land would also have increased somewhat if it were not used for bioenergy), resulting in the generated bioelectricity of Scenario 20 having a GHG intensity of around 200 kg CO_2e/MWh over 40 or 100 year time horizons. Scenario 21 has the greatest GHG intensity (significantly greater than power from coal), where a Canadian coniferous forest is harvested more frequently (*e.g.* similar to the scenarios considered in the section “Increased Harvest of Naturally-Regenerated Timberland: Scenarios 10-13”, starting on page 77).

199. The GHG intensity of the bioenergy for BEAC Scenarios 19-21, for different additional counterfactual trucking distances between the forest and the wood product manufacturer, is shown in Figure 47. This represents cases where harvested wood would be transported further in South USA to a wood product manufacturer (for non-energy uses) if the demand for wood for bioenergy were not there (the counterfactual), than to a pellet facility if the demand for wood for energy were there. The GHG intensity of the bioenergy would reduce slightly, if the counterfactual involves longer trucking distances of up to 500 km; however, changes in the carbon stock of the land dominate the life cycle and have a much greater impact on the overall GHG intensity than the transport distances.

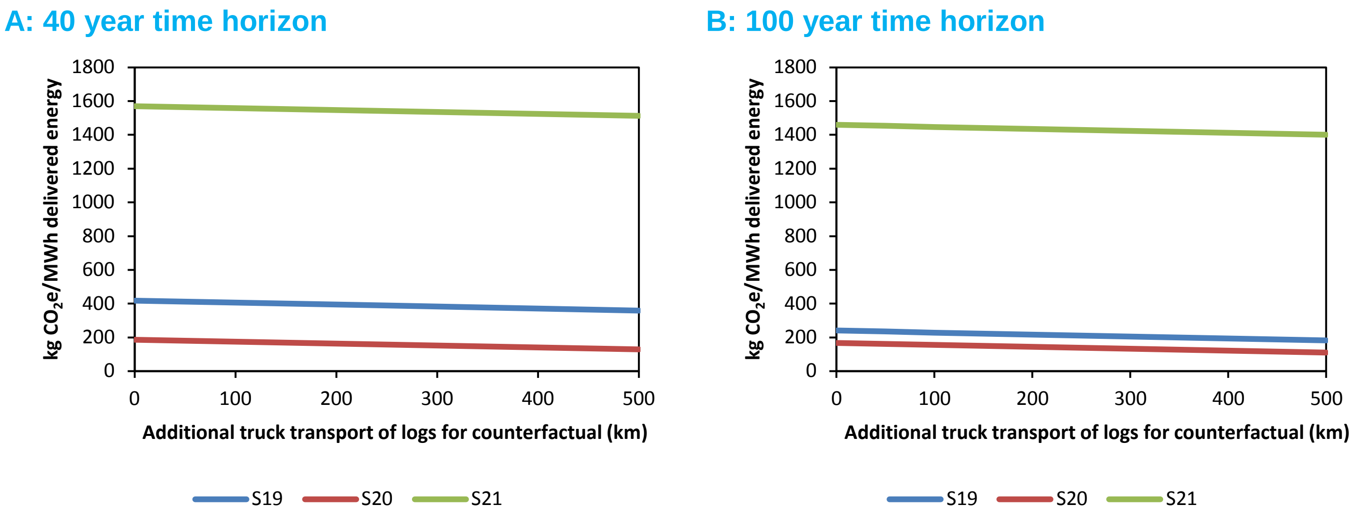

Figure 47. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from South USA and shipped to the UK, displacing non-bioenergy wood uses (BEAC Scenarios 19 to 21), with varying additional wood transport by truck for the counterfactual. cfl: counterfactual. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

Energy Input Requirement: Bioenergy Displacing Non-Bioenergy Uses

200. The Energy Input Requirements (energy carrier input basis) for BEAC Scenarios 19 to 21 over all time horizons are shown in Figure 48, assuming the wood is dried prior to pelletisation by using biomass (the default in BEAC), or using natural gas.

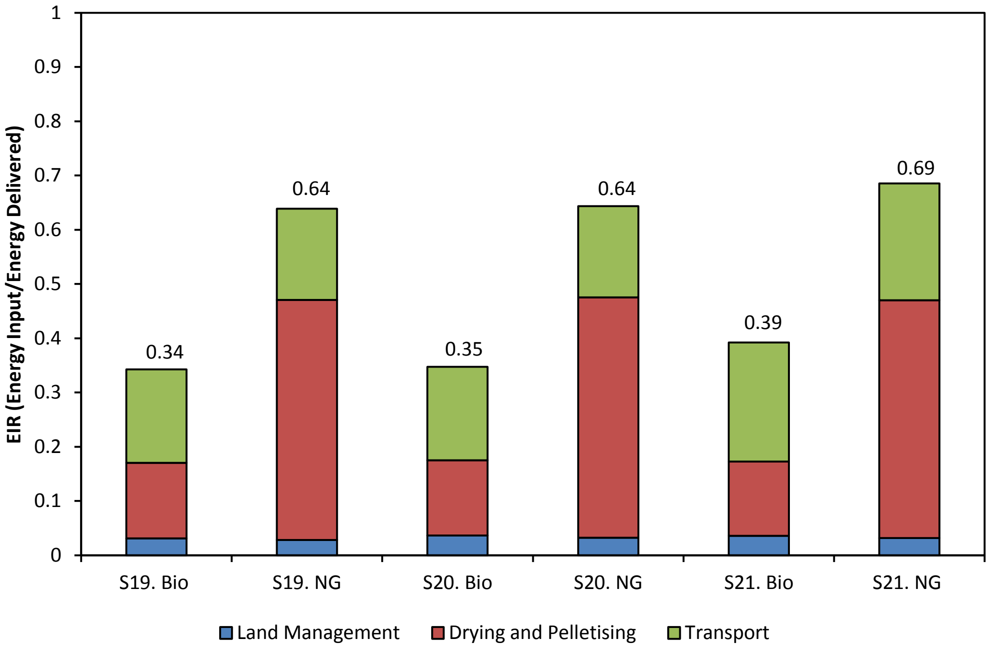

Figure 48. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from pulpwood from South USA, causing the displacement of non-bioenergy wood products to Brazil (BEAC Scenarios 19 - 20) and Canada (BEAC Scenario 21), over all time horizons, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: Bioenergy Displacing Non-Bioenergy Uses

201. The predicted resource availability of North American wood causing the displacement of non-bioenergy uses which are then supplied by imports, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 23.

Table 23. Potential resource of North American wood causing the displacement of non-bioenergy uses by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[75] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020	GHG intensity		EIR		Details
	Modt/y	kg CO_2e/MWh		MWh per MWh		
		40 y	100 y	EC basis	PE basis	
Additional wood imports to North America for non-bioenergy uses	0 to 172.0	144 to 1893	127 to 1761	0.25 to 0.89	0.39 to 1.31	**Min**: BEAC Scenario 20 **Max**: BEAC Scenario 21

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[75] EIR range is the same over all 40 and 100 year time horizons.

New Plantations on Naturally-Regenerated Timberland in South USA: Scenarios 22 to 25

202. It has been reported that increased demand for wood from bioenergy could result in the establishment of new plantations in South USA (Abt *et al.*, 2012; Evans *et al.*, 2013; Davis *et al.*, 2012; USDA, 2012; Zhang and Polyakov, 2010; Sedjo *et al.*, 2013). In the past, new pine plantations in the South USA have been established on both productive naturally-regenerated timberland and agricultural land (discussed later in the report, starting page 113) (Wear and Greis, 2002). The USDA (2012) have projected that if increased demand for biomass for energy in the future were to result in increased areas of pine plantations, natural pine forests would likely be displaced.

203. It is important to note that land devoted to intensively-managed plantations is often less biologically diverse than natural forest land, but can compare favourably in its diversity to land used for agriculture or urbanization (Andreu *et al.*, 2011). The conversion of naturally-regenerated forests to intensively-managed plantations can therefore have detrimental biodiversity implications; in South USA this is often cited as a major risk factor associated with increased demand for bioenergy (Evans *et al.*, 2013). However, the establishment of new plantations on agricultural land can result in increased biological diversity on the land.

Scenarios: New Plantations on Southern US Timberland

204. The GHG intensity and EIR values associated with using the additional biomass for bioenergy created from converting naturally-regenerated timberland in South USA to new plantations (both energy crops[76], and intensively-managed pine plantations) in North America has been investigated in BEAC Scenarios 22 to 25 (described in Table 24). The original forest types were chosen to represent typical productive naturally-regenerated timberlands in the South USA, which are already harvested regularly. Other scenarios representative of different regions, which could be considered in further studies, include the conversion of unmanaged, or old-growth forests to plantations.

205. Conversions of naturally-regenerated forests to intensively-managed pine plantations that are harvested every 25 years were considered, as a 25 year rotation time is currently typical practice. However, increased demand for pulpwood can result in shorter rotation times of pine plantations. For example, rotations are typically shorter in Florida and Georgia than they are in North Carolina, Virginia, and South Carolina, as the demand for pulpwood is greater in these regions (Abt, 2013). The conversion of natural-regenerated timberland to intensively-managed plantations that are harvested every 20 years was also considered. Conversion to SRC energy crop plantations was also investigated; currently SRC is not grown to a significant extent in North America, therefore this represents a case where the requirement of high yields of low quality wood causes new management practices to be introduced.

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[76] Defined here as woody energy crops (such as SRC hardwoods) and herbaceous energy crops (such as Miscanthus, Switch grass). Intensively-managed pine plantations, which are harvested every 20-25 years, are not classified as energy crops in this report (rather, short rotation forestry) and are discussed separately.

Table 24. Scenarios modelled to represent using roundwood from converting natural-regenerated forested land to new plantations for bioenergy feedstocks.

Scenario number	Feedstock used for pellets	Counterfactual scenario
22	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated coniferous forest in South USA that is harvested every 50 years, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years.	Continue harvesting the forest every 50 years, and leaving to regenerate naturally.
23	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated hardwood forest in South USA that is harvested every 70 years, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years.	Continue harvesting the forest every 70 years, and leaving to regenerate naturally.
24	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated coniferous forest in South USA that is harvested every 50 years, to an SRC hardwood plantation that is coppiced every 3 years. Conversion takes (a) 3 years, (b) 50 years.	Continue harvesting the forest every 50 years, and leaving to regenerate naturally.
25	Additional wood (in comparison to the counterfactual) from the conversion of a naturally-regenerated hardwood forest in South USA that is harvested every 70 years, to an SRC hardwood plantation that is coppiced every 3 years. Conversion takes (a) 3 years, (b) 70 years.	Continue harvesting the forest every 70 years, and leaving to regenerate naturally.

Considerations for Scenario Plausibility: New Plantations on Southern US Timberland

206. Figure 49 shows how the area of pine plantations increased in South USA, between the years of 1980 and 2012. During the period 1990 to 2010, the area of plantations in South USA increased by approximately by ~ 5 Mha, reaching ~ 18 Mha, whilst the area of natural pine and oak-pine reduced by ~ 6 Mha (Abt *et al.*, 2013b). Between 2008 and 2010, the area of planted pine in the South approximately stabilised, owing to the recession; however, Figure 49 shows that from 2010, the area of planted pine started to increase again. As mentioned in the section “Potential Impacts of Increased Demand for Wood for Energy”, starting on page 37, it has been suggested that the establishment of new plantations on naturally-regenerated forests could be a potential consequence of increased demand for pulpwood (Abt *et al.*, 2012; Evans *et al.*, 2013; Davis *et al.*, 2012; USDA, 2012; Zhang and Polyakov, 2010), therefore the total planted area in the South may increase further. However, the future planted forest area will depend on future prices and is therefore difficult to predict.

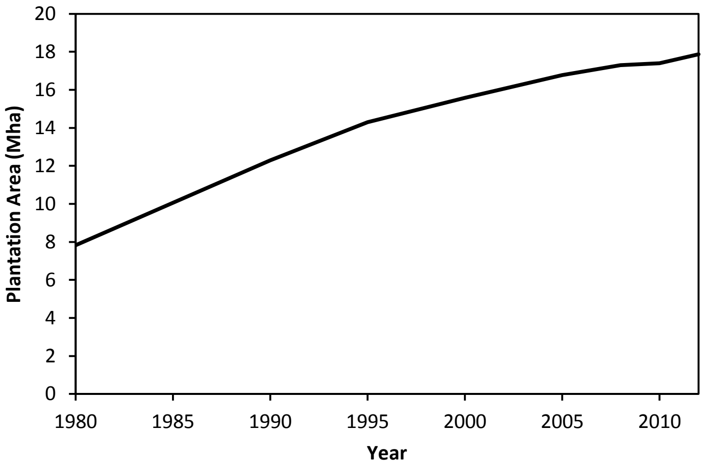

Figure 49. Area of planted pine in South USA, in different years. Includes the states of Texas, Oklahoma, Louisiana, Arkansas, Mississippi, Alabama, Tennessee, Georgia, Florida, North Carolina, South Carolina and Virginia (using data from Sheffield, 2014).

207. At current prices, plantations managed to produce a mix of saw logs and pulpwood (Scenarios 22 and 23) are financially preferable to dedicated pulpwood plantations. Henderson and Munn (2012) reported that the pulpwood stumpage price of Loblolly pine in South USA would have to increase to 44 to 84% of the saw log price (currently this value is ~ 30%) for pulpwood only regimes to become financially preferable. The relative stumpage price of pulpwood and saw logs is not the only factor determining how foresters manage pine plantations in South USA; the stability and resilience of the product market is also highly important, therefore for pulpwood only plantations to be viable, the pulpwood market would require long-term stability.

208. Forest-owners in the US have stated that it is currently unlikely that naturally-regenerated forests would be converted to energy crop plantations (Scenarios 24 and 25), owing to the high establishment costs required to prepare the land (*e.g.* stump removal *etc*.). However, we judge it important to model this scenario, in case it becomes financially viable in the future.

Resource Availability: New Plantations on Southern US Timberland

209. To estimate the upper value of wood resource which may be available by 2020 from the conversion of naturally-regenerated timberland to intensively-managed plantations, we assume the upper value of the rate of establishment of new, intensively-managed plantations in South USA to be similar to the rate of establishment between 1980 and 1990, a period of rapid expansion of plantation area in the region (average ~ 0.45 Mha/y, translating to an estimated maximum overall increase in plantation area of 2.70 Mha between 2014 and 2020). To estimate an upper bound of resource availability, we also assume that 100% of these plantations would be established on naturally-regenerated timberland, and the conversion of naturally-regenerated timberland to intensively-managed pine plantations would increase the average yield of the timberland from 1.8 to 5.9 odt/ha/y[77] (Smith *et al.*, 2006), whereas the conversion of naturally-regenerated timberland to energy crop plantations would increase the average yield from 1.8 to 15 odt/ha/y.

210. The lower limit for the conversion of naturally-regenerated timberland in South USA to either intensively-managed pine plantations, or energy crop plantations, was taken

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[77] 1.8 odt/ha/y is for a naturally-regenerated Loblolly forest, harvested every 50 years; 5.9 odt/ha/y is for an intensively-managed Loblolly pine plantation, harvested every 25 years (Smith *et al.*, 2006).

as zero, representing a case where it is not economically attractive to convert naturally-regenerated timberland to either form of plantation. For conversions to energy crop plantations, this reflects the view expressed by some stakeholders from the US forest industry that the high establishment costs required to prepare the land for energy-crops would prevent this type of land conversion.

211. The above assumptions result in estimated ranges of resource availability in 2020 from the conversion of naturally-regenerated timberland to intensively-managed plantations in South USA of 0.0 to 11.1 odt/ha/y for conversions to pine plantations, and 0.0 to 35.6 odt/ha/y for conversions to energy-crop plantations.

GHG Emission Intensity: New Plantations on Southern US Timberland

212. The main assumptions used to construct the BEAC scenarios are shown in Table 43 of the Annex. For each scenario, it has been assumed that the additional wood created by the bioenergy scenario, in comparison to the counterfactual, is used for bioenergy, and any changes in carbon stock in the forest relative to the counterfactual are attributed to this wood output.

213. When considered at the individual forest level, scenarios where the forest is converted either to an intensively-managed pulpwood plantation which is harvested every 20 years, or to an SRC plantation, would result in additional low-quality wood being produced in comparison to the counterfactual. If the forest were converted to an intensively-managed plantation, harvested every 25 years, there would also likely be additional saw logs produced. However, when considered at a larger scale, FAO have predicted that promoting wood energy would likely result in a reduction in the annual growth rate of wood being used for construction between 2010 and 2030 (UNECE and FAO, 2012). For example, if the demand for pulpwood were high, on average a greater proportion of the wood output from each forest might be used for purposes requiring pulpwood, rather than purposes requiring saw logs (*e.g.* construction products). This outcome may already be happening in South USA, where the high demand for low quality wood has been reported to have reduced the availability of chip-n-saw in the region (Forest2Market, 2013a); chip-n-saw are logs with dimensions greater than pulpwood but smaller than saw logs, and are traditionally used to make products requiring larger logs (*e.g.* construction products), therefore this trend implies that the size of logs used for purposes requiring low quality wood (*e.g.* paper, OSB and pellets) in the region could be increasing. In Nova Scotia, it has also been reported that high-quality hardwoods, which would usually be used as materials for flooring and lumber, are instead being used for electricity generation since a new biomass power plant was built (Ayers, 2014). It has been assumed in the BEAC scenarios that the overall amount of wood being used for non-bioenergy uses (*e.g.* construction) would be the same for the bioenergy scenario, or the counterfactual scenario. However, the sensitivity of the GHG intensity to the amount of additional wood ending up in long-term (> 100 years) storage (*e.g.* in long-lived wood products) has been considered for Scenarios 22a and 23a.

214. The assumed carbon stored in a stand of each of the forest types investigated in these scenarios is shown in Figure 50. For each scenario and associated counterfactual, the wood output and non-soil carbon stored in the forest, calculated as averages over all stands, are shown in Figure 51. Owing to the increased growth rate, an intensively-managed Loblolly plantation that is harvested every **20 years**, has a similar non-soil carbon stock to a naturally-regenerated Loblolly forest that is harvested every 50 years (Scenario 22b), whereas an intensively-managed Loblolly plantation that is harvested every **25 years**, has a greater non-soil carbon stock than a naturally-regenerated Loblolly forest that is harvested every 50 years (Scenario

22a). The non-soil carbon stock in a naturally-regenerated hardwood forest that is harvested every 70 years, is significantly greater than in an intensively-managed plantation that is harvested every **20 years** (Scenario 23b), and similar to in an intensively-managed plantation that is harvested every **25 years** (Scenario 23a). For both scenarios 24 and 25, the non-soil carbon per unit area stored in an SRC plantation is significantly lower than that stored in a naturally-regenerated forest, as SRC is coppiced frequently (assumed here to be every 3 years), meaning that there is little time to accumulate large amounts of above-ground biomass.

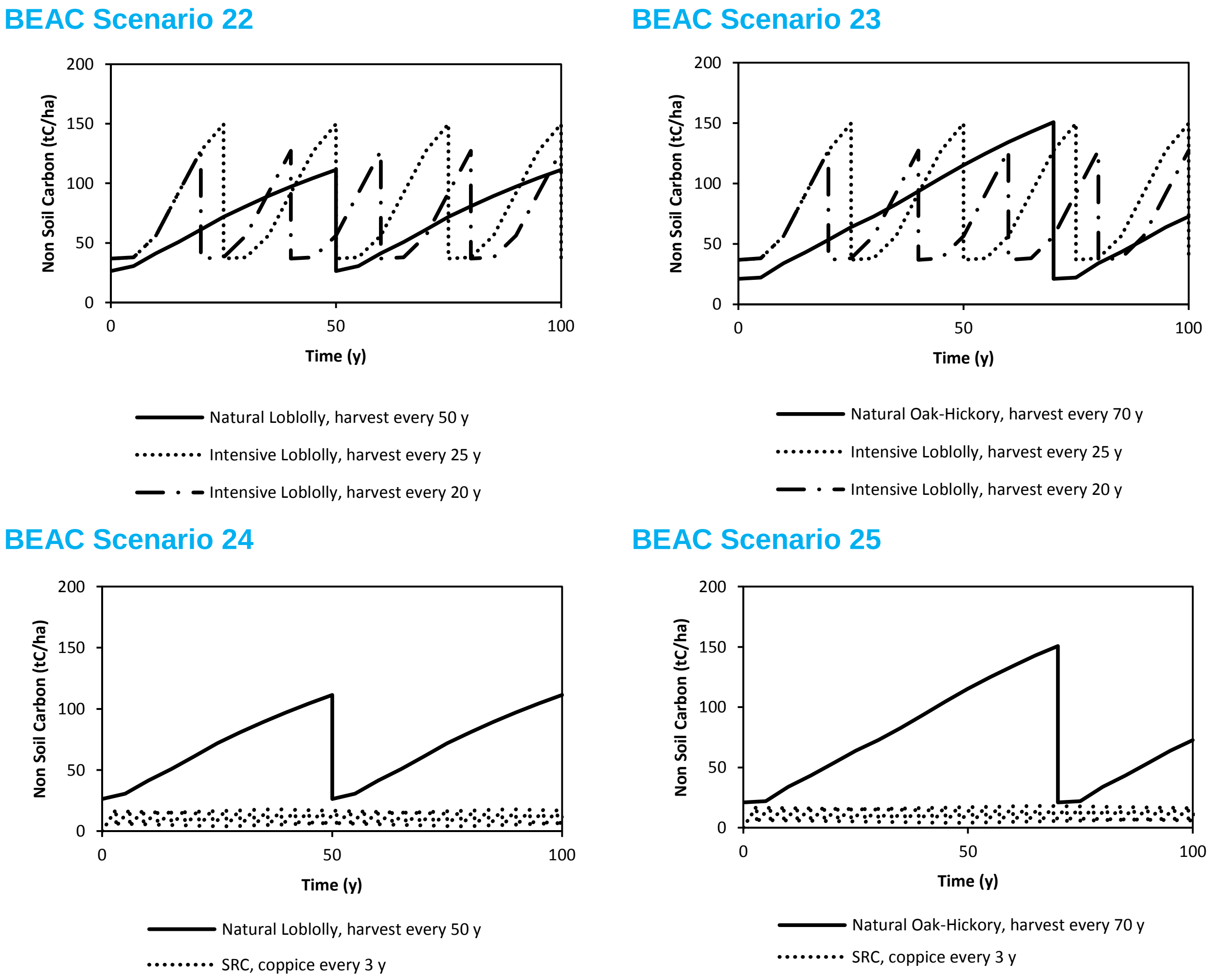

Figure 50. Non-soil carbon stock of stands of a forest at different ages, for BEAC Scenarios 22 to 25. Data sources: Smith *et al.* (2006).

215. A summary of the GHG intensities of biomass electricity for scenarios 22 to 25 is shown in Figure 52. These results have been calculated using the default key parameters[78] (details in Table 29), including that biomass is used to dry the wood prior to pelletisation. It can be seen that the carbon stock changes associated with replacing naturally-regenerated timberland with intensively-managed plantations are significantly lower than the scenarios of increasing wood output by reducing rotation length alone (BEAC Scenarios 10 to 13). For the case of converting a naturally-regenerated Loblolly forest that is harvested every 50 years, to an intensively-managed plantation that is harvested every 25 years, the carbon stored in the forest can increase, resulting in a negative GHG intensity of the produced bioenergy.

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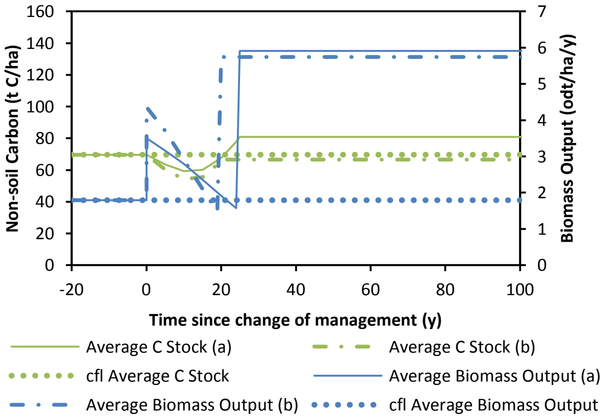
[78] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

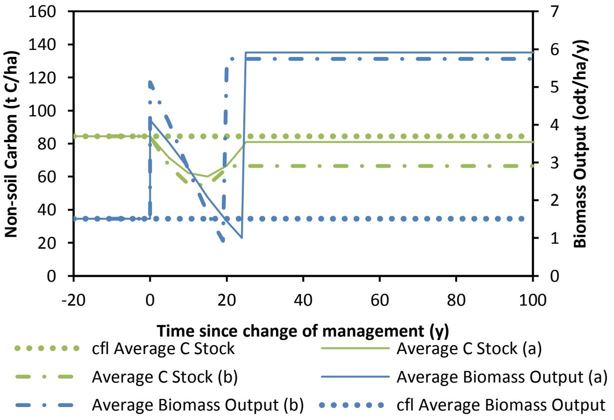
However, if the forest is converted to a plantation that is harvested every 20 years, or an SRC plantation, the GHG intensities are shown to be significantly positive.

216. These results show that the GHG intensity of bioenergy from new, intensively-managed plantations, established on naturally-regenerated forest, would depend strongly on the management practices of the plantation, and the naturally-regenerated forest it replaces; longer rotation lengths of naturally-regenerated forests (*e.g.* 70 years for Scenarios 23 and 25) generally result in greater reductions in carbon stock when converted to intensively-managed plantations.

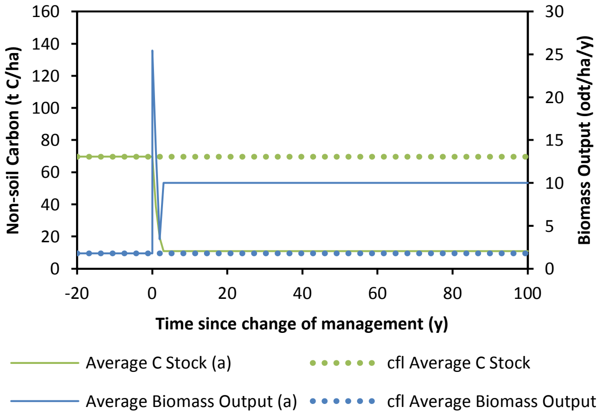
BEAC Scenario 22



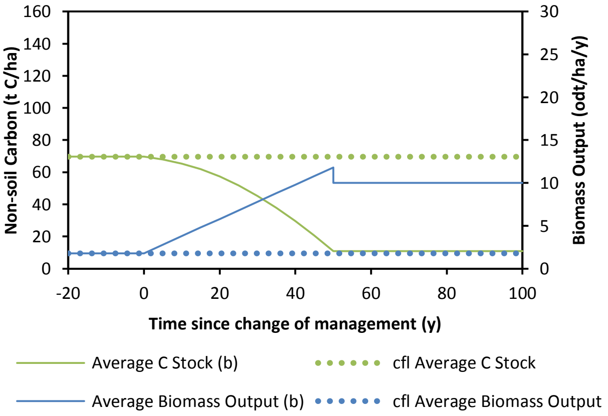
BEAC Scenario 23



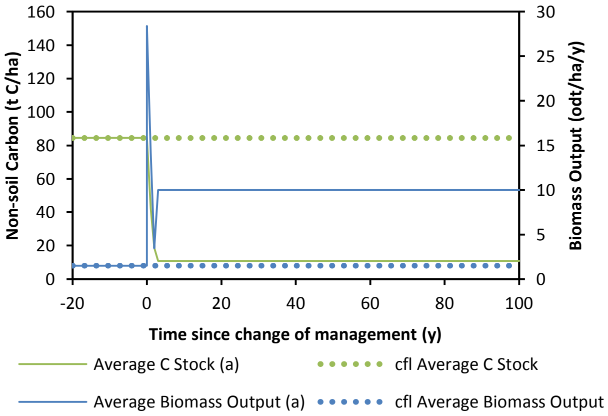
BEAC Scenario 24a



BEAC Scenario 24b



BEAC Scenario 25a



BEAC Scenario 25b

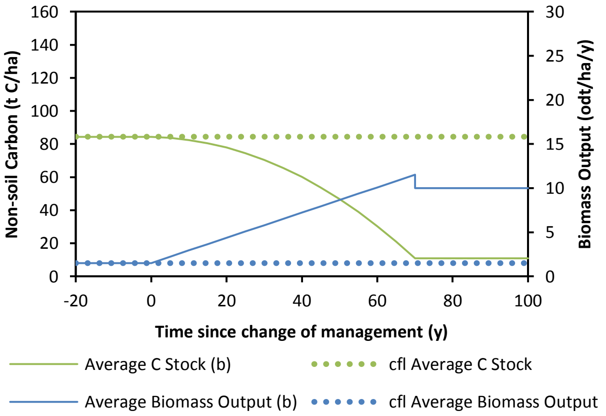
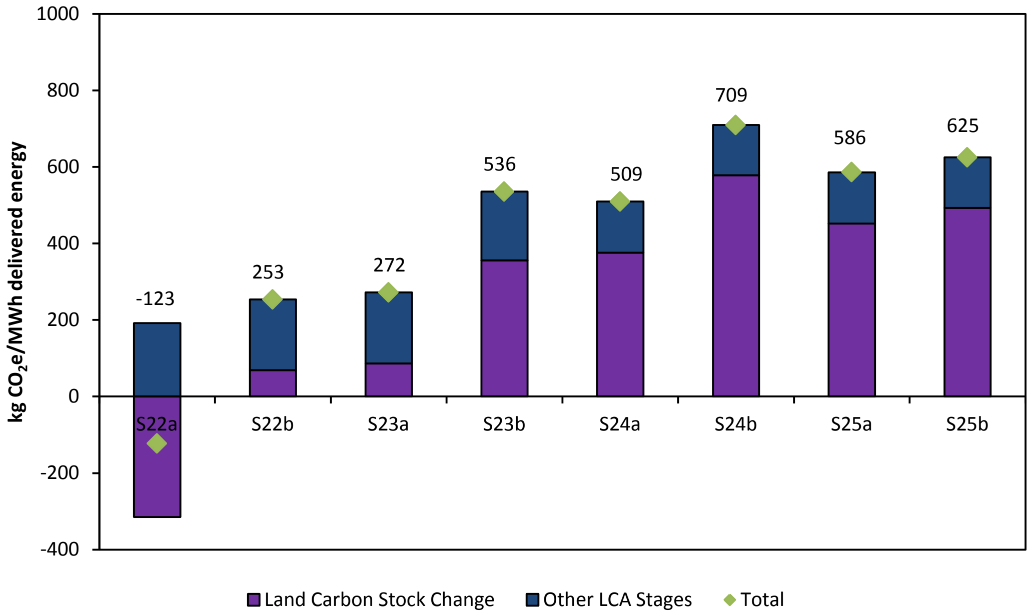


Figure 51. Total biomass output from, and non-soil carbon stored in, new plantations established on naturally-regenerated timberland, calculated as average values over all stands in the forests, for BEAC Scenarios 22 to 25, using data from Smith *et al.* (2006). cfl: counterfactual.

A: 40 year time horizon



B: 100 year time horizon

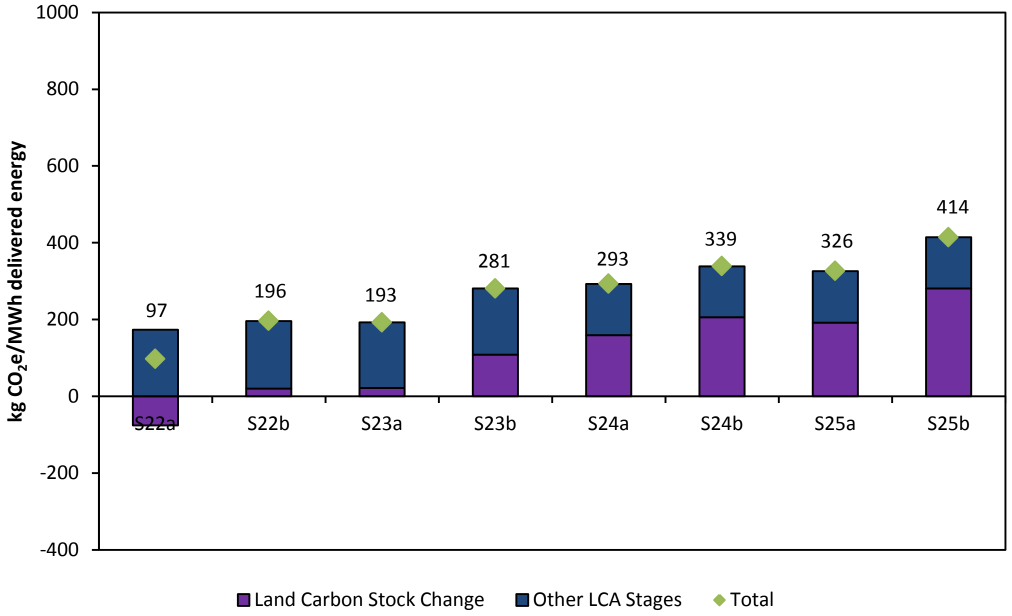


Figure 52. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from South USA and shipped to the UK, from intensively-managed pine plantations established on naturally-regenerated timberland (BEAC Scenarios 22 to 25). Default BEAC values have been used for key parameters (see Table 29 in the Annex).

217. As mentioned previously, the default assumption in determining the GHG intensity of each scenario is that overall, there is no change in the amount of wood used for non-bioenergy purposes, and that all the additional wood harvested is used for bioenergy. However, as a sensitivity analysis, the impact of a change in the amount of wood which ends up in long-term storage[79] on the GHG intensity of the electricity has been investigated for Scenarios 22a and 23a (Figure 53). If an increased demand for biomass for energy were to result in more wood in long-term storage in comparison to the counterfactual (the positive % values on the x-axes in Figure 53), the GHG intensity of the electricity would be lower than the default (0 on the x-axes in Figure

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[79] Stored for longer periods than the time horizon that the GHG intensity is analysed over, *e.g.* 40 or 100 years.

53). On the other hand, if an increased demand for biomass for energy were to result in less wood in long-term storage in comparison to the counterfactual (the negative % values on the x-axes in Figure 53), the GHG intensity of the electricity would be higher than the default. To put the x-axes values in context, Ingerson (2009) reported that typically between 0.0 and 4.6% of the carbon originally present in a standing tree remains stored in wood products after 100 years, therefore it is unlikely that large positive x-axis values would be most representative of real scenarios considered over an 100 year time horizon.

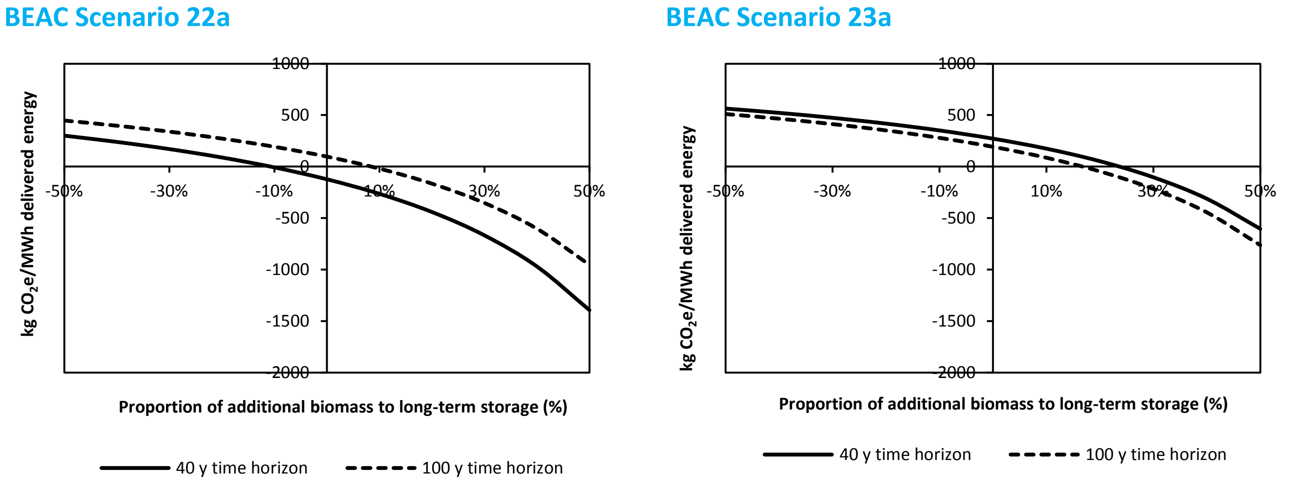

Figure 53. GHG intensity of electricity from additional biomass produced from converting naturally-regenerated timberland to intensively-managed pine plantations that are harvested every 25 years, as a function of the amount of the additional wood output that ends up in long-term storage[80]. Zero x-axis: All the additional wood output is used for bioenergy. Positive x-axis values: a proportion of the additional wood output ends up in long-term storage, and the remaining is used for bioenergy. Negative x-axis values: the additional biomass from the change of management is used for bioenergy, as well as some further wood that would otherwise go to long-term storage.

Energy Input Requirement: New Plantations on Southern US Timberland

218. The Energy Input Requirements for BEAC Scenarios 22 to 25 (energy carrier input basis; see page 50 for description) over all time horizons are shown in Figure 54, where the wood is dried prior to pelletisation by using biomass, or using natural gas. All these scenarios use roundwood from South USA, therefore the EIR values do not vary significantly between scenarios (unless natural gas is used to dry the pellets, instead of biomass). If naturally-regenerated timberland from other regions in North America were converted to plantations, the transport distances would be different, which would affect the EIR.

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[80] Stored for longer periods than the time horizon that the GHG intensity is analysed over, *e.g.* 40 or 100 years.

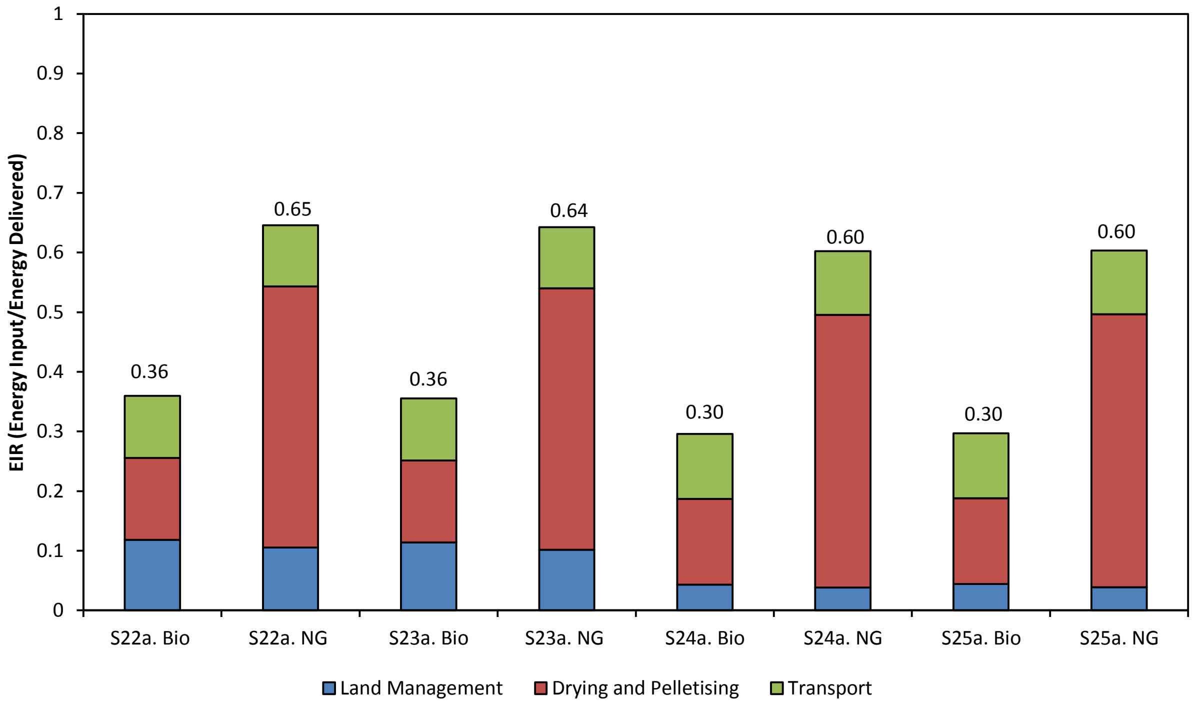

Figure 54. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from intensively-managed plantations established on naturally-regenerated timberland (BEAC Scenarios 22a – 25a: Scenarios b have slightly different EIR values), over a time horizon of 40 years, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: New Plantations on Southern US Timberland

219. The predicted resource availability in 2020 of North American wood from the conversion of naturally-regenerated timberland to intensively-managed plantations, the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 25.

Table 25. Potential resource of wood by 2020 from intensively-managed plantations established on naturally-regenerated timberland in South USA, and the estimated GHG intensity and Energy Input Requirement (EIR)[81] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

	Resource in 2020 Modt/y	GHG intensity[82] kg CO_2e/MWh		EIR MWh per MWh		Details
		40 years	100 years	EC basis	PE basis	
Conversion of South US naturally-regenerated timberland to intensively-managed pine plantations	0.0 to 11.1	-185 to 685	62 to 417	0.26 to 0.83	0.39 to 1.24	**Min**: BEAC Scenario 22a **Max:** BEAC Scenario 23b
Conversion of South US naturally-regenerated timberland to intensively-managed energy crop plantations	0.0 to 35.6	426 to 870	235 to 561	0.20 to 0.78	0.34 to 1.21	**Min**: BEAC Scenario 24a over 40 years, 25b over 100 years. **Max:** BEAC Scenario 24b

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[81] EIR values calculated over a time horizon of 40 years. There are minor changes to the EIR when considered over 100 years.

[82] Assuming default assumption that the amount of wood entering long-term storage is the same for the bioenergy and counterfactual scenario.

New Plantations on Abandoned Agricultural Land: Scenarios 26 - 29

220. If productive agricultural land is used for the establishment of new plantations dedicated to producing bioenergy feedstocks at a large scale, the production of commodities that were previously grown there will likely be displaced to other regions, causing indirect GHG impacts. However, if agricultural land that is no longer required for the production of other commodities is used for the establishment of new bioenergy plantations, these indirect effects can be avoided. Such land includes agricultural land that is abandoned owing to relocation of agriculture or its degradation from intensive use.

221. Campbell *et al.* (2008) estimated that between the years 1700 and 2000, between 474 and 579 million hectares of land shifted out of agricultural use globally, with the majority being left to revert to native ecosystems. The highest concentrations of abandoned croplands were found over the Eastern United States, as a result of the relocation of cropland to the Midwest region of North America; much of these lands have transitioned to secondary forests. It is important to note that allowing land to revert to its native state can have significant ecological benefits over mono-culture plantations (Monbiot, 2013) which should be considered when determining whether land should be used for the establishment of bioenergy plantations.

Scenarios: New Plantations on Abandoned Agricultural Land

222. The GHG intensity and EIR values associated with using the additional biomass for bioenergy created from converting abandoned agricultural land to new plantations (both energy crops[83], and intensively-managed pine plantations) in North America has been investigated in BEAC Scenarios 26 - 29. As abandoned agricultural land is assumed not to be required for other agricultural purposes, the counterfactual to using it for new bioenergy plantations is assumed to be leaving the land to revert to its native state.

223. There is a wide range of potential yields of energy crops, depending on the species (*e.g.* herbaceous crops, such as Miscanthus, and woody energy crops, such as SRC hardwoods), land type, and climate; lower yields are expected on abandoned agricultural land, and higher yields on high-quality arable land. The average global yields typically vary between 5 odt/ha/y (on low quality land) and 15 odt/ha/y (on high-quality land) (UK Committee of Climate Change, 2011). Campbell *et al.*, (2008) estimated the global-average potential yield of bioenergy crops grown on abandoned agricultural land to be 4.3 odt/ha/y. In the United States, average yields of switchgrass energy crops, grown on upland sites, have been reported to be 8.7 odt/ha/y, whereas lowland sites on average achieved 12.9 odt/ha/y (Wullschleger *et al.*, 2010). However, on some sites, very high yields of up to 30 odt/ha/y have been reported (Wullschleger *et al.*, 2010). Energy crop yields of 5, 10 and 15 odt/ha/y have therefore been investigated for each scenario to represent a typical range, and 30 odt/ha/y has also considered to investigate the lowest potential impact.

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[83] Defined here as woody energy crops (such as SRC hardwoods) and herbaceous energy crops (such as Miscanthus and Switch grass). Intensively-managed pine plantations, which are harvested every 20-25 years, are not classified as energy crops in this report (rather, short rotation forestry) and are discussed separately.

Table 26. Scenarios modelled to represent using new plantations for bioenergy (energy crop plantations and intensively-managed pine plantations), grown on abandoned agricultural land.

Scenario number	Feedstock used for pellets	Counterfactual scenario
26	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land in USA that was previously annually ploughed, to an SRC hardwood plantation that is coppiced every 3 years. Assumed exported to UK from South USA. SRC yields of: (a) 5 odt/ha/y (b) 10 odt/ha/y (c) 15 odt/ha/y (d) 30 odt/ha/y.	Abandoned agricultural land left to revert to sub-tropical, moist, deciduous forest.
27	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land in USA that was previously annually ploughed, to an SRC hardwood plantation that is coppiced every 3 years. Assumed exported to UK from Northeast USA. SRC yields of: (a) 5 odt/ha/y (b) 10 odt/ha/y (c) 15 odt/ha/y (d) 30 odt/ha/y.	Abandoned agricultural land left to revert to temperate grassland.
28	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land in the USA that was previously annually ploughed, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years. Assumed exported to UK from South USA.	Abandoned agricultural land left to revert to sub-tropical, moist, deciduous forest.
29	Additional wood (in comparison to the counterfactual) from the conversion of abandoned agricultural land that was previously annually ploughed, to an intensively-managed pine plantation that is harvested (a) every 25 years, (b) every 20 years. Assumed exported to UK from Northeast USA.	Abandoned agricultural land left to revert to temperate grassland.

Considerations for Scenario Plausibility: New Plantations on Abandoned Agricultural Land

224. As mentioned previously, it has been reported that the establishment of new plantations on agricultural land is a potential consequence of increased demand for biomass for energy (Abt *et al.*, 2012; Davis *et al.*, 2012; Zhang and Polyakov, 2010; Sedjo *et al.*, 2013; Daigneault *et al.*, 2012). However, the establishment of plantations will depend on various factors, including future prices of biomass for energy and other uses, and is therefore difficult to predict.

Resource Availability: New Plantations on Abandoned Agricultural Land

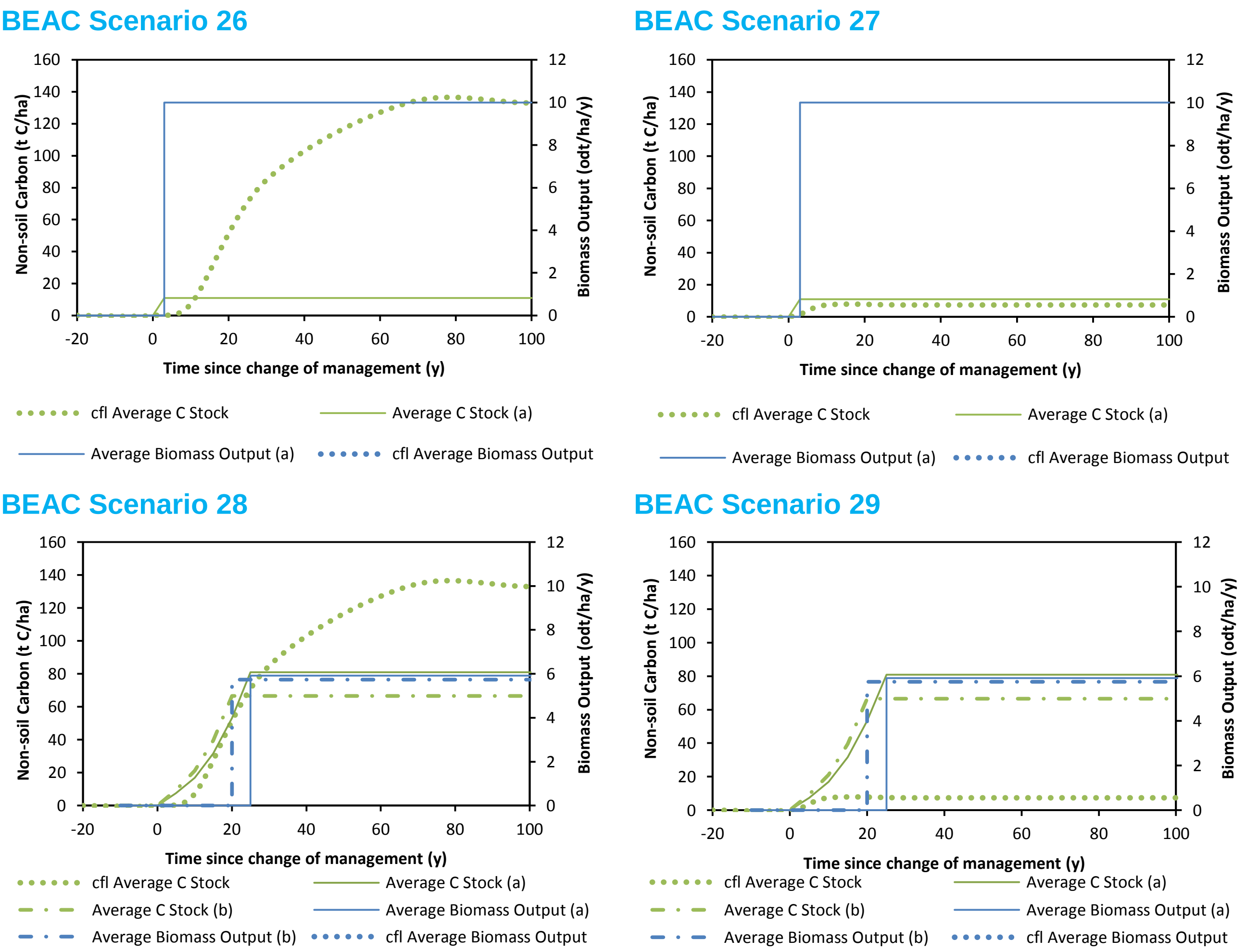
225. Cai *et al.* (2011) estimated that ~ 43 million hectares of degraded, low-quality cropland exists in the USA, which is either already abandoned, or, owing to its low

productivity, would have little impact on food production if it became abandoned. However, the amount of degraded land that is converted to biomass plantations in the future will depend on demand (for bioenergy and other uses), economic factors, such as the establishment cost of plantations, and the land rent, therefore it is highly unlikely that all this land will be used for plantations by 2020. Sedjo *et al.* (2013) used a forest sector management model to examine the economic potential of dedicated fuel-wood plantations on US marginal lands, as well as the use of existing forests to produce pulpwood, saw logs and residues for bioenergy (alongside other products). They estimated that between 0.46 to 0.56 million hectares of new dedicated plantations that are economically viable could be established on US degraded land by 2020. If all this land were used to grow new, intensively-managed, dedicated pine plantations, with an average yield of 5.9 odt/ha/y (Smith *et al.*, 2006), a total of 2.7 to 3.3 Modt/y of biomass could be produced. Although this analysis is specific to new, dedicated fuel-wood plantations, the authors claim that these results would also apply to using marginal lands for new energy crop plantations. If all this land were used to grow energy crops, with an average yield of 15 odt/ha/y (actual typical yield could be lower as the land is marginal), then a total of 6.9 to 8.4 Modt/y of biomass could be produced by 2020.

226. Looking further into the future at the potential availability of abandoned land, Powell and Lenton (2012) reported that by 2050, if diets shift towards lower meat consumption, and agricultural efficiencies were to increase significantly, significant areas of newly abandoned agricultural land could be available (up to 1 Gha globally). However, the authors concluded that current trend towards higher meat diets is likely to limit the availability of land dedicated to bioenergy plantations. The World Resources Institute (2013) recently concluded that climate change, amongst other factors, may detrimentally affect food crop yields to such an extent that there will be little agricultural land available to be dedicated to non-food purposes. Sedjo *et al.* (2013) estimated that between 0.72 and 0.93 million hectares of new dedicated plantations will be established on US degraded land by 2060.

GHG Emission Intensity: New Plantations on Abandoned Agricultural Land

227. The main assumptions used to construct the BEAC scenarios are shown in Table 45 of the Annex. For each scenario, it has been assumed that the additional wood created by the bioenergy scenario, in comparison to the counterfactual, is used for bioenergy, and any changes in carbon stock in the forest relative to the counterfactual are attributed to this wood output. For each scenario and associated counterfactual, the wood output and non-soil carbon stored in the forest, calculated as averages over all stands, are shown in Figure 55.



BEAC Scenario 26

BEAC Scenario 27

BEAC Scenario 28

BEAC Scenario 29

Figure 55. Total biomass output from, and non-soil carbon stored in, new plantations established on abandoned agricultural land, calculated as average values over all stands, for BEAC Scenarios 26 to 29. Forest data from Smith *et al.* (2006). SRC data displayed for a yield of 10 odt/ha/y (yields of 5, 15 and 30 odt/ha/y have also been modelled). cfl: counterfactual.

228. A summary of the GHG intensities of bioelectricity for these scenarios is shown in Figure 56. These results have been calculated using the default key parameters[84] (details in Table 29), including that biomass is used to dry the wood prior to pelletisation. The achieved yield of the plantation, and the foregone carbon sequestration, greatly affect the GHG intensity of the generated electricity.

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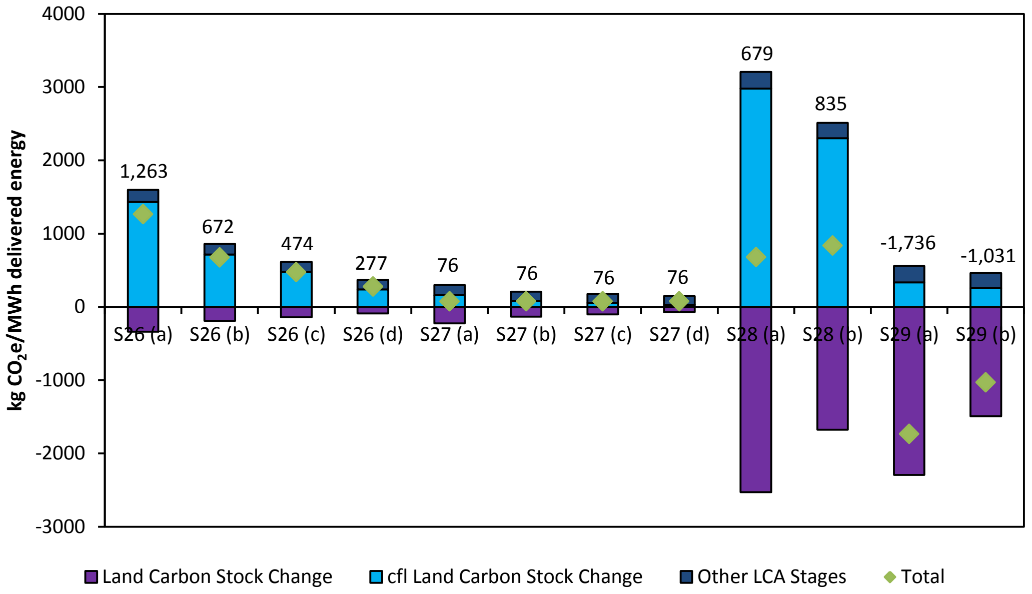
[84] Transport distances, transport fuel requirements, drying method, pelletising electrical requirements, and efficiency of electricity generation at the biomass power station.

A: 40 year time horizon



B: 100 year time horizon

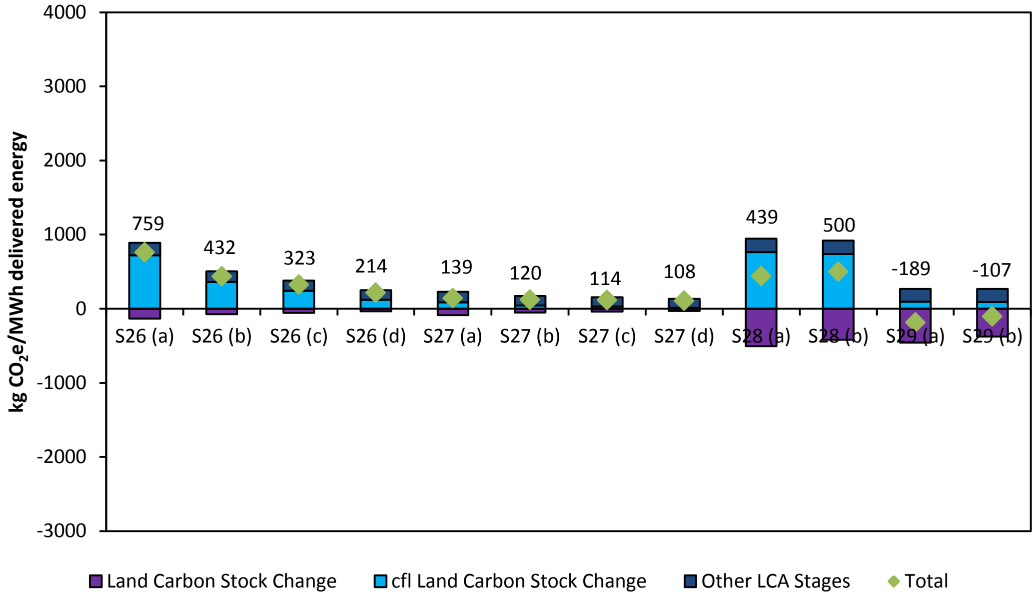


Figure 56. GHG intensity over time horizons of (A) 40 years, and (B) 100 years of electricity from pelletised wood from the conversion of abandoned agricultural land to energy crop plantations (BEAC Scenarios 26-27) and intensively-managed pine plantations (BEAC Scenario 28-29), and shipped to the UK. cfl: counterfactual. Default BEAC values have been used for key parameters (see Table 29 in the Annex).

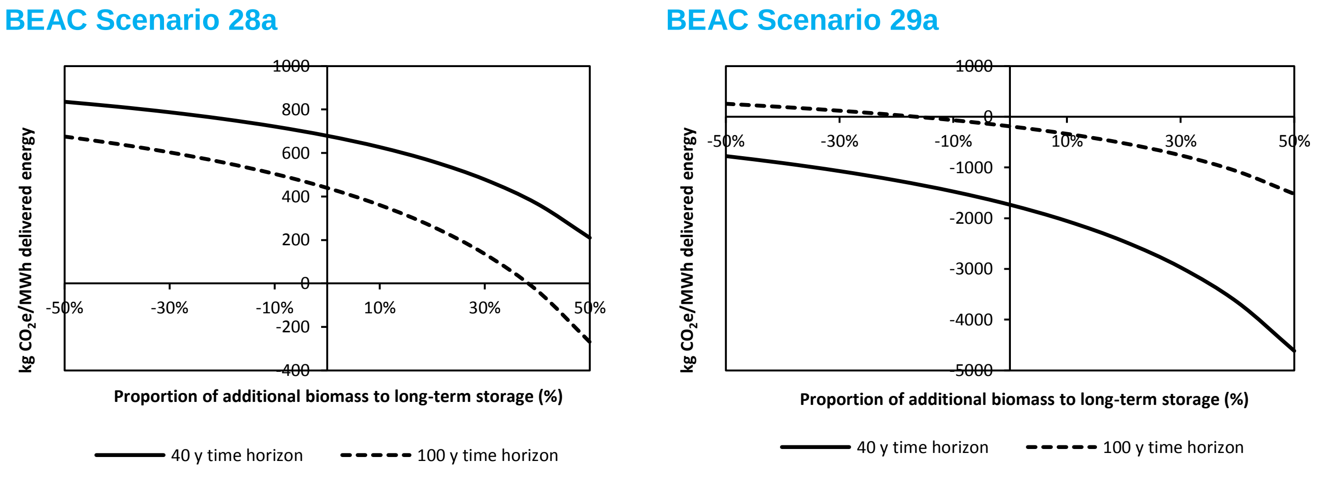
229. For scenario 26, electricity generated from energy crops that achieve a yield of 30 odt/ha/y has a lower GHG impact than electricity generated from energy crops with lower yields (5 to 15 odt/ha/y), assuming all other variables (*e.g.* fertiliser input) are constant, because the greater the amount of biomass which can be produced from the land, the greater the amount of energy which the life cycle GHG impact is divided by.

230. If energy crops are grown on abandoned land that would otherwise revert to sub-tropical deciduous forest (Scenario 26), the foregone biomass growth dominates the life cycle, and the overall GHG intensity of biomass electricity is significant (*e.g.* 277 to 1263 kg CO_2e/MWh over 40 years, and 214 to 759 kg CO_2e/MWh over 100 years,

using BEAC default values). If the land would otherwise revert to grassland (Scenario 27), the foregone biomass growth is much smaller, hence the overall GHG impact of using the land for bioenergy is significantly lower.

231. If abandoned land is used to establish intensively-managed pine plantations, with rotation lengths of 20 - 25 years (Scenario 28 and 29), the carbon stock of the land would increase to a greater equilibrium value than if the land were used for energy crops, but still lower than if the land were left to revert to sub-tropical deciduous forest (as shown in Figure 55). The GHG intensity of the electricity is therefore significantly positive if the land would otherwise revert to a sub-tropical deciduous forest (679 to 835 kg CO_2e/MWh over 40 years, and 439 to 500 kg CO_2e/MWh over 100 years, using BEAC default values), and negative if the land would otherwise revert to grassland. However, it is important to note that the foregone carbon growth depends on many factors, including the region, type of natural vegetation, and quality of the land (*e.g.* whether it has been degraded), so these values have large uncertainties (Zawadzka *et al.*, 2013).

232. As mentioned previously, the default assumption in determining the GHG intensity of each scenario is that overall, there is no change in the amount of wood used for non-bioenergy purposes, and that all the additional wood harvested is used for bioenergy. However, as a sensitivity analysis, the impact of a change in the amount of wood that ends up in long-term storage[85] on the GHG intensity of the electricity has been investigated for Scenarios 28a and 29a (Figure 57). If an increased demand for biomass for energy were to result in more wood in long-term storage in comparison to the counterfactual (the positive % values on the x-axes in Figure 57), the GHG intensity of the electricity would be lower than the default (0 on the x-axes in Figure 57). On the other hand, if an increased demand for biomass for energy were to result in less wood in long-term storage in comparison to the counterfactual (the negative % values on the x-axes in Figure 57), the GHG intensity of the electricity would be higher than the default.


BEAC Scenario 28a

BEAC Scenario 29a

Figure 57. GHG intensity of electricity from additional biomass produced from converting abandoned agricultural land to intensively-managed pine plantations that are harvested every 25 years, as a function of the amount of the additional wood output that ends up in long-term[86] storage. Zero x-axis: All the additional wood output is used for bioenergy. Positive x-axis values: a proportion of the additional wood output ends up in long-term storage, and the remaining is used for bioenergy. Negative x-axis values: the additional biomass from the change of management is used for bioenergy, as well as some further wood that would otherwise go to long-term storage.

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[85] Stored for longer periods than the time horizon that the GHG intensity is analysed over, *e.g.* 40 or 100 years.

[86] Stored for longer periods than the time horizon that the GHG intensity is analysed over, *e.g.* 40 or 100 years.

Energy Input Requirement: New Plantations on Abandoned Agricultural Land

233. The Energy Input Requirements (energy carrier input basis) for BEAC Scenarios 26 to 29 over all time horizons are shown in Figure 58, assuming the wood is dried prior to pelletisation by using biomass (the default in BEAC), or using natural gas. All these scenarios use wood from South or Northeast USA, therefore the EIR values do not vary significantly between scenarios (unless natural gas is used to dry the pellets, instead of biomass).

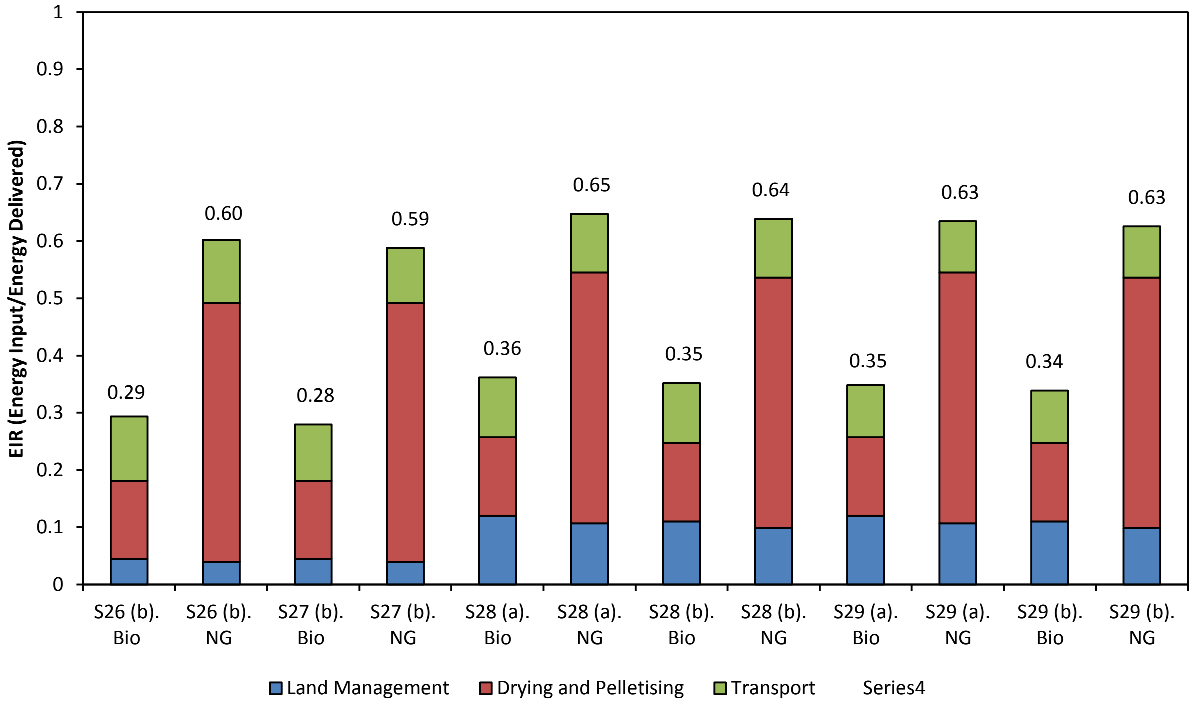

Figure 58. Energy Input Requirement (EIR) for different scenarios of generating electricity in the UK from plantations established on abandoned agricultural land (BEAC Scenarios 26 – 29), over a time horizon of 40 years, using default BEAC values for key parameters (see Table 29 in the Annex). EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. Bio: dry using biomass; NG: dry using natural gas.

Summary: New Plantations on Abandoned Agricultural Land

234. The predicted resource availability in 2020 of North American wood from the conversion of abandoned agricultural land to plantations (energy crops and intensively-managed pine), the range of GHG emission intensities of electricity generated from pellets produced from this feedstock and shipped to the UK, and the associated EIR values, are shown below in Table 27.

Table 27. Potential resource from the establishment of new plantations of abandoned agricultural land by 2020, and the estimated GHG intensity and Energy Input Requirement (EIR)[87] associated with electricity generated from pellets produced from this feedstock and shipped to the UK. Low and high values in each range have been determined by varying the following key parameters: transport distances, transport fuel requirements, pelletising electrical requirements, drying methods and efficiency of electricity generation at the biomass power station (see Table 29 in the Annex for assumed values of parameters).

Scenario	cfl	Resource availability in 2020 Modt/y	GHG intensity kg CO_2e/MWh		EIR MWh per MWh		Details
			40 years	100 years	EC basis	PE basis	
Conversion of abandoned land to energy crop plantations	Revert to forest	6.9 to 8.4	219 to 1526	164 to 929	0.18 to 0.82	0.32 to 1.25	**Min**: BEAC Scenario 26(d) **Max:** BEAC Scenario 26(a)
	Revert to grassland	6.9 to 8.4	41 to 206	69 to 272	0.16 to 0.80	0.31 to 1.23	**Min**: BEAC Scenario 27(d) **Max:** BEAC Scenario 27(a)
Conversion of abandoned land to intensively-managed pine plantations	Revert to forest	2.7 to 3.3	578 to 1016	336 to 621	0.26 to 0.83	0.39 to 1.24	**Min**: BEAC Scenario 28(a) **Max:** BEAC Scenario 28(b)
	Revert to grassland	2.7 to 3.3	-2093 to -721	-263 to 10	0.25 to 0.81	0.38 to 1.22	**Min**: BEAC Scenario 29(a) **Max:** BEAC Scenario 29(b)

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[87] EIR values calculated over a time horizon of 40 years. There are minor changes to the EIR when considered over 100 years.

Summary: Roundwood and Energy Crops for 2020

235. The projected resource of North American roundwood and woody energy crops that may be available by 2020, along with their GHG intensities when used for dedicated electricity generation in the UK, are shown in Figure 59 and Figure 60, for time horizons of 40 and 100 years, respectively. The projected resource is plotted against the Energy Input Requirement (EIR) in Figure 61.

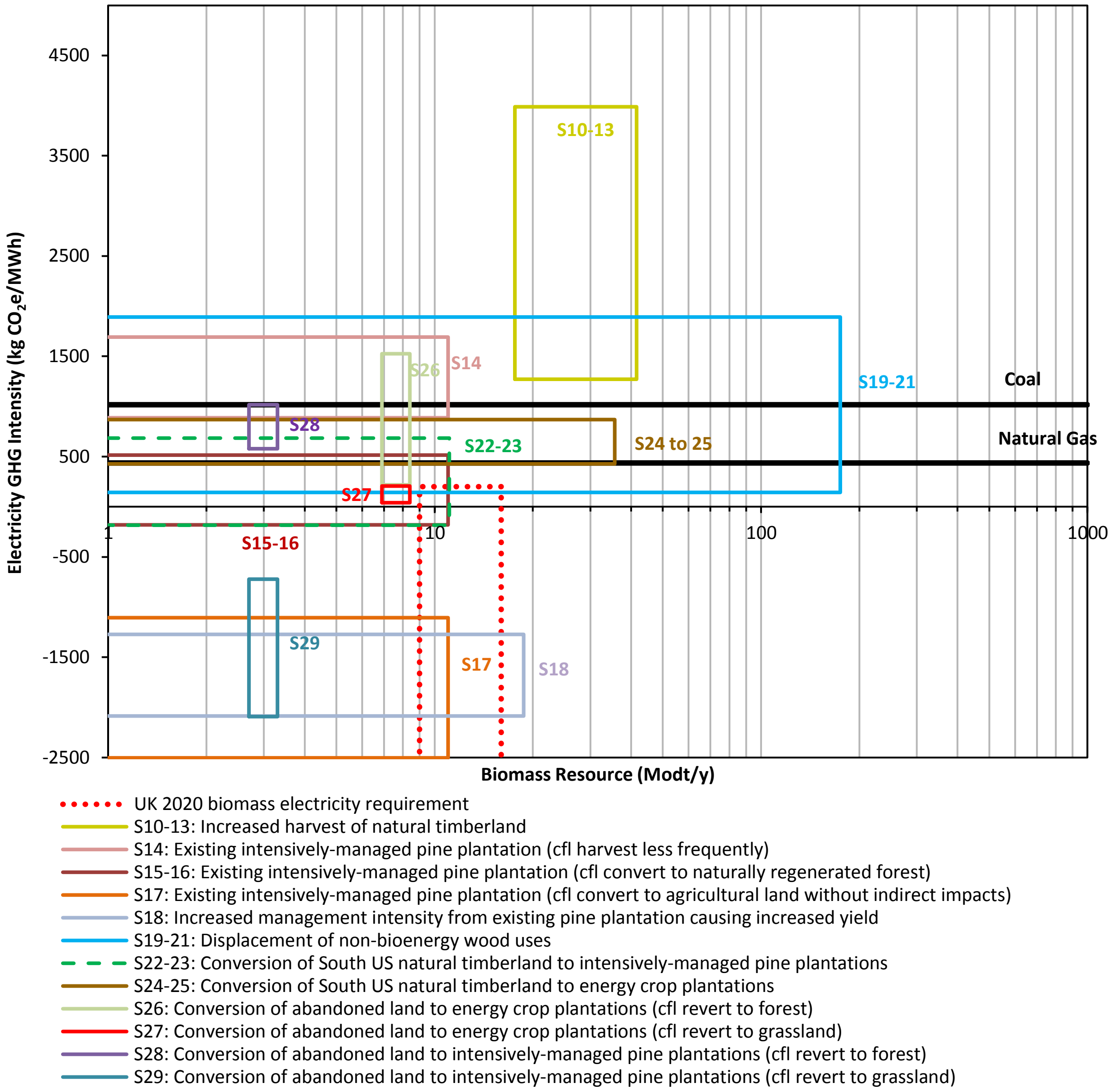

Figure 59. Summary of resource availability of North American roundwood and woody energy crops that may be available by 2020, and their GHG intensity over 40 years. cfl: counterfactual.

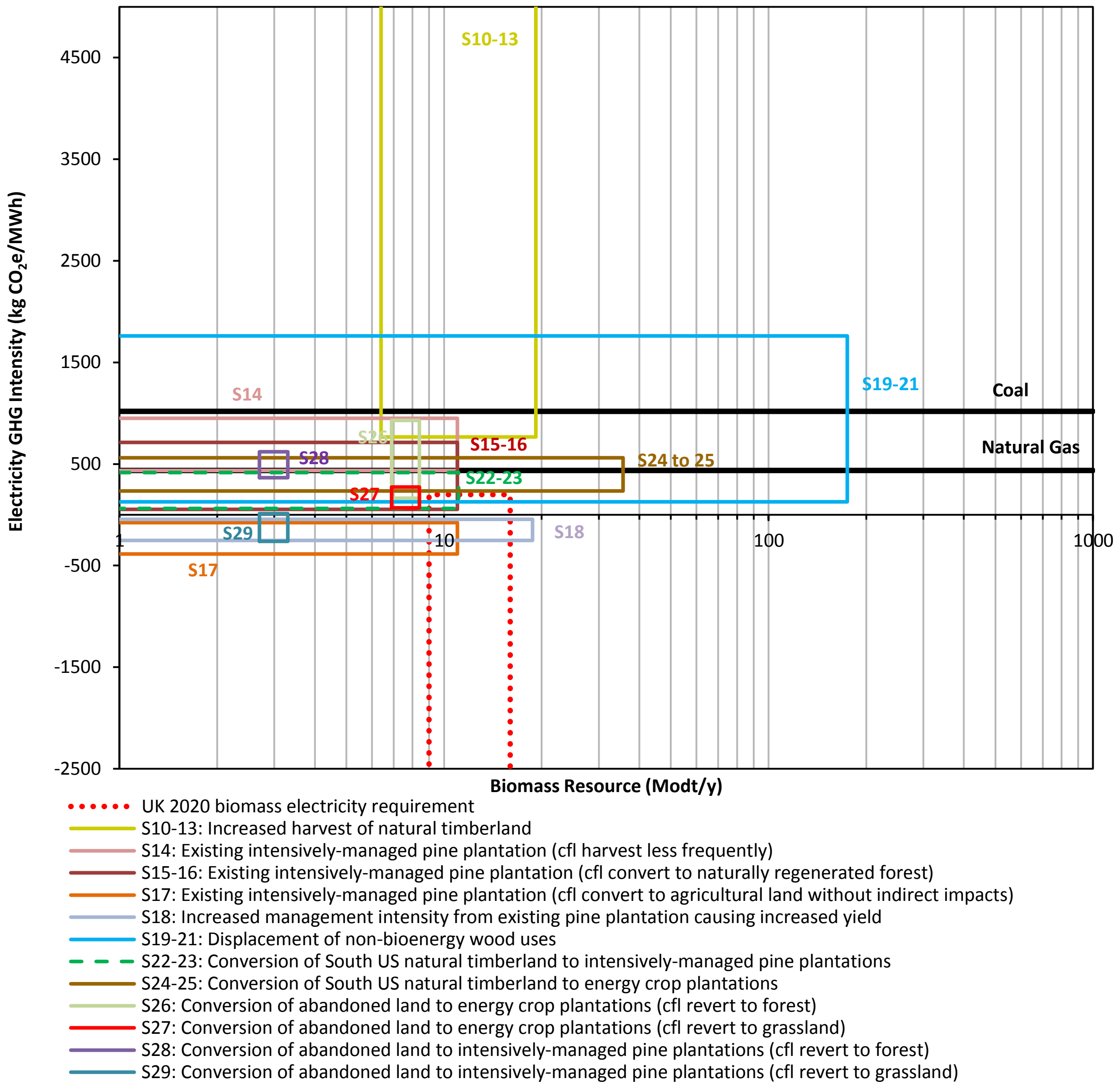

Figure 60. Summary of resource availability of North American roundwood and woody energy crops that may be available by 2020, and their GHG intensity over 100 years. cfl: counterfactual.

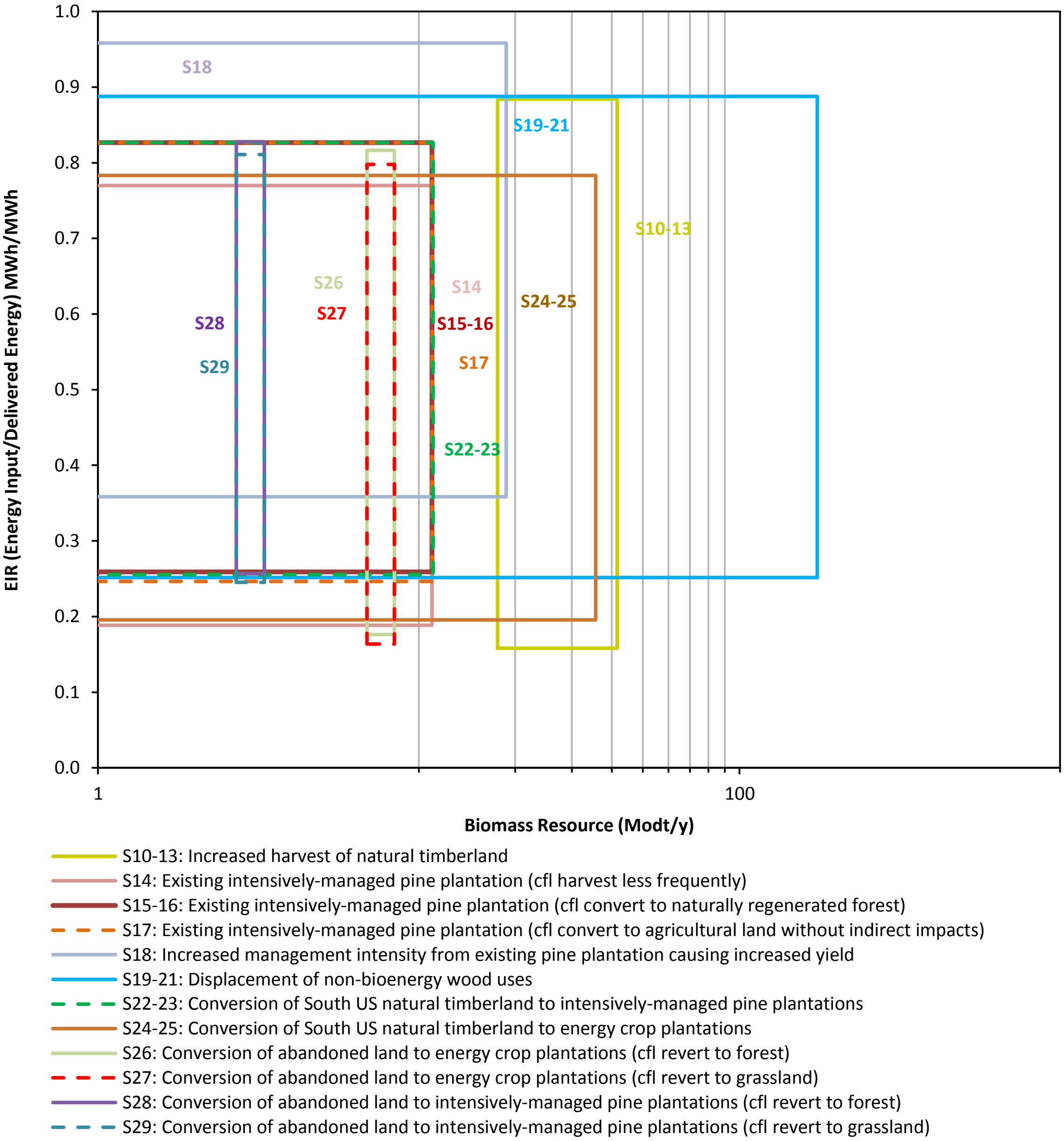

Figure 61. Summary of resource of North American roundwood and woody energy crops that may be available by 2020, and their Energy Input Requirement (40 year time horizon). The EIR is calculated using energy carrier inputs. See page 50 for definition of EIR. cfl: counterfactual.

Conclusions

236. A summary of the GHG impacts of different scenarios is shown below in Table 28.

237. This work shows that in 2020 it may be possible to meet the UK's demand for solid biomass for electricity[88] using biomass feedstocks from North America that result in electricity with GHG intensities lower than 200 kg CO_2e/MWh, when fully accounting for changes in land carbon stock changes [89]. However, there are other bioenergy scenarios that could lead to high GHG intensities (*e.g.* greater than electricity from coal, when analysed over 40 or 100 years) but would be found to have GHG intensities less than 200 kg CO_2e/MWh by the Renewable Energy Directive LCA methodology.

238. The energy input requirement of biomass electricity generated from North American wood used by the UK in 2020 is likely to be in the range 0.13 to 0.96 MWh energy carrier input per MWh delivered energy, significantly greater than other electricity generating technologies, such as coal, natural gas, nuclear and wind. The Energy Input Requirement is smallest when (i) the transport distances are minimised, (ii) the moisture content of the biomass is reduced by passive drying and drying using local biomass resources as fuel, and (iii) the energetic efficiency of the technology is maximised.

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[88] Projected to be 9.0 to 16.0 Modt/y.

[89] Using the BEAC methodology, where forest carbon stocks, foregone carbon sequestration and indirect impacts are taken into consideration.

Table 28. Overview of GHG impacts of bioenergy scenarios, for continuous bioenergy generation over 40 years.

	GHG Impact in kg CO_2e/MWh electricity			
	less than 100	**between 100 and 400**	**greater than 400**	**varies significantly, depending on precise details of scenario**
Woody residues	Forest residues that would otherwise be burned as a waste. Saw-mill residues that would otherwise be burned as a waste. Trees killed from natural disturbances (*e.g.* beetles), that would otherwise burned as a waste.	Fine residues that would otherwise be left to decay in a forest (all regions). Coarse residues that would otherwise be left to decay in a Southern US forest.	Coarse residues that would otherwise be left to decay in a boreal forest (*e.g.* Canada). Trees killed from natural disturbances (*e.g.* beetles), that would otherwise be left in a boreal forest (*e.g.* Canada)[90].	
Roundwood and energy crops	Increasing the yield of a plantation, without increasing the rate of harvest. Wood from a forest that would otherwise be converted to agricultural land (if no indirect impacts). Converting land that would otherwise revert to grassland to biomass plantations (pine or energy crops).		Additional wood output from increasing the harvest rate of forests (reducing the rotation length). Wood from a forest that would otherwise be harvested less frequently[91]. Converting forests into energy crop plantations (*e.g.* Short Rotation Coppice). Converting land that would otherwise revert to forests to biomass plantations (pine or energy crops)[92].	Converting naturally-regenerated forests into pine plantations (increasing the growth rate)[93]. Additional wood output from an intensively-managed plantation that would otherwise be converted to a naturally-regenerated forest[94].

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[90] It was assumed that the increase in carbon stock of the forest by natural regeneration would occur at the same rate if the beetle-killed trees were salvaged or left untreated in the forest. Further research into the future carbon stocks of both scenarios would be beneficial, accounting for different species compositions, and different future natural disturbances.

[91] Additional wood in comparison to the counterfactual used for energy, where the counterfactual forest management involves longer rotation times, hence a greater carbon stock.

[92] For all scenarios considered in this report, the GHG intensity of energy crops grown on land reverting to forest is greater than 400 kg CO_2e/MWh over 40 years, apart from if the yield of the energy crop is 30 odt/ha/y, in which case the GHG intensity was calculated to be 277 kg CO_2e/MWh using the default BEAC key parameters.

[93] Depends strongly on the rotation lengths and growth rates of both the bioenergy scenario and the counterfactual.

[94] Depends strongly on the rotation lengths and growth rates of both the bioenergy scenario and the counterfactual.

Annex: Scenario Assumptions

BEAC Standard Assumptions

239. The assumptions in Table 29 apply to all the example scenarios included in the BEAC model, and outlined in this report. The detailed results and references can be found in the BEAC model.

Table 29. Assumptions used for all the BEAC scenarios outlined in this report.

Details	Assumption	Data Source
Biomass carbon content.	47%.	Anderson-Teixei and Delucia, 2011.
Dry biomass lower heating value.	Softwood: 19.2 MJ/kg. Hardwood: 19.0 MJ/kg. SRC willow: 18.4 MJ/kg.	AEBIOM, 2008.
Biomass moisture content.	Harvested roundwood: 50 wt%.	Ofgem, 2012a.
	Harvested forest residues and deadwood: 25 wt%.	Ofgem, 2012a.
	Saw mill residues: 10 to 50 wt%.	Cal Recycle, 2014.
	Wood pellets: 7 wt%.	Discussions with pellet manufacturers.
Drying fuel prior to wood pelletisation.	Default: Biomass. Low: Biomass. High: Natural Gas.	Data from Ofgem, 2012a. See BEAC model for details of energy requirements (this depends on initial moisture content).
Drying fuel requirements prior to pelletisation, using biomass.	Initial moisture content 10 wt%: no drying. Initial moisture content 25 wt%: 130 kWh/t output. Initial moisture content 50 wt%: 519 kWh/t output.	Ofgem, 2012a.
Drying fuel requirements prior to pelletisation, using natural gas.	Initial moisture content 10 wt%: no drying. Initial moisture content 25 wt%: 133 kWh/t output Initial moisture content 50 wt%: 532 kWh/t output	Ofgem, 2012a.
Pelletising electrical requirement (excluding drying).	Default: 190 kWh per tonne of pellets.	Discussions with pellet manufacturers.
	Low: 100 kWh per tonne of pellets.	NNFCC, 2013.
	High: 239 kWh per tonne of pellets.	NNFCC, 2013.

Details	Assumption	Data Source
Combust in dedicated biomass power station.	Default: Efficiency 35.5% based on the lower heating value of fuel (LHV). Low: Efficiency 30% based on LHV. High: Efficiency 40% based on LHV.	Default: DECC modelling assumptions. High and low from discussions with industry.
Surface transport methods and distances.	Default: Transport wood 50 km from forest to pellet facility by truck, pellets 100 km from pellet facility to the port by truck (apart from pellets from Interior-West Canada, which are transported 630 km by rail), and 100 km from port to plant by rail. Low: Transport wood 25 km from forest to pellet facility by truck, pellets 75 km from pellet facility to the port by truck (apart from pellets from Interior-West Canada, which are transported 320 km by rail), and 75 km from port to plant by rail. High: Transport wood 75 km from forest to pellet facility by truck, pellets 150 km from pellet facility to the port by truck (apart from pellets from Interior-West Canada, which are transported 1600 km by rail), and 150 km from port to plant by rail.	Discussion with pellet manufacturers; NNFCC, 2013.
Shipping distances.	South USA to UK: 7200 km Pacific Canada to UK: 16300 km Interior-West Canada to UK: 16300 km[95] North West USA to UK:16000 km Northeast USA: 5800 km East Canada to UK: 4900 km Brazil to Southeast USA: 5200 km Pacific Canada to Southeast USA: 10500 km.	Sea Distances Voyage Caculator, 2013.
Rail emissions and energy requirements.	Default: Pellet rail emissions would reduce by 15% between 2013 and 2020, from 0.017 to 0.015 kg CO_2e/t km, and energy consumption will reduce by 7.5% from 0.054 to 0.050 kWh/t km. Low: Pellet rail emissions would reduce by 15% between 2013 and 2020, from 0.017 to 0.015 kg CO_2e/t km, and energy consumption will reduce by 7.5% from 0.054 to 0.050 kWh/t km. High: Pellet rail emissions and energy consumption in 2020 would stay the same as in 2013, at 0.017 kg CO_2e/t km,	Emissions in 2013: US Department of Transportation, Bureau of Transportation Statistics, 2014. Future emissions reduction: NNFCC, 2013. Assuming 50% emissions savings from energy savings and 50% from fuel switching.

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[95] Assumes pellets are transported to Pacific coast for shipping.

Details	Assumption	Data Source
	and 0.054 kWh/t km, respectively.	
Truck emissions and energy requirements.	Default: Pellet truck emissions and energy consumption would reduce by 12.35% between 2013 and 2020. Emissions would reduce from 0.110 kg CO_2e/t km to 0.096 kg CO_2e/t km, and energy consumption would reduce from 0.339 to 0.297 kWh/t km. Low: Pellet truck emissions and energy consumption would reduce by 12.35% between 2013 and 2020. Emissions would reduce from 0.110 kg CO_2e/t km to 0.096 kg CO_2e/t km, and energy consumption would reduce from 0.339 to 0.297 kWh/t km. High: Pellet truck emissions and energy consumption in 2020 would stay the same as in 2013, at 0.110 kg CO_2e/t km, and 0.339 kWh/t km, respectively.	Emissions in 2013: Oakridge, 2013; US Department of Transportation, Bureau of Transportation Statistics, 2014a. Assuming 50% load factor. Future emission reduction: ETI, 2012. Assuming 100% emissions savings from energy savings.
Shipping emissions and energy requirements.	Default: Pellet shipping emissions would reduce by 20% between 2013 and 2020, from 0.006 to 0.005 kg CO_2e/t km, and energy consumption would reduce by 10% from 0.018 to 0.016 kWh/t km. Low: Pellet shipping emissions would reduce by 20% between 2013 and 2020, from 0.006 to 0.005 kg CO_2e/t km, and energy consumption would reduce by 10% from 0.018 to 0.016 kWh/t km. High: Pellet shipping emissions and energy consumption in 2020 would stay the same as in 2013, at 0.006 kg CO_2e/t km, and 0.018 kWh/t km, respectively.	Emissions in 2013: MAN Diesel and Turbo, 2014. Future emission reduction: NNFCC, 2013. Assuming 50% emissions savings from energy savings and 50% from fuel switching.
US electrical grid.	US grid GHG intensity (in kg CO_2e/MWh) would reduce by 16% between 2013 and 2020, from 520 to 439 kg CO_2e/MWh.	NNFCC, 2013.
Canadian electrical grid.	Canadian grid GHG intensity (in kg CO_2e/MWh) would reduce by 18% between 2013 and 2020, from 180 to 148 kg CO_2e/MWh.	NNFCC, 2013.
Industrial-scale electricity generation methane emissions.	Methane emissions from electricity generation assumed to be 30 g CH_4/GJ (based on HHV in feedstock), equivalent to 0.0029 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.
Industrial-scale electricity generation nitrous oxide emissions.	Nitrous oxide emissions from electricity generation assumed to be 4 g N_2O/GJ (based on HHV in feedstock), equivalent to 0.0046 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.

Details	Assumption	Data Source
Losses of feedstock per transport leg.	Truck: 0.1 wt%. Rail: 0.1 wt%. Ship: 0.1 wt%.	Discussion with pellet facilities.

Assumptions Specific to Individual Scenarios

BEAC Scenarios 1 to 3

- **Bioenergy Scenario**: Pellets produced from saw mill residues, originating from the (a) US South, and (b) Pacific Canada, for the production of electricity in a dedicated biomass power station in the UK.
- **Land Counterfactual**: Burn the saw mill residues as a waste. No energy recovery.

The assumptions in Table 30 were used to determine the GHG intensities and EIR values for BEAC Scenarios 1 to 3, along with the standard assumptions listed in Table 29.

Table 30. Assumptions used specifically in BEAC Scenarios 1 to 3.

Details	Assumption	Data Source
Saw mill residue moisture.	Scenario 1: 10 wt% Scenario 2: 25 wt%. Scenario 3: 50 wt%.	Cal Recycle, 2014.
Methane emissions from saw-mill residue combustion (when treated as a waste).	Assumed similar to methane emissions from domestic wood combustion, at 300 g CH_4/GJ (based on HHV in feedstock), equivalent to 0.029 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.
Nitrous oxide emissions from saw-mill residue combustion (when treated as a waste).	Assumed similar to nitrous oxide emissions from domestic wood combustion, at 4 g N_2O/GJ (based on HHV in feedstock) equivalent to 0.0046 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.

BEAC Scenarios 4 to 7

- **Bioenergy Scenario**: Pellets produced from removing coarse (Scenarios 4 and 6) and fine (Scenarios 5 and 7) forest residues from forests in (a) South USA and (b) Pacific Canada, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: Leave the residues to decay in the forest.

The assumptions in Table 31 were used to determine the GHG intensities and EIR values for BEAC Scenarios 4 to 7, along with the standard assumptions listed in Table 29.

Table 31. Assumptions used specifically in BEAC Scenarios 4 to 7.

Details	Assumption	Data Source
Decay rate of coarse woody debris (Scenarios 4 and 6).	Decay constant 0.083 year^{-1} in South USA.	Mattson *et al.*, 1987.
	Decay constant 0.028 year^{-1} in Pacific Canada.	Chambers *et al.*, 2000.
Decay rate of fine woody debris (Scenarios 5 and 7).	Decay constant 0.185 year^{-1} in South USA.	Mattson *et al.*, 1987.
	Decay constant 0.097 year^{-1} in Pacific Canada.	Vavrova *et al.*, 2009.
Decay of woody debris.	Methane emissions are negligible.	Schlesinger, 2014; Harmon, 2014; Anderson-Teixei and Delucia, 2011; Biomass Energy Resource Centre, 2012; IPCC, 2006.
Diesel required for harvest.	4 litres diesel per oven dry tonne of residue harvested.	Forestry Commission, 2012.

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 4 to 7, are listed in Table 32; these data have been calculated using the decay constants in Table 31.

Table 32. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 4 to 7.

	Total residue harvested during time horizon, if 1 odt of residues are removed from a different stand each year (odt).		**Carbon from removed residues that would remain in the forest at the end of the time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 4a. Coarse residues, South USA, Continuous removal.				
40 years	40	0	0	5.46
100 years	100	0	0	5.66
Scenario 4b. Coarse residues, Pacific Canada, Continuous removal.				
40 years	40	0	0	11.31
100 years	100	0	0	15.77
Scenario 5a. Fine residues, South USA, Continuous removal.				
40 years	40	0	0	2.54
100 years	100	0	0	2.54
Scenario 5b. Fine residues, Pacific Canada, Continuous removal.				
40 years	40	0	0	4.77
100 years	100	0	0	4.87
Scenario 6a. Coarse residues, South USA, Removal for 15 years only.				
40 years	15	0	0	0.51
100 years	15	0	0	0.00
Scenario 6b. Coarse residues, Pacific Canada, Removal for 15 years only.				

	Total residue harvested during time horizon, if 1 odt of residues are removed from a different stand each year (odt).		Carbon from removed residues that would remain in the forest at the end of the time horizon (t C/ha)	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
40 years	15	0	0	2.86
100 years	15	0	0	0.53
Scenario 7a. Fine residues, South USA, Removal for 15 years only.				
40 years	15	0	0	0.02
100 years	15	0	0	0.00
Scenario 7b. Fine residues, Pacific Canada, Removal for 15 years only.				
40 years	15	0	0	0.33
100 years	15	0	0	0.00

BEAC Scenario 8

- **Bioenergy Scenario**: Pellets produced from removing forest residues from forests in (a) South USA and (b) Pacific Canada, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: Burn the residues at the roadside as a waste.

The assumptions in Table 33 were used to determine the GHG intensities and EIR values for BEAC Scenario 8, along with the standard assumptions listed in Table 29.

Table 33. Assumptions used specifically in BEAC Scenario 8.

Details	Assumption	Data Source
Methane emissions from forest residue combustion (when treated as a waste).	Assumed similar to methane emissions from domestic wood combustion, at 300 g CH_4/GJ (based on HHV in feedstock), equivalent to 0.029 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.
Nitrous oxide emissions from forest residue combustion (when treated as a waste).	Assumed similar to nitrous oxide emissions from domestic wood combustion, at 4 g N_2O/GJ (based on HHV in feedstock) equivalent to 0.0046 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.

BEAC Scenario 9

- **Bioenergy Scenario**: Pellets produced from salvaged dead trees, which have been killed by the mountain pine beetle in Pacific Canada, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: (a) leaving the dead trees in the forest, and (b) removing the dead trees and burning as a waste.

The assumptions in Table 34 were used to determine the GHG intensities and EIR values for BEAC Scenario 9a, along with the standard assumptions listed in Table 29.

Table 34. Assumptions used specifically in BEAC Scenario 9a.

Details	Assumption	Data Source
Decay rate of dead trees.	Decay constant 0.028 year^{-1} in Pacific Canada.	Chambers *et al.*, 2000.
Decay of dead trees.	Methane emissions are negligible.	Schlesinger, 2014; Harmon, 2014; Anderson-Teixei and Delucia, 2011; Biomass Energy Resource Centre, 2012; IPCC, 2006.
Diesel required for harvest.	2.45 litres diesel per m^3 of wood harvested.	Forestry Commission, 2012.

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenario 9a, are listed in Table 35; these data have been calculated using the decay constant in Table 34.

Table 35. Key carbon stock data used to determine the GHG intensity of BEAC Scenario 9a.

	Total wood harvested during time horizon, if 100 odt of dead trees are salvaged from a forest at the start of the time horizon (odt)		**Carbon from removed dead wood that would remain in the forest at the end of the time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
40 years	100	0	0	15.34
100 years	100	0	0	2.86

The assumptions in Table 36 were used to determine the GHG intensities and EIR values for BEAC Scenario 9b, along with the standard assumptions listed in Table 29.

Table 36. Assumptions used specifically in BEAC Scenario 9b.

Details	Assumption	Data Source
Methane emissions from forest residue combustion (when treated as a waste).	Assumed similar to methane emissions from domestic wood combustion, at 300 g CH_4/GJ (based on HHV in feedstock), equivalent to 0.029 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.
Nitrous oxide emissions from forest residue combustion (when treated as a waste).	Assumed similar to nitrous oxide emissions from domestic wood combustion, at 4 g N_2O/GJ (based on HHV in feedstock) equivalent to 0.0046 kg CO_2e/kWh (based on LHV in feedstock).	US Environmental Protection Agency, 2008.

BEAC Scenarios 10 to 13

- **Bioenergy Scenario**: Pellets produced from the additional wood output from increasing the rate of harvest of a North American naturally-regenerated forest, for the production of electricity in a dedicated biomass electricity station in the UK (apart from 13b, where the harvest rate of the forest does not change).
- **Land Counterfactual**: See Table 16. Continue previous management regime (apart from 13b, where the forest is harvested less frequently).

The assumptions in Table 37 were used to determine the GHG intensities and EIR values for BEAC Scenarios 10 to 13, along with the standard assumptions listed in Table 29.

Table 37. Assumptions used specifically in BEAC Scenarios 10 to 13.

Details	Assumption	Data Source
Forest carbon modelling:		
Scenario 10.	Naturally-regenerated hardwood forest, based on Birch, Yield Class 4 m^3/ha/y, spacing between trees 1.5 m.	C-SORT model of Forest Research. Details on page 48.
Scenario 11.	Naturally-regenerated conifer growth, based on Douglas fir, Yield Class 12 m^3/ha/y, spacing between trees 1.2 m.	C-SORT model of Forest Research. Details on page 48.
Scenario 12.	Naturally-regenerated conifer growth, based on Lodgepole pine, Yield Class 4 m^3/ha/y, spacing between trees 1.5 m.	C-SORT model of Forest Research. Details on page 48.
Scenario 13.	Naturally regenerated hardwood forests, based on Southeastern US Oak-Hickory forests.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Soil Organic Carbon	No difference in SOC between bioenergy scenario and land counterfactual.	Discussed on page 81.
Diesel required for harvest.	2.45 litres diesel per m^3 of wood harvested.	Forestry Commission, 2012.

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 10 to 13, are listed in Table 38; these data have been calculated using the growth models listed in Table 37 (see Figure 37 for growth curves).

Table 38. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 10 to 13.

	Average wood production over time horizon (odt/ha/y)		**Non-soil carbon stock at end of time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 10a.				
40 years	3.068	1.664	43.53	80.72
100 years	2.610	1.664	41.84	80.72
Scenario 10b.				
40 years	2.044	1.664	70.77	80.72
100 years	1.992	1.664	68.78	80.72
Scenario 11.				
40 years	5.537	4.386	84.83	114.32
100 years	4.910	4.386	83.41	114.32

	Average wood production over time horizon (odt/ha/y)		Non-soil carbon stock at end of time horizon (t C/ha)	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 12a.				
40 years	2.501	1.526	31.36	67.74
100 years	1.888	1.526	29.49	67.74
Scenario 12b.				
40 years	1.830	1.526	57.34	67.74
100 years	1.715	1.526	54.56	67.74
Scenario 13a.				
40 years	1.668	1.508	75.20	84.42
100 years	1.563	1.508	74.02	84.42
Scenario 13b.				
40 years	1.508	1.365	84.42	91.06
100 years	1.508	1.430	84.42	93.12

BEAC Scenarios 14 to 18

- **Bioenergy Scenario**: Pellets produced from existing intensively-managed pine plantations in South USA, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: See Table 19 and Table 20.

The assumptions in Table 39 were used to determine the GHG intensities and EIR values for BEAC Scenarios 14 to 18, along with the standard assumptions listed in Table 29.

Table 39. Assumptions used specifically in BEAC Scenarios 14 to 18.

Details	Assumption	Data Source
Forest carbon modelling for Bioenergy Scenarios:		
Scenarios 14 to 18.	Intensively-managed Loblolly pine plantation (achieving high productivity) using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Land carbon modelling for Counterfactuals:		
Scenario 14.	Intensively-managed Loblolly pine plantation, using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Scenarios 15 and 16.	Low productivity, naturally-regenerated Loblolly forest, using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Scenario 17.	Cotton plantation above-ground carbon stock of 2.2 t C/ha.	Winrock, 2011.

Details	**Assumption**	**Data Source**
Scenario 18.	Loblolly pine plantation, managed to a medium-intensity, achieving 74% of the yield of an intensively-managed plantation.	Allen *et al.*, 2005.
Soil Organic Carbon:		
Scenarios 14 to 16, and 18.	No difference in SOC between bioenergy scenario and land counterfactual.	Discussed on page 81.
Scenario 17.	IPCC methods used to estimate changes in SOC content when the forest is converted to cotton, assuming the carbon content under native vegetation would be 40.09 t C/ha, and the Stock Change Factor[96], F, would change from 1 to 0.69.	IPCC, 2006; Winrock, 2011.
Site preparation of pine plantations:		
Intensively-managed plantations.	Chopping: 28.1 litres diesel/ha Piling: 149.76 litres diesel/ha Burning: 18.7 litres diesel/ha Disking: 37.4 litres diesel/ha Bedding: 37.4 litres diesel/ha Herbicides: 18.7 litres diesel/ha Planting: 56.1 litres diesel/ha	Dwivedi *et al.*, 2011.
Plantations managed to medium-intensity.	Burning: 18.7 litres diesel/ha Bedding: 37.4 litres diesel/ha Herbicides: 18.7 litres diesel/ha Planting: 56.1 litres diesel/ha	Dwivedi *et al.*, 2011.
Fertilisation of plantations:		
Intensively-managed plantations.	Average annual application calculated by assuming application of 54.7 kg P/ha at planting, then 27.3 kg P/ha and 191 kg N/ha at ages 7, 14 and 21 years.	Fox *et al.*, 2007a; North Carolina Forestry Service, 2012.
	Total of 4 applications of fertiliser during 1 rotation, requiring 18.7 litres diesel/ha per application.	Dwivedi *et al.*, 2011.
Plantations managed to medium-intensity.	Application of 27.3 kg P/ha at planting, then 27.3 kg P/ha and 191 kg N/ha at mid-rotation.	
	Total of 2 applications of fertiliser during 1 rotation, requiring 18.7 litres diesel/ha per application.	Dwivedi *et al.*, 2011.

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[96] Carbon stock change = SOC under native vegetation × ($F_{final} – F_{initial}$).

Details	**Assumption**	**Data Source**
Diesel required for harvest.	3.42 litres diesel per odt of wood harvested.	Timmons and Mejia, 2010.

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 14 to 18, are listed in Table 40; these data have been calculated using the growth data detailed in Table 39 (see Figure 42 for growth curves).

Table 40. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 14 to 18.

	Average wood production over time horizon (odt/ha/y)		**Non-soil carbon stock at end of time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 14a.				
40 years	5.913	4.608	80.92	103.01
100 years	5.913	4.669	80.92	103.01
Scenario 14b.				
40 years	6.183	4.608	66.53	103.01
100 years	5.917	4.669	66.53	103.01
Scenario 15a.				
40 years	5.913	4.804	80.92	73.42
100 years	5.913	3.115	80.92	69.64
Scenario 15b.				
40 years	6.183	4.804	66.53	73.42
100 years	5.917	3.115	66.53	69.64
Scenario 16a.				
40 years	5.913	3.696	80.92	75.30
100 years	5.913	1.478	80.92	146.83
Scenario 16b.				
40 years	6.183	3.696	66.53	75.30
100 years	5.917	1.478	66.53	146.83
Scenario 17a.				
40 years	5.913	3.696	80.92	2.20
100 years	5.913	1.478	80.92	2.20
Scenario 17b.				
40 years	6.183	3.696	66.53	2.20
100 years	5.917	1.478	66.53	2.20
Scenario 18.				
40 years	4.949	4.371	80.92	59.81
100 years	5.528	4.371	80.92	59.81

BEAC Scenarios 19 to 21

- **Bioenergy Scenario**: Pellets produced from pulpwood in South USA, for the production of electricity in a dedicated biomass electricity station in the UK, causing the displacement of non-bioenergy wood uses, which are then supplied by imports.
- **Land Counterfactual**: Pulpwood used for non-bioenergy purposes.

The assumptions in Table 41 were used to determine the GHG intensities and EIR values for BEAC Scenarios 19 to 21, along with the standard assumptions listed in Table 29.

Table 41. Assumptions used specifically in BEAC Scenarios 19 to 21.

Details	Assumption	Data Source
Forest carbon modelling for Bioenergy Scenarios (indirect impacts):		
Scenario 19 and 20.	Eucalyptus plantations are established over 6 years (staggered planting). Each stand is harvested every 6 years, and achieves an average yield of 30 odt/ha/y on good quality land (Scenario 19) and 20 odt/ha/y on degraded land (Scenario 20).	FAO, 2013a.
	Average non-soil carbon stock calculated by approximating the time-averaged, above-ground carbon stock to be 50% of the carbon stock when the trees are 6 years old, and that the carbon in the roots represents 35% of the above-ground carbon.	IPCC, 2006.
Scenario 21.	Naturally-regenerated conifer growth, based on Douglas fir, Yield Class 12 m^3/ha/y, spacing between trees 1.2 m.	C-SORT model of Forest Research. Details on page 48.
Land carbon modelling for Counterfactuals (indirect impacts):		
Scenario 19.	Mature tropical rainforest, where the carbon stock stays constant over time (carbon emissions from biomass decay are equal to absorption from new growth).	
Scenario 20.	Abandoned pasture land; for the first 10 years the land would revert to native grassland, with a final non-soil carbon content of 7.18 t C/ha. The land would then start to revert to native woody savannah, with rate of growth of above ground biomass of 4 t dry matter/ha/y, until reaching a total above ground biomass level of 80 t dry matter/ha (~ 37.6 t C/ha). The roots would provide	Using data from IPCC (2006).

Details	Assumption	Data Source
	an additional 15.0 t C/ha.	
Scenario 21.	Naturally-regenerated conifer growth, based on Douglas fir, Yield Class 12 m^3/ha/y, spacing between trees 1.2 m.	C-SORT model of Forest Research. Details on page 48.
Soil Organic Carbon (indirect impacts):		
Scenarios 19 and 21.	No difference in SOC between bioenergy scenario and land counterfactual.	Discussed on page 81.
Scenario 20.	The soil in the region is mineral, with a SOC content of 45.3 t C/ha under native vegetation. IPCC methods were used to estimate changes in SOC content when the land is converted to Eucalyptus, or left to revert to its native state, assuming the Stock Change Factor would change from 0.7 to 1.0.	Winrock, 2011; IPCC, 2006.
	When the land is converted to Eucalyptus plantations, it was assumed that a new SOC equilibrium would be reached after 20 years.	IPCC, 2006.
	When land is left to revert to its native state, the soils of abandoned land typically reach a new equilibrium after 30 - 100 years, depending on the state of degradation of the land and the climate, with tropical land reaching equilibrium sooner. We assumed that the soil would reach new equilibrium in 50 years.	Post and Kwon, 2000; Uhl *et al*., 1988; Richter *et al*., 1999; Johnson, 1992.
Management of Eucalyptus plantations:		
Diesel for establishment.	19.82 litres/ha/y (annualised).	Ofgem, 2012a.
Herbicides.	2.0 kg Active Ingredient/ha/y.	
Phosphate fertiliser.	13.06 kg P_20_5/ha/y.	
Potassium fertiliser.	11.94 kg K_2O/ha/y.	
Lime.	7.78 kg lime/ha/y.	
Harvest and chipping.	3.49 litres diesel per odt of wood harvested.	

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 19 to 21, are listed in Table 42.

Table 42. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 19 to 21.

	Average wood production over time horizon (odt/ha/y)		**Non-soil carbon stock at end of time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 19.				
40 years	28.125	0	57.11	202.83
100 years	29.250	0	57.11	202.83
Scenario 20.				
40 years	18.75	0	38.07	52.64
100 years	19.50	0	38.07	52.64
Scenario 21.				
40 years	5.537	4.386	84.83	114.32
100 years	4.910	4.386	83.41	114.32

BEAC Scenarios 22 to 25

- **Bioenergy Scenario**: Pellets produced from wood from new plantations in South USA, established on naturally-regenerated timberland, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: Leave the forest as naturally-regenerated timberland.

The assumptions in Table 43 were used to determine the GHG intensities and EIR values for BEAC Scenarios 22 to 25, along with the standard assumptions listed in Table 29.

Table 43. Assumptions used specifically in BEAC Scenarios 22 to 25.

Details	**Assumption**	**Data Source**
Forest carbon modelling for Bioenergy Scenarios:		
Scenarios 22 and 23.	Intensively-managed Loblolly pine plantation (achieving high productivity) using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Scenario 24 and 25.	SRC hardwood plantation, based on SRC willow that is harvested every 3 years, and achieves an average yield of 10 odt/ha/y.	Biomass Energy Centre, 2014.
	Average non-soil carbon stock calculated by approximating the time-averaged, above-ground carbon stock to be 50% of the carbon stock when the trees are 3 years old, and that the carbon in the roots represents an additional 3.9 tC/ha.	Using data from Zan *et al.*, 2001.

Details	Assumption	Data Source
Land carbon modelling for Counterfactuals:		
Scenarios 22 and 24.	Low productivity, naturally-regenerated Loblolly forest, using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Scenario 23 and 25.	Low productivity, naturally-regenerated Oak-Hickory forest, using data specific to the US Southeast from the USDA.	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.
Soil Organic Carbon.	No difference in SOC between bioenergy scenarios and the relevant counterfactuals.	Discussed on page 81.
Management of intensively-managed pine plantations.	Same as in Table 39.	
Management of SRC plantations:		
Diesel for establishment.	12.3 litres/ha/y (annualised).	Ofgem, 2012a.
Herbicides.	2.25 kg Active Ingredient/ha/y.	
SRC cutting requirements.	250 kg cutting/ha/y.	
Harvest and chipping.	3.1 litres diesel per odt of wood harvested.	

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 22 to 25, are listed in Table 44; these data have been calculated using the growth data detailed in Table 43 (see Figure 51 for growth curves).

Table 44. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 22 to 25.

	Average wood production over time horizon (odt/ha/y)		**Non-soil carbon stock at end of time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 22a.				
40 years	3.771	1.795	80.92	69.64
100 years	5.056	1.795	80.92	69.64
Scenario 22b.				
40 years	4.281	1.795	66.53	69.64
100 years	5.157	1.795	66.53	69.64
Scenario 23a.				
40 years	3.742	1.508	80.92	84.42
100 years	5.045	1.508	80.92	84.42
Scenario 23b.				
40 years	4.278	1.508	66.53	84.42
100 years	5.156	1.508	66.53	84.42

	Average wood production over time horizon (odt/ha/y)		Non-soil carbon stock at end of time horizon (t C/ha)	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 24a.				
40 years	10.821	1.795	10.95	69.64
100 years	10.328	1.795	10.95	69.64
Scenario 24b.				
40 years	5.795	1.795	29.63	69.64
100 years	8.398	1.795	10.95	69.64
Scenario 25a.				
40 years	10.902	1.508	10.95	84.42
100 years	10.361	1.508	10.95	84.42
Scenario 25b.				
40 years	4.366	1.508	60.05	84.42
100 years	7.557	1.508	10.95	84.42

BEAC Scenarios 26 to 29

- **Bioenergy Scenario**: Pellets produced from wood from new plantations in South USA, established on abandoned agricultural land, for the production of electricity in a dedicated biomass electricity station in the UK.
- **Land Counterfactual**: Leave the forest to revert to its native state.

The assumptions in Table 45 were used to determine the GHG intensities and EIR values for BEAC Scenarios 26 to 29, along with the standard assumptions listed in Table 29; these data have been calculated using the growth data detailed in Table 44 (see Figure 55 for growth curves).

Table 45. Assumptions used specifically in BEAC Scenarios 26 to 29.

Details	Assumption	Data Source
Forest carbon modelling for Bioenergy Scenarios:		
Scenarios 26 and 27.	SRC hardwood plantation, based on SRC willow that is harvested every 3 years, and achieves an average yield of 5 to 30 odt/ha/y.	Discussed on page 113.
	Average non-soil carbon stock calculated by approximating the time-averaged, above-ground carbon stock to be 50% of the carbon stock when the trees are 3 years old, and that the carbon in the roots represents an additional 3.9 tC/ha.	Using data from Zan *et al.*, 2001.
Scenarios 28 and 29.	Intensively-managed Loblolly pine plantation (achieving high productivity) using data specific to the US Southeast from the	United States Department for Agriculture data (Smith *et al.*, 2006). Details on page 48.

Details	Assumption	Data Source
	USDA.	
Land carbon modelling for Counterfactuals:		
Scenarios 26 and 28.	Abandoned agricultural land that was previously ploughed annually; for the first 10 years the land would revert to native scrub land, with a final non-soil carbon content of 7.18 t C/ha. The land would then start to revert to native sub-tropical, moist, deciduous forest, with the rate of growth of above ground biomass of 7.0 t dry matter/ha/y for 20 years, and then 2.0 t dry matter/ha/y until reaching a total above ground biomass level of 220 t dry matter/ha (~ 103.4 t C/ha). The roots would provide an additional 24.8 t C/ha and litter 4.8 t C/ha.	Using data from IPCC (2006).
Scenario 27 and 29.	Abandoned agricultural land that was previously ploughed annually; for the first 10 years the land would revert to native scrub land, with a final non-soil carbon content of 7.4 t C/ha. The land would stay as scrub land and the carbon stock would stay at 7.4 t C/ha.	Using data from IPCC (2006).
Soil Organic Carbon.		
Scenarios 26 and 28.	The soil in the region is mineral, with a SOC content of 40.1 t C/ha under native vegetation. IPCC methods were used to estimate changes in SOC content when the land is converted to plantations, or left to revert to its native state, assuming the Stock Change Factor would change from 0.48 (full till in tropical, moist region) to 1.	Winrock, 2011; IPCC, 2006.
	When the land is converted to plantations, it was assumed that a new SOC equilibrium would be reached after 20 years.	IPCC, 2006.
	When land is left to revert to its native state, the soils of abandoned land typically reach a new equilibrium after 30 - 100 years, depending on the state of degradation of the land and the climate, with tropical land	Post and Kwon, 2000; Uhl *et al*., 1988; Richter *et al*., 1999; Johnson, 1992.

Details	Assumption	Data Source
	reaching equilibrium sooner. We assumed that the soil in this region would reach new equilibrium in 50 years.	
Scenarios 27 and 29.	The soil in the region is mineral, with a SOC content of 56.5 t C/ha under native vegetation. IPCC methods were used to estimate changes in SOC content when the land is converted to plantations, or left to revert to its native state, assuming the Stock Change Factor would change from 0.8 (full till in temperate, dry region) to 1.	Winrock, 2011; IPCC, 2006.
	When the land is converted to plantations, it was assumed that a new SOC equilibrium would be reached after 20 years.	IPCC, 2006.
	When land is left to revert to its native state, the soils of abandoned land typically reach a new equilibrium after 30 - 100 years, depending on the state of degradation of the land and the climate, with tropical land reaching equilibrium sooner. We assumed that the soil in this region would reach new equilibrium in 75 years.	Post and Kwon, 2000; Uhl *et al*., 1988; Richter *et al*., 1999; Johnson, 1992.
Management of intensively-managed pine plantations.	Same as in Table 39.	
Management of SRC plantations.	Same as in Table 43.	

The key data used to determine the difference in the land carbon stock between the bioenergy scenario and counterfactual, for BEAC Scenarios 26 to 29, are listed in Table 46; these data have been calculated using the growth data detailed in Table 45.

Table 46. Key carbon stock data used to determine the GHG intensities of BEAC Scenarios 26 to 29.

	Average wood production over time horizon (odt/ha/y)		**Non-soil carbon stock at end of time horizon (t C/ha)**	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
Scenario 26a.				
40 years	4.875	0.000	7.43	103.29
100 years	4.950	0.000	7.43	133.00
Scenario 26b.				
40 years	9.750	0.000	10.95	103.29

	Average wood production over time horizon (odt/ha/y)		Non-soil carbon stock at end of time horizon (t C/ha)	
	Bioenergy Scenario	Counterfactual Scenario	Bioenergy Scenario	Counterfactual Scenario
100 years	9.900	0.000	10.95	133.00
Scenario 26c.				
40 years	14.625	0.000	14.48	103.29
100 years	14.850	0.000	14.48	133.00
Scenario 26d.				
40 years	29.25	0.000	25.05	103.29
100 years	29.70	0.000	25.05	133.00
Scenario 27a.				
40 years	4.875	0.000	7.43	7.40
100 years	4.950	0.000	7.43	7.40
Scenario 27b.				
40 years	9.750	0.000	10.95	7.40
100 years	9.900	0.000	10.95	7.40
Scenario 27c.				
40 years	14.625	0.000	14.48	7.40
100 years	14.850	0.000	14.48	7.40
Scenario 27d.				
40 years	29.25	0.000	25.05	7.40
100 years	29.70	0.000	25.05	7.40
Scenario 28a.				
40 years	2.217	0.000	80.92	103.29
100 years	4.435	0.000	80.92	133.00
Scenario 28b.				
40 years	2.870	0.000	66.53	103.29
100 years	4.592	0.000	66.53	133.00
Scenario 29a.				
40 years	2.217	0.000	80.92	7.40
100 years	4.435	0.000	80.92	7.40
Scenario 29b.				
40 years	2.870	0.000	66.53	7.40
100 years	4.592	0.000	66.53	7.40

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