Research to support the review of the Renewable Obligation Scotland and impact of the Renewable Heat Incentive

Part 2: Biomass thresholds for electricity, CHP and heat generation

Designing practical solutions for a sustainable future NORTH ENERGY

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Part 2: Biomass threshold for electricity; CHP and heat generation

Nigel Mortimer, Charlotte Hatto, Garry Jenkins and Onesmus Mwabonje

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North Energy Associates Limited
5 Bearl Farm • Bywell • Stocksfield • Northumberland • NE43 7AJ • UK
Telephone: +44 (0)1661 843545 • Fax: +44 (0)1661 844085

Watson's Chambers • 5-15 Market Place • Castle Square • Sheffield • S1 2GH • UK
Telephone: +44 (0)114 201 2604 • Fax: +44 (0)114 272 7374

enquiries@northenergy.co.uk
www.northenergy.co.uk
Registered in England and Wales 2654074
VAT Reg. No. 621 2737 65

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Executive Summary

1. This report was prepared by North Energy Associates Ltd, in collaboration with Forest Research, on behalf of Forestry Commission Scotland for the Scottish Government. It addresses the potential use of wood in Scotland for different energy purposes, in terms of possible prioritising specific uses, mainly from the perspective of comparative greenhouse gas (GHG) emissions. This was achieved by using existing sources of information and life cycle assessment, chiefly in the form of MS Excel workbooks.

2. Possible capacity thresholds have been explored by comparing the total GHG emissions for forest wood products and waste wood used in domestic, commercial and industrial heating, combined heat and power (CHP) generation and dedicated power only generation at different scales. The range of plant scales varied typically, from 15 kWt to 320 kWt for domestic heating, from 50 kWt to 20 MWt for commercial and industrial heating, from 1.8 MWt to 125 MWt of heat and from 0.4 MWe and 50 MWe for electricity in CHP generation, and from 5 MWe to 350 MWe for dedicated power only generation.

3. Typical results were generated to answer the basic question; "do wood-fired heat and CHP plants have lower total GHG emissions than those of power only plants that use the same source of wood fuel?" On the basis of comparing 1 MWh of electricity directly with 1 MWh of delivered heat, these results demonstrated that, assuming typical ranges for wood fuel transport distances and for plant design specifications, total GHG emissions associated with all wood-fired heating applications, and heating from all CHP applications and electricity from some CHP applications are markedly lower than those for power only generation. However, some overlap occurs in total GHG emissions associated with power only generation and the generation of electricity from wood-fired CHP plants that combine large scale, low overall energy efficiency and large wood fuel delivery distances.

4. Further investigation of the factors which influence the comparison of total GHG emissions required idealised modelling, in particular, to analyse the trade-off between the relative thermal efficiencies of different wood-fired applications and the distances involved in transporting wood fuel for heat and CHP plants. As part of idealised modelling and to enhance the robustness of results, it was favourably assumed that power only plants would be located at the centre of forests or next to sources of waste wood, thereby minimising transport distances. Subsequent analysis enabled the following question to be addressed; "what is the maximum distance for delivering wood fuel to heat and CHP plants at which their total GHG emissions equal those of power only plants using the same source of wood?"

5. This analysis demonstrated that the advantage of heat and CHP plants using Scottish forest wood fuels over power only plants, in terms of lower total GHG emissions and with the direct comparison of 1 MWh of electricity with 1 MWh of delivered heat, could be maintained for the national supply across Scotland (a radius of supply up to 500 km) of roundwood pellets for domestic heating, roundwood and unclean waste wood chips for commercial and industrial heating, roundwood, and clean and unclean waste wood chips for CHP generation with wood fuel deliveries nationally. This advantage would be achieved for the regional supply (a radius of supply up to 200 km) of roundwood logs, roundwood briquettes, and forest residue and clean waste wood pellets for domestic heating, and forest residue and clean waste wood chips for commercial and industrial

heating and CHP. The advantage for clean waste wood briquettes used in domestic heating would only be attained if wood fuel was delivered on a very locally (a radius of supply less than 50 km).

6. It was established that these results are influenced by the basis for comparing 1 MWh of electricity with 1 MWh of delivered heat, and different existing methods for doing this were examined. Detailed analysis was performed to produce variations of the proportional price differential, expressing the price of electricity relate to the price of delivered heat, with the distance for delivering wood fuel to heat and CHP plants. These variations addressed the specific question; “what proportional price differential is required to ensure that the total GHG emissions of heat and CHP plants using wood fuel supplied within a given radius of supply do not exceed those of a power only plant using the same source of wood fuel?”

7. Assuming that national delivery across Scotland, the prices of delivered heat relative to those of electricity necessary to retain the total GHG emissions advantage of heat and CHP plants over power only plants were derived. These depended on specific wood fuel types and end use applications, ranging from a price for delivered heat from roundwood pellets in domestic heating no more than 37% lower than the price of electricity from roundwood, to a price of delivered heat from clean waste wood briquettes in domestic heating at least 194% higher than the price of electricity from clean waste wood.

8. The possible implications for policy measures to promote the preferential use of wood fuel in Scotland were outlined. The application of these results were qualified in terms of limitations to conclusions based solely on the consideration of comparative GHG emissions, the likely need to incorporate detailed technical specifications of potential wood fuel applications into policy measures, the issue of other sensitivities, such as variations in thermal efficiencies, on results, and potential differences in this approach to the proposed extension of the European Commission’s Renewable Energy Directive to biomass heat and electricity generation which is based on exergy rather than price.

9. Finally, the possibility of determining a threshold capacity for wood-fired CHP plants, from the perspective of total GHG emissions relative to those of power only plants was investigated. It was established that, because of complex considerations of design specifications, firm and practical conclusions could not be drawn on this issue. Instead, the results reinforced the need to promote “good quality” CHP, partly based on higher overall energy efficiencies and it was noted that opportunities for very large scale CHP applications were limited in Scotland unless policy measures and incentives are put in place to encourage town- and city-wide district heating networks.

Contents

1 Introduction

1.1 Policy context

There is a significant potential resource of wood in Scotland for use in a variety of applications. This not only encompasses wood products and residues available from extensive commercial forestry but also waste wood from a number of companies that are closely associated with wood product processing in all its different and diverse forms. This includes clean waste wood from such processing industries and waste wood that has been contaminated during its former use. Given Scotland's commitment to substantial reliance on renewable energy in the foreseeable future, this wood presents a prospective major source of energy, either as heat and/or electricity. However, although Scotland's wood is sustainable, the amount available on a regular basis is finite. Hence, it is important to ask whether there are priority energy applications for this substantial and sustainable yet ultimately limited source of biomass supply. In particular, it is necessary to determine whether it is better to use specific types or sources of wood for heating, or in combined heat and power (CHP) generation or in power only plants and, if so, whether the size or scale of the end use application has a noticeable and defining influence.

1.2 Assessment framework

Within this policy context, the priority energy use of wood can be assessed in many different ways. Leaving aside economic assessment, it is meaningful to address competing energy applications for different sources of wood from a natural resource and greenhouse gas (GHG) emissions perspective. Despite recent policies promoting renewable energy, the Scottish economy is still heavily reliant of depletable energy resources, especially fossil fuels. This is an important consideration for policy makers not only because of likely longer-term future scarcity but also due to shorter-term price volatility and escalation. Hence, it is logical to consider the relative impact on fossil fuel consumption of using Scotland's wood in different types and scales of energy applications. Another natural resource aspect concerns the relative efficiency of using the biomass resource for different energy applications. This recognises the finite extent of the available biomass resource in the face of rapidly expanding demand. Finally and most significantly, these deliberations have to be framed against the fundamental issue of global climate change and this has to consider the relative total GHG emissions associated with different energy applications for Scotland's wood.

1.3 Programme of work

In order to address these issues, Forest Research were commissioned, in collaboration with North Energy Associates Ltd, by the Scottish government, via Forestry Commission Scotland, to investigate the fossil fuel, biomass resource and GHG emissions implications of using Scotland's wood for heating, CHP generation and power only generation at different appropriate scales. The programme of work to accomplish this was divided into 5 Tasks:

<u>Task A: Basic Data Collection – Biomass Energy Technology</u>: This involved using relevant sources to establish the key design and performance parameters of appropriate energy technologies for the current use of wood in Scotland.

<u>Task B: Basic Data Collection – Biomass Feedstock Supply</u>: This involved specifying the essential features of the wood resource and its potential supply chains, in the

form of biomass feedstock provision, processing, transport and conversion, for energy production in Scotland.

Task C: Workbook Modification: This involved using existing MS Excel workbooks, mainly in the public domain, to devise a single workbook for calculating fossil fuel consumption, biomass resource utilisation and total GHG emissions associated with relevant biomass chains.

Task D: Idealised Modelling: This involved combining the outputs of Tasks A to C to explore the general effects of technology and scale on fossil fuel consumption, biomass resource utilisation and total GHG emissions assuming idealised models of forests and supply chains.

Task E: Report Preparation: This involved producing the current report and providing a MS PowerPoint presentation of the major results and key findings of this work.

2 Methodology

2.1 Life cycle assessment

Life cycle assessment (LCA) provides the main technique for assessing relative impacts, in terms of fossil fuel consumption, biomass resource utilisation and total GHG emissions associated with different biomass chains for heating, CHP and power only generation. LCA is an established technique which has been applied to assessing biomass energy technologies, in general (see, for example, Refs. 1 and 2) and wood energy supply chains, in particular (see, for example, Refs. 3 and 4). There are a number of methodologies, based on LCA principles, for calculating total GHG emissions associated with the provision of specific products and services. The methodology which is the most relevant to this study is the European Commission's Renewable Energy Directive (RED) (Ref. 5). Although the methodology set out in the RED is specifically for application to liquid and gaseous biofuels, this is in the process of being extended to biomass energy technologies that supply heat and/or electricity (Ref. 6).

The expected features of the RED for biomass energy technologies have been adopted here to the calculation of GHG emissions and, where relevant, to the estimation of energy resource consumption. The main features that apply to both energy resource consumption and GHG emissions relate to the coverage of inputs and the treatment of residues and wastes. In particular, calculations exclude GHG emissions (and, by extension, energy resource consumption) associated with the manufacture and maintenance of machinery, equipment and plant used as part of the life cycle of a biomass energy technology. All other identified inputs to the sequence of process stages that make up the biomass energy chain are included.

Under the RED methodology, any biomass energy chain includes the provision of the biomass its original source apart from "agricultural residues and wastes" (Ref. 5). Currently, official definitions of such residues and wastes are being elaborated. However, in this work, it is assumed that GHG emissions (and, by extension, energy resource consumption) associated the provision of forest residues, and clean and unclean waste wood are excluded from calculations. It should be noted that this assumption has an impact on calculations for forestry products, such as roundwood, as well as forest residues themselves. This is because of the allocation procedure for dividing GHG emissions (and energy resource consumption) associated with forest operations between subsequent co-products, such as roundwood and sawn timber. As a consequence, forest residues, and clean and unclean waste wood have lower total GHG emissions than designated forestry products such as roundwood. In a policy context based on relative GHG emissions savings, this would favour the former sources of wood energy over the latter.

In keeping with the RED, such allocation is based on the energy content, or net calorific value, of the co-products. Also in compliance with the RED, no effects of reference systems are taken into account. In particular, this means that impacts relative to alternative uses or disposal of forest residues and waste wood are not evaluated. Furthermore, the consequences of alternative use of land on which forests currently grow are not incorporated. In general, the alternative use of land is related to the controversial issue of indirect land use change (iLUC) which arises when a new use of land replaces an existing use. This, in turn, can lead to the displacement of existing production elsewhere in the world. Depending on whether there are significant limitations on the availability of productive land, this can result in the conversion of uncultivated land and, in extreme cases, cause the destruction of high carbon stocks, such as natural forests, peatlands, etc. Substantial amounts of GHGs can be released which, in some instances, could be allocated to the original change of land use which precipitated this sequence of events.

Official procedures for incorporating iLUC into GHG emissions calculations have not yet been determined by the European Commission in the context of the RED. However, this is not an important consideration for this current report provided that all sources of wood available for use in Scotland are derived from established sources that are managed sustainably. The major source of wood in Scotland is commercial forestry which was created many years ago and which is maintained in a sustainable manner by the planting of new trees as older stands of trees are progressively thinned and felled. Provided that this policy of forestry management is continued, then the effects of iLUC can be ignored for current purposes. Related to the exclusion of total GHG emissions from land use change, the potential carbon storage effects of forestry have not been included mainly because the possible generation of negative results only confuses their subsequent interpretation. This is not a major issue in this analysis which focuses on comparisons between results when considering the implications of using wood from a given source in different energy applications.

One feature associated with the adoption of the RED methodology for the calculation of GHG emissions in this report concerns the choice of global warming potentials (GWPs) that are used to convert methane (CH_4) and nitrous oxide (N_2O) emissions into equivalent (eq.) carbon dioxide (CO_2) emissions. The GWPs specified in the RED are 23 kg eq. CO_2/kg CH_4 and 296 kg eq. CO_2/kg N_2O which is consistent with the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (Ref. 7).

2.2 Choice of metrics

The metrics adopted in this study are determined by the specific issues against which the alternative energy uses of Scotland’s wood are being assessed. Concern about Scotland’s exposure to energy insecurity can be addressed by estimating the relative effects on energy resource depletion, mainly in the form of fossil fuels. This can be achieved by measuring total primary energy consumption as “primary energy” is defined as depletable energy resources in this instance. Primary energy is normally measured in units of MJ, MWh, etc. It is also possible to determine Scotland’s energy sustainability by evaluating the consumption of biomass energy, in this instance consisting of wood and measured in units of oven dry tonnes (odt). Relative contributions to global climate change can be determined by means of total GHG emissions measured in kg eq. CO_2. To assist the use of this report, results presented here focus on total GHG emissions whilst estimates of primary energy and biomass energy consumption are recorded, along with other supporting information, in the Appendices for this report.

In all these cases, relative impact is evaluated per unit of energy delivered to end users through alternative uses of wood. This energy consists of either heat and/or electricity, and, in this report, it is measured in units of MWh. However, it is essential to ensure that an equivalent basis for delivered energy is adopted for estimating and comparing results for each end use. With heating applications, it is assumed that the delivered energy is in the form of heat provided directly to end users on their own premises without further significant losses. This consideration also applied to the heat provided by CHP plants which are assumed to be located where the heat demand arises. It is assumed that the electricity provided by CHP plants is chiefly consumed where they are located although it is recognised that some surpluses may be delivered to other consumers via the electricity transmission and distribution network. For power only plants, it assumed that all the electricity they generated is transported to consumers via the electricity transmission and distribution network. Hence, an allowance for transmission and distribution losses has to be taken into account. A general estimate of 5.7% total losses has been adopted based on the latest published figures for Scotland (Ref. 8).

One final point for the calculations is that it was necessary to apply a means of dividing GHG emissions (and primary energy consumption) between the heat and electricity output of CHP plants. This is normally achieved by weighting the “value” of the heat output relative to the “value” of the electricity output. The approach adopted in the guidelines for the UK Emissions Trading Scheme (ETS) is to give a weighting of 2 times to 1 MWh of electricity relative to 1 MWh of heat (Ref. 9). However, for simplicity, a weighting has not been applied in CHP calculations that provide the initial results presented here[1]. There are broader issues involved in the application of any weighting and its extension to comparing results for delivered heat with those for electricity. For such reasons, the application of weighting is explored in detail in Section 4 which addresses different approaches to the comparison of delivered heat and electricity.

2.3 Biomass energy chains

In total, 21 biomass energy chains were examined in this report. Summaries of these biomass energy chains are illustrated in Figures 1 to 21. The codes documented in these particular Figures refer to the relevant worksheets in the biomass chain worksheet (see Section 2.4). With the use of roundwood and forest residues, represented by Figures 1 to 11, it has been assumed that transportation by road will take place on forest roads and, possibly, on public roads. Transportation to end users, in Figures 1 to 21, can either be undertaken by road (on public roads), rail or coastal shipping. Additionally, options are provided for up to three different consecutive modes of transport to the end user.

Figure 1 Biomass Energy Chain for Individual Domestic Heating by Combustion of Roundwood Logs (DRWL)

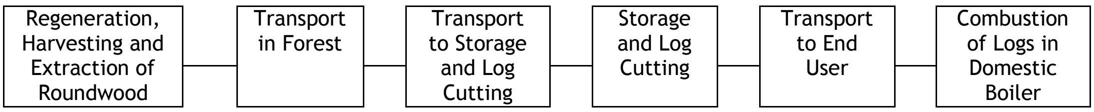
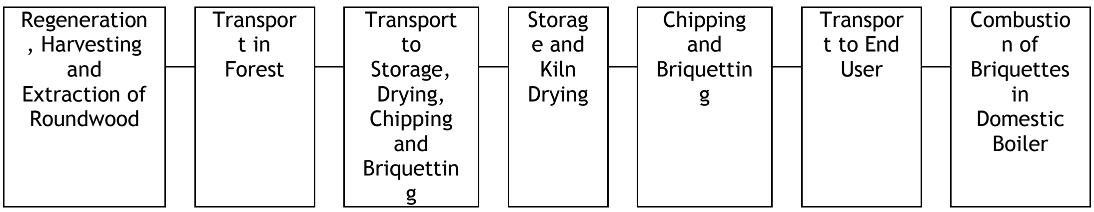


Figure 2 Biomass Energy Chain for Individual Domestic Heating by Combustion of Wood Briquettes from Roundwood (DRWB)



[1] The consequence of this is that 1MWh of electricity is equated to 1 MWh or delivered heat, thereby meaning that initial results compared, directly, in terms of “per MWh”.

Figure 3 Biomass Energy Chain for Individual Domestic Heating by Combustion of Wood Pellets from Roundwood (DRWP)

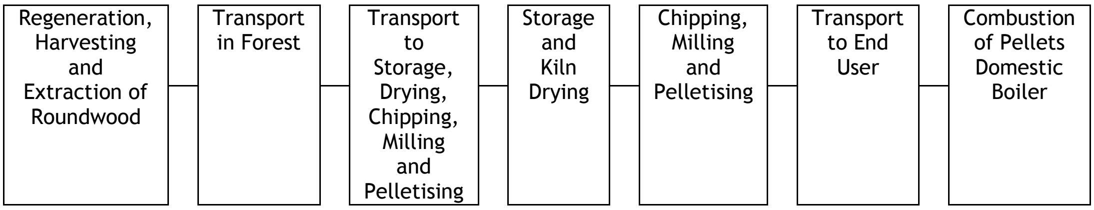


Figure 4 Biomass Energy Chain for Commercial or Industrial Heating by Combustion of Wood Chips from Roundwood (IRWC)

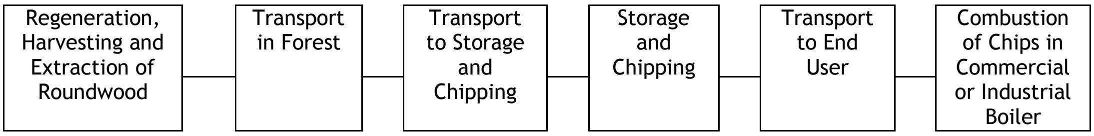


Figure 5 Biomass Energy Chain for Commercial or Industrial Combined Heat and Power by Combustion of Wood Chips from Roundwood (CRWC)

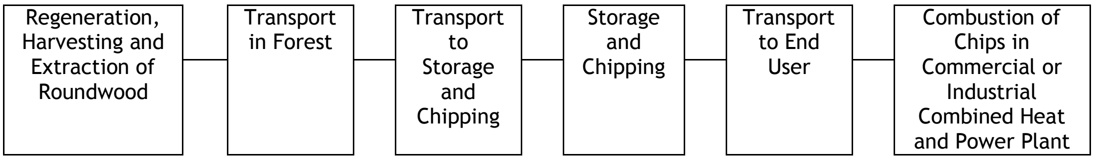


Figure 6 Biomass Energy Chain for Power Only Generation from Combustion of Roundwood with Chipping/Milling of Roundwood at Power Plant (PRWC)

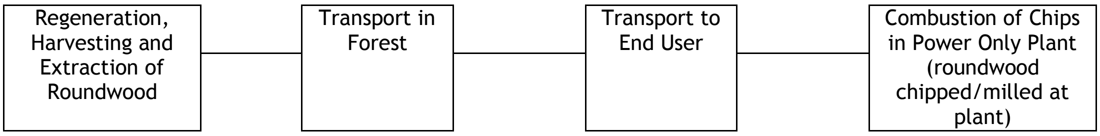


Figure 7 Biomass Energy Chain for Individual Domestic Heating by Combustion of Wood Pellets from Forest Residue (DFRP)

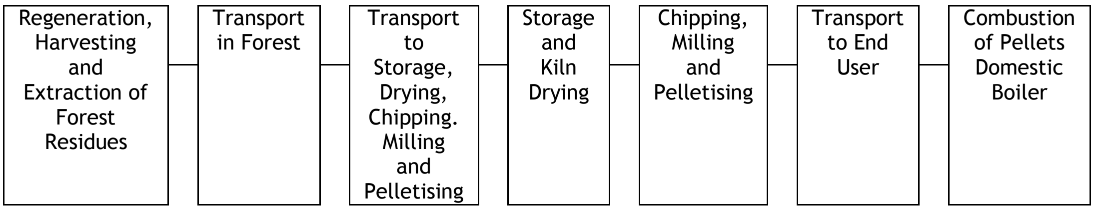


Figure 8 Biomass Energy Chain for Commercial or Industrial Heating by Combustion of Wood Chips from Forest Residue (IFRC)

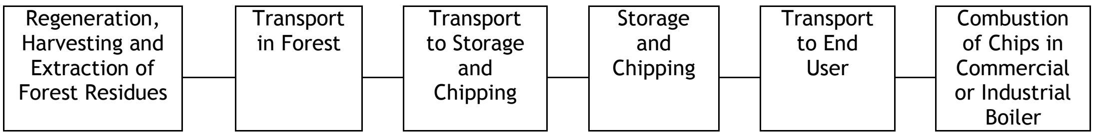


Figure 9 Biomass Energy Chain for Commercial or Industrial Combined Heat and Power by Combustion of Wood Chips from Forest Residue (CFRC)

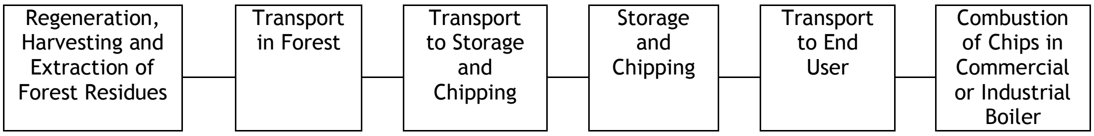


Figure 10 Biomass Energy Chain for Power Only Generation by Combustion of Wood Chips from Forest Residue with Chipping/Milling of Bales at Power Plant (PFRC)

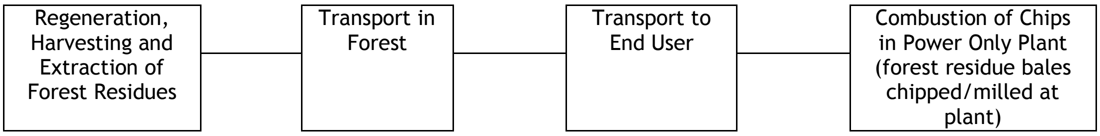


Figure 11 Biomass Energy Chain for Power Only Generation by Combustion of Wood Pellets from Forest Residues (PFRP)

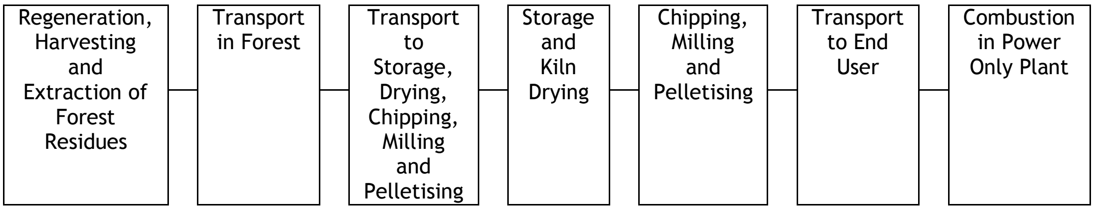


Figure 12 Biomass Energy Chain for Individual Domestic Heating by Combustion of Wood Briquettes from Clean Waste Wood (DCWB)

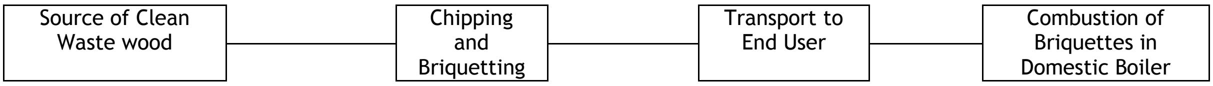


Figure 13 Biomass Energy Chain for Individual Domestic Heating by Combustion of Wood Pellets from Clean Waste Wood (DCWP)

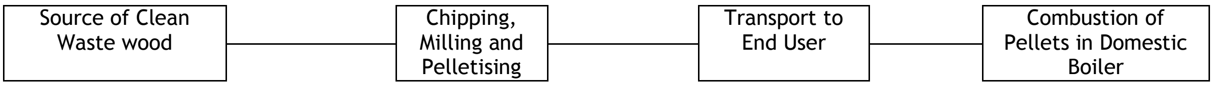


Figure 14 Biomass Energy Chain for Commercial or Industrial Heating by Combustion of Wood Chips from Clean Waste Wood (ICWC)

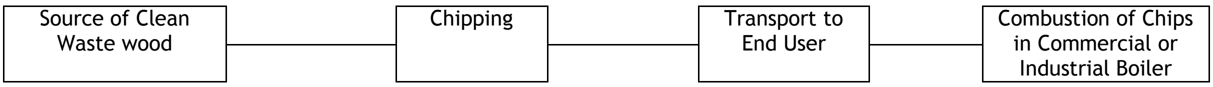


Figure 15 Biomass Energy Chain for Commercial or Industrial Combined Heat and Power Generation by Combustion of Wood Chips from Clean Waste Wood (CCWC)

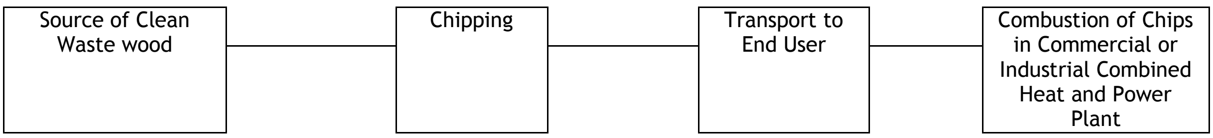


Figure 16 <u>Biomass Energy Chain for Power Only Generation by Combustion of Wood Chips from Clean Waste Wood (PCWC)</u>

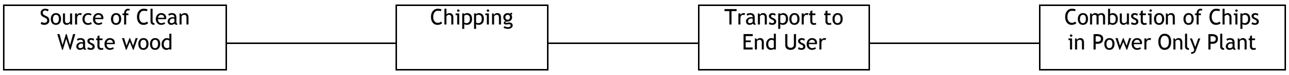


Figure 17 <u>Biomass Energy Chain for Power Only Generation by Combustion of Wood Pellets from Clean Waste Wood (PCWP)</u>

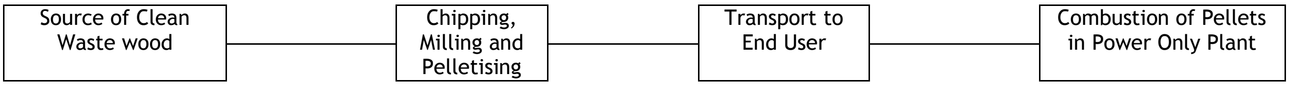


Figure 18 <u>Biomass Energy Chain for Commercial or Industrial Heating by Combustion of Wood Chips from Unclean Waste Wood (IUWC)</u>

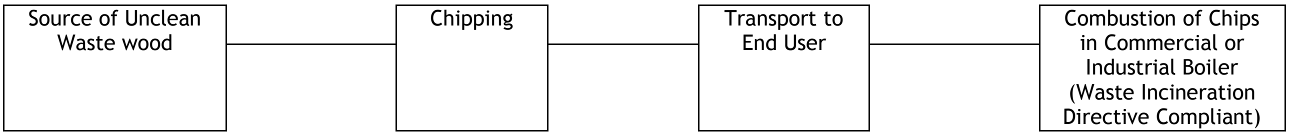


Figure 19 <u>Biomass Energy Chain for Commercial or Industrial Combined Heat and Power Generation by Combustion of Wood Chips from Unclean Waste Wood (CUWC)</u>

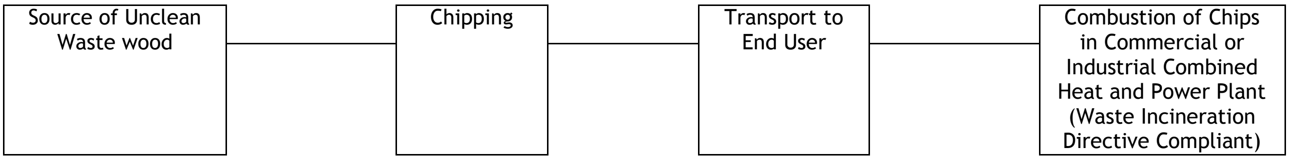


Figure 20 <u>Biomass Energy Chain for Power Only Generation by Combustion of Wood Chips from Unclean Waste Wood (PUWC)</u>

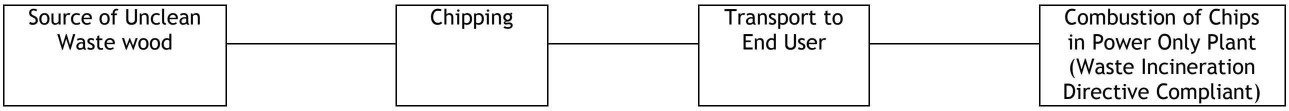
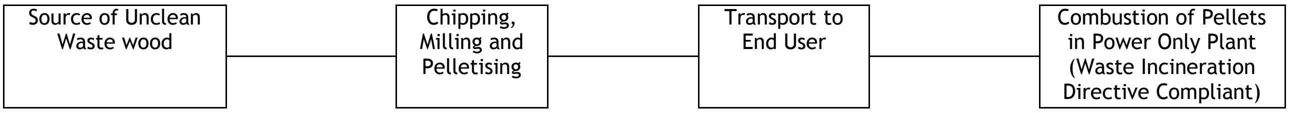


Figure 21 <u>Biomass Energy Chain for Power Only Generation by Combustion of Wood Pellets from Unclean Waste Wood (PUWP)</u>



2.4 Workbook development

A simplified MS Excel workbook (current version; SG RO Biomass Chains 12 NM.xls) was developed for this study based on previous work in connection with the use of wood to generate heat and/or electricity. This workbook contains individual worksheets that represent each of the biomass energy chains selected for evaluation. They are mainly based on information available from the relevant $BEAT_2$ workbooks covering kiln drying, chipping, milling, pelletising, and the operation of heating boilers, CHP plants and power only plants, in particular, the consumption of start-up fuel and GHG emissions[2], specifically CH_4 and N_2O, from wood combustion (Ref. 1).

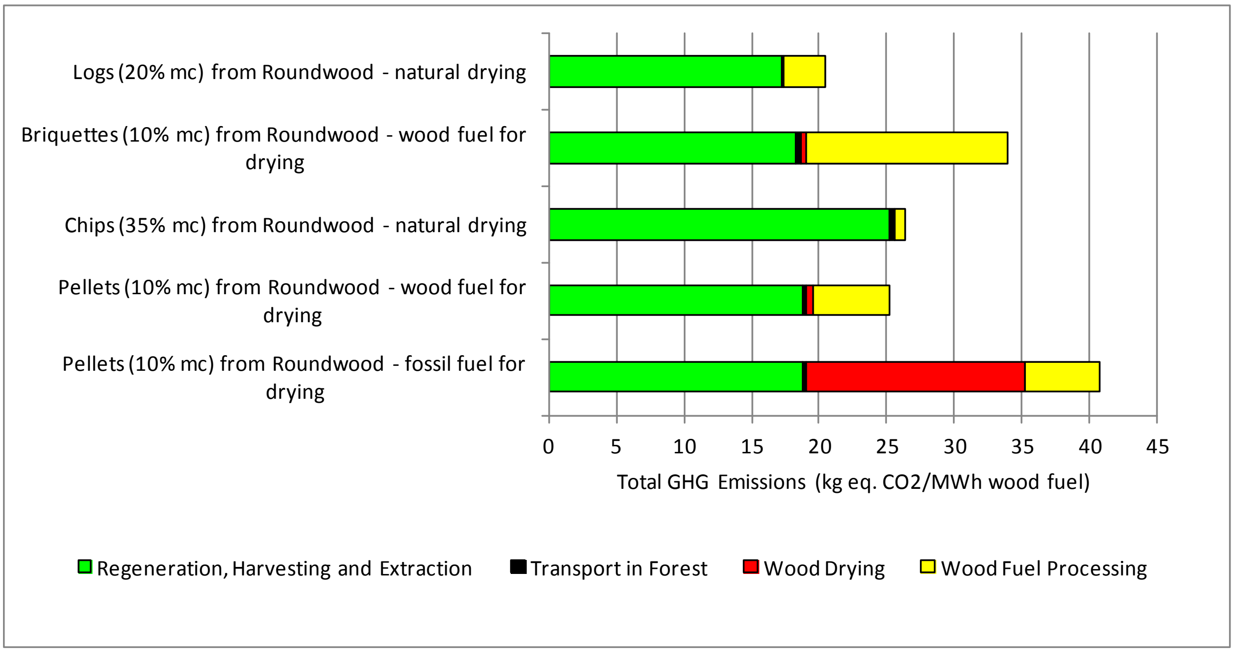
One important modification to the kiln drying data is that it has been assumed that the fuel used will be the wood itself rather than fossil fuels such as fuel oil. Currently, calculations in $BEAT_2$ workbooks are based the assumption that fossil fuels are used for wood drying. However, biomass drying is becoming increasingly common. The importance of this modification can be appreciated by considering Figure 22 which illustrates the estimated total GHG emissions of producing different types of wood fuel incorporating biomass-fired and fossil fuel-fired drying. Apart for the effects of different means of wood drying, Figure 22 indicates that estimated total GHG emissions are influenced by the processing of different types of wood fuel and final moisture content (mc) which determines the subsequent net calorific value of the wood fuel. This affects the results in Figure 22 because these are measured in units of heat, measured in MWh, available from the wood fuel. This influences the relative contributions to total GHG emissions for each wood fuel, particularly those from regeneration, harvesting and extraction. For example, wood fuels derived in a specific manner with higher moisture contents have lower net calorific values and, hence, higher total GHG emissions per MWh.

Returning to the development of the simplified workbook, information on forest regeneration, harvesting and extraction was obtained from more recent work on including the characteristics and management of UK forestry into $BEAT_2$ (Ref. 3). Data on the transport of roundwood and forest residues on forest and public roads was taken from work conducted for the Timber Transport Forum via the Confederation of Forest Industries (UK) Ltd (Ref. 4), supplemented with data on smaller road vehicles for local deliveries of wood fuels (Ref. 11), and rail and coastal shipping transportation (Refs. 12 and 13). New data from primary sources were added on log cutting and briquetting.

For simplification, the workbook does not contain the normal level of transparency applied in previous work. However, all essential information is referenced to original workbooks that contain the customary degree of transparency. This ensures that the necessary audit trail is provided. Additionally, the workbooks do not contain the full functionality of more detailed workbooks that have been incorporated into software tools such as $BEAT_2$. In particular, the moisture content of the wood at any given stage in a biomass energy chain is fixed at typical values. However, the required level of functionality for the purposes of this study has been introduced into the simplified workbook, especially the ability to vary transport distances and the design specifications of end use plants, including net thermal efficiency, and the heat-to-power ratio of CHP plants as well as the weighting value for electricity relative to heat.

[2] CO_2 emissions from combustion are excluded as these are derived from biogenic sources; that is, the wood itself.

Figure 22 Variations in Total Greenhouse Gas Emissions for Producing Different Types of Wood Fuel and the Effect of Different Means of Drying



3 Results

3.1 Basis for results

Two types of results were generated using the simplified workbook; typical results and idealised modelling results. Typical results were produced to reflect the likely full range of total GHG emissions (and primary energy inputs and, where relevant, biomass resources requirements) associated with the provision of heat and/or electricity from different sources of wood. As explained in Section 3.2, these results, which are given in terms of "per MWh" of heat or electricity, were derived by varying wood fuel transport distances and the thermal efficiencies of specific end use applications over realistic ranges that might be encountered in practice. Based on subsequent outcomes, the comparison of results for heat and CHP generation with power only generation was extended using idealised modelling. As shown in Section 3.3, this enables results for idealised power only plants to be examined in relation to those for transporting the same wood fuels over different distances for use in heat and CHP generation. This provides the basis for exploring the weighting of electricity relative to heat and aspects of CHP plant scale in Section 4.

3.2 Typical results

In order to generate typical results using the simplified workbook (SG RO Biomass Chains 12 NM.xls) developed for this report, a data search was conducted to obtain specifications for existing and proposed heating, CHP and power only plants fired by the types of wood represented in the selected biomass energy chains. Recorded ranges for specified parameters, including of plant scale, as indicated by the net output power rating, net thermal efficiency, and, for CHP plants, the heat-to-power ratio, are reported, along with other related information, in Appendix A. Typical results were generated with the workbook using the range of specified parameters and assumed ranges for transport distances, in terms of round trips, for appropriate modes of transport at different stages in the relevant biomass energy chains. It was assumed that typical round trip transport distances for roundwood and forest residues would be 16 km on forest roads and 66 km on public roads (Ref. 4). For delivery of subsequent wood fuels to end users, it was assumed that round trip distances would range between 80 km for relatively local delivery and 600 km for delivery anywhere in Scotland. These results, in the form of estimated total primary energy [fossil fuel] inputs, total primary energy [biomass] requirements and total GHG emissions, are summarised in Appendix B.

Before considering the relative differences in the ranges covered by these typical results, it is important to emphasise that the total GHG emissions (and total primary [fossil fuel] energy inputs) associated with all the biomass energy chains addressed here are considerably lower than those of current conventional means of providing heat and electricity from fossil fuels. This is demonstrated in Table 1 for estimated total GHG emissions with estimated total primary energy [fossil fuel] inputs recorded in Appendix C. In general, it can be seen that total GHG emissions (and total primary energy [fossil fuel] inputs) for wood-fired options are approximately an order of magnitude lower than those for their fossil fuel-fired alternatives. It should be noted that typical values of thermal efficiency have been assumed for fossil fuel –fired domestic heating, commercial and industrial heat only plant and power only plants. To assist comparison, the same design specifications have been adopted for all CHP plants; ranging from a "best" combination of an overall energy efficiency of 86.5% with a heat-to-power ratio of 4.4 to a "worst" combination of an overall energy efficiency of 54.0% with a heat-to-power ratio of 1.2 (see Appendix A). In Table 1 and Appendix C, a weighting of 2 was adopted for the value of electricity relative to that of heat in all results for CHP plants.

Table 1 Comparison of Total Greenhouse Gas Emissions for Providing Heat and/or Electricity from Fossil Fuels and Wood

Option	Total Greenhouse Gas Emissions ($kg\ eq.\ CO_2/MWh$)
Domestic Heating:	
- coal-fired	492 - 689
- oil-fired	330 - 440
- natural gas-fired	229 - 295
- wood-fired (roundwood logs)	39 - 43
- wood-fired (roundwood briquettes)	54 - 60
- wood-fired (roundwood pellets)	40 - 47
- wood-fired (forest residue pellets)	22 - 29
- wood-fired (clean waste wood briquettes)	19 - 20
Commercial or Industrial Heating from Heat Only	
Plant:	431 - 492
- coal-fired	293 - 377
- oil-fired	229 - 295
- natural gas-fired	43 - 60
- wood-fired (roundwood chips)	36 - 36
- wood-fired (forest residue chips)	11 - 20
- wood-fired (clean waste wood chips)	29 - 39
- wood-fired (unclean waste wood chips)	
Commercial or Industrial Heat from CHP Plant:	
- coal-fired	335 - 439
- oil-fired	256 - 335
- natural gas-fired	201 - 263
- wood-fired (roundwood chips)	30 - 59
- wood-fired (forest residue chips)	9 - 31
- wood-fired (clean waste wood chips)	2 - 13
- wood-fired (unclean waste wood chips)	18 - 35
Commercial or Industrial Electricity from CHP Plant:	
- coal-fired	673 - 878
- oil-fired	515 - 673
- natural gas-fired	403 - 526
- wood-fired (roundwood chips)	60 - 117
- wood-fired (forest residue chips)	18 - 62
- wood-fired (clean waste wood chips)	4 - 27
- wood-fired (unclean waste wood chips)	37 - 70
Electricity from Power Only Plant:	
- coal-fired	985 - 1,379
- oil-fired	754 - 1,055
- natural gas-fired	459 - 688
- wood-fired (roundwood)	84 - 127
- wood-fired (forest residue chips)	34 - 78
- wood-fired (forest residue pellets)	53 - 77
- wood fired (clean waste wood chips)	24 - 48
- wood-fired (clean waste wood pellets)	39 - 51
- wood-fired (unclean waste wood chips)	60 - 85
- wood-fired (unclean waste wood chips)	76 - 88

The ranges of typical results, in terms of total GHG emissions, are illustrated in Figures 23 to 26. Similar results, for total primary energy [fossil fuel] inputs and total primary energy [biomass] requirements are presented in Appendices D and E, respectively. All these variations are contained in a workbook (SG RO Typical Results 09.xls). It should be noted that different scales on the axes in Figures 23 to 26 were selected, as relevant, for clarity in comparison of results. In order to encompass the possible range of scales for biomass energy end use applications, the axes for output ratings, measured in MW, are logarithmic. It should also be noted that these illustrations compare 1 MWh of heat and 1 MWh on an equal basis, with no adjustment for the relative values that might be placed on these different forms of delivered energy. This consideration is examined in more detail later (see Section 4). To assist interpretation of Figures 23 to 26, the areas covered by the ranges of scales and estimated total GHG emissions are bounded by boxes with dashed lines for heat and CHP plants and by boxes with solid lines for power only plants.

Such typical results can be applied to address the basic question; "do wood-fired heat and CHP plants have lower total GHG emissions than those of power only plants that use the same source of wood fuel?" Figures 23 to 26 demonstrate that, in all instances, total GHG emissions for roundwood, forest residues and clean and unclean waste wood used to generate heat from heat only and CHP plants are lower than those of power only plants. This is principally due to the low thermal energy efficiencies of the power only plants relative to heat only and CHP plants, and partly due to the direct comparison of 1 MWh of electricity with 1 MWh of heat. This is the case regardless of whether the power only plants use roundwood which is chipped/milled on site or wood pellets derived from roundwood, forest residues, or clean or unclean waste wood.

However, there is some noticeable overlap with results for electricity (but not heat) generated from all wood-fired CHP plants and power only plants. This requires further articulation of the question posed earlier which is now "what factors influencing wood-fired CHP and power only plants determine whether the total GHG emissions of their generated electricity are equal or different?" In general, the scales of the CHP plants are less than those for the power only plants. In particular, the output electrical power ratings of the CHP plants range from 0.4 to 50 MW, whilst those for the power only plants range from 5 MW to 350 MW. Hence, the scale overlap is for plants with output power ratings of between 5 MW and 50 MW. The overlap in terms of total GHG emissions arises from the upper range of the results for CHP plants and the lower range of the results for power only plants. The upper range of results for CHP plants are characterised by the "worst" combination of overall thermal energy efficiency (reducing towards 54%) and heat-to-power ratio (declining towards1.2), along with longer wood fuel round trip transport distances (increasing towards 600 km). The lower range of results for power only plants reflect the relatively shorter wood fuel round trip transport distances (decreasing towards 80 km). Hence, the overlap occurs when electricity from relatively large scale, "poor quality" CHP plants which source wood fuel over relatively long distances is compared with electricity from relatively small scale power only plants that obtain wood fuel over relatively short distances. The implications of these considerations are explored further in Section 5 which also addresses the issue of CHP plant "quality".

Figure 23 Range of Typical Results for Total Greenhouse Gas Emissions for the Use of Roundwood

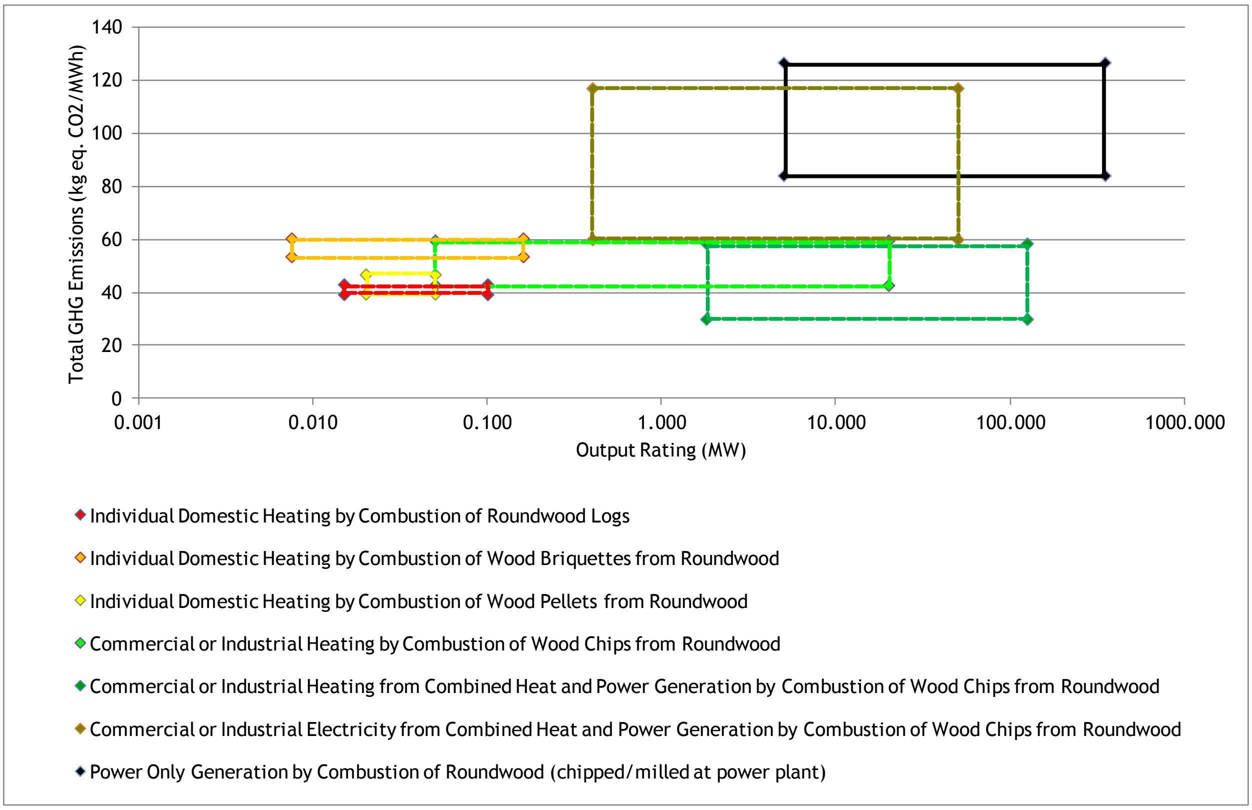


Figure 24 Range of Typical Results for Total Greenhouse Gas Emissions for the Use of Forest Residues

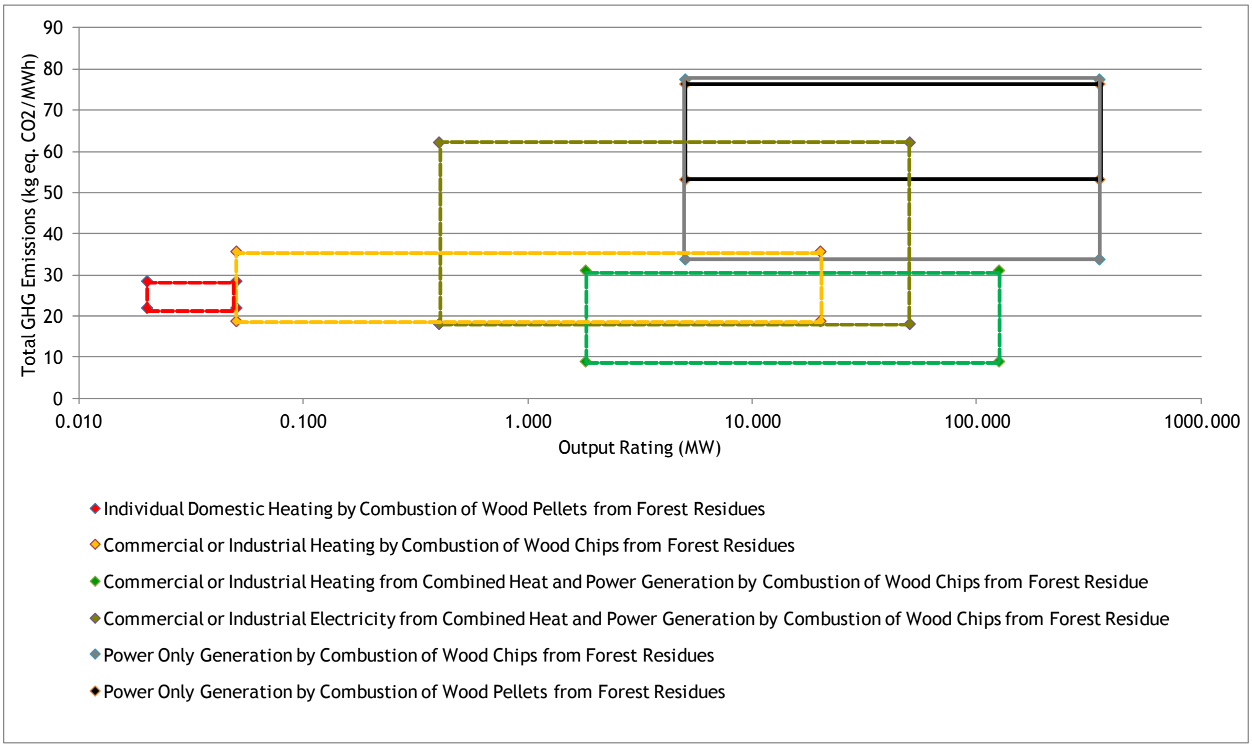


Figure 25 Range of Typical Results for Total Greenhouse Gas Emissions for the Use of Clean Waste Wood

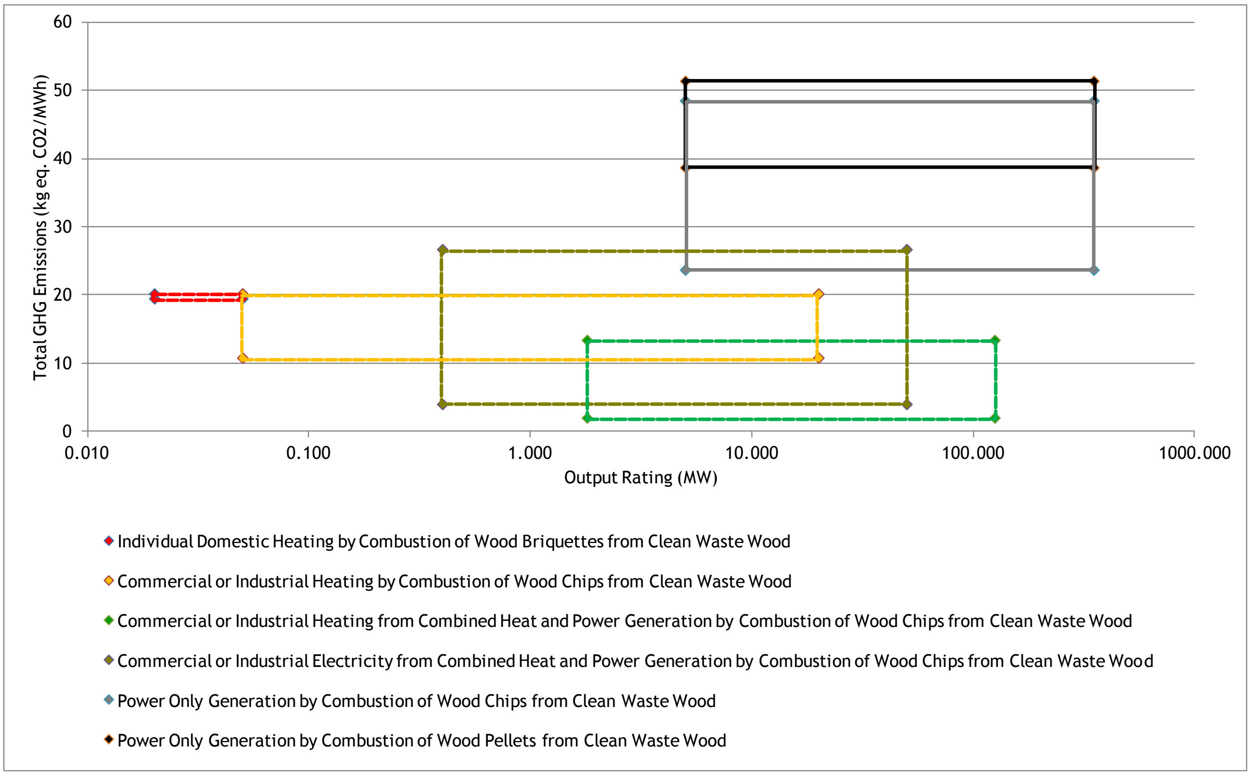
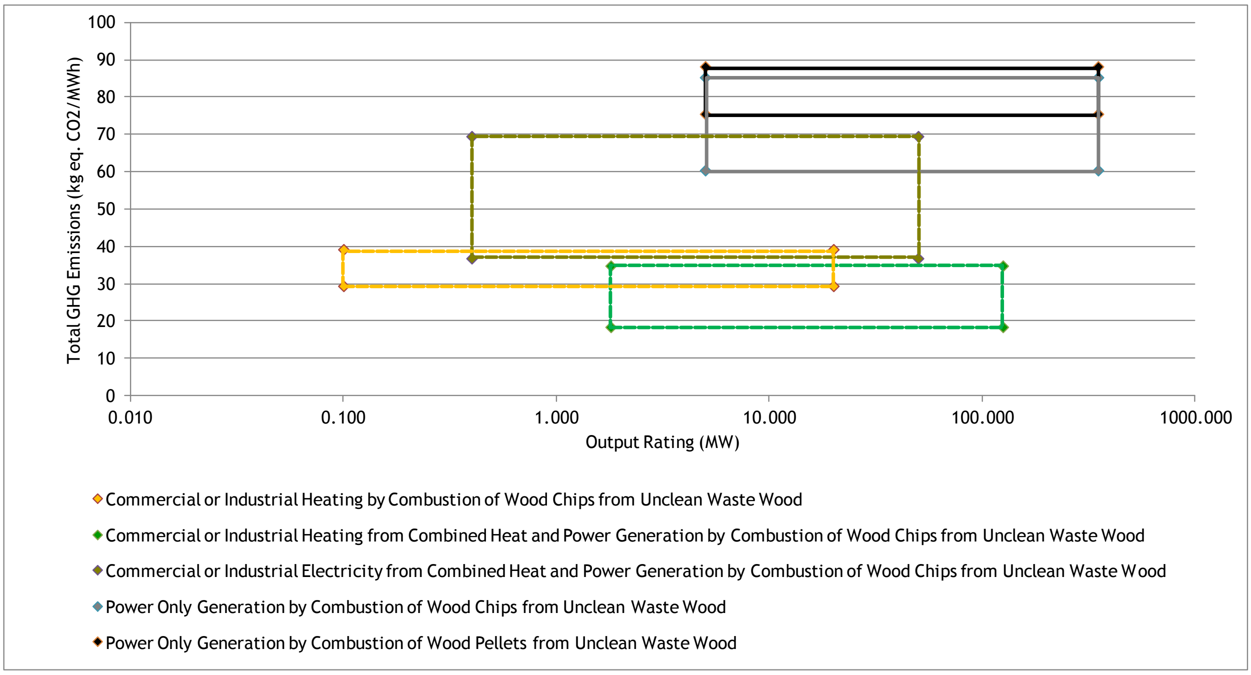


Figure 26 Range of Typical Results for Total Greenhouse Gas Emissions for the Use of Unclean Waste Wood



3.3 Modelling results

3.3.1 *Introduction*

Modelling was undertaken with the simplified workbook (SG RO Biomass Chains 12 NM.xls) to investigate and qualify further the typical results presented in Section 3.2. This established that, on the basis of the direct comparison of 1 MWh of electricity with 1 MWh of heat, using wood fuel for heating and most CHP applications results in lower total GHG emissions than wood fired power only plants. However, it is necessary to explore the conditions under which these particular findings persist. It is apparent that one of the most important factors which influence the total GHG emissions associated with heating and CHP applications is the transport distance involved in delivering wood fuel to end users. This distance can be referred to as the radius of supply which defines the complete area within which wood fuel is delivered to end users. In logistical terms, this radius is half the round trip distance which is the total distance travelled by a delivery vehicle, usually assuming a laden outward journey and an empty return journey. To assist with the interpretation of such distances, geographically generalised specifications of typical radii of supply relevant to Scotland are indicated in Table 2. These generalised distances, which take approximate adjustments for the likely effects of actual road networks into account, are proposed as indications of local, regional and national wood fuel supply markets[3].

On this basis, idealised models for the logistics of wood fuel delivery can be formulated to enable total GHG emissions associated with heating and CHP applications to be compared with those of power only applications. In particular, relevant modelling can be used to determine those circumstances under which wood-fired heat only and CHP plants have total.

Table 2 Generalised Specifications of Radii of Supply

Specification	Radius of Supply		Round Trip Distance	
	km	miles	km	Miles
Local	50	~30	100	~60
Regional	200	~125	400	~250
National (Scotland)	500	~300	1,000	~600

GHG emissions equal to those of power only plants that use the same sources of wood fuel. When this occurs, the radius of supply for delivering wood fuel for heating and CHP applications has reached a maximum. Beyond this maximum radius of supply, the total GHG emissions associated with heating and CHP applications are higher than those for power only generation. Maximum radii of supply for forest and waste wood fuel are evaluated using idealised models in Sections 3.3.1 and 3.3.2. It should be noted that, in addition to derivation of typical and idealised modelling results, the simplified workbook can, of course, be used to estimate total GHG emissions associated with proposed and actual wood-fired plants.

3.3.2 *Idealised Modelling for Forest Wood Fuel*

For wood fuels derived from forests, idealised modelling was based on the simplest (and best possible) case for a power only plant which was to locate it in the middle of a forest with a circular collection area for roundwood or forest residues. This minimises

[3] It should be noted that whilst these specifications of supply radii are notional they are intended to encompass the potential to deliver wood fuel across Scotland (national), within regions of Scotland (regional) and within areas smaller than regions (local).

transport distances and obviates the need to process the biomass feed, with roundwood and forest residue being chipped/milled at the power only plant, thereby avoiding the need for chipping elsewhere or for pelletisation. This idealised case, which amounts to "exporting wood energy by wire" from the forest, is represented in Figure 27. It should be appreciated that, in most practical instances, wood would probably be collected from a number of individual forests or areas of a forest, from where it would be transported to a specific power only plant. This would increase transportation and related GHG emissions relative to this idealised case.

For all other uses of wood, it is assumed that roundwood or forest residues are collected at the edge of a semi-circular area of forest where it can be processed (into logs, briquettes, chips or pellets) and transported to end users (one or many collectively). This situation is represented in Figure 28 which is a simplification of the likely circumstances in which the wood fuel processing point is, effectively, at the centre of circular distribution area. Whilst this is an idealisation over practical situations in which additional transportation is involved between the forest and the processing point, it is probably closer to realistic arrangements than those of the idealised power only plant. Based on these assumptions which, in effect, favour power only applications, it was considered that the findings of this idealised modelling should be soundly robust.

Figure 27 Idealised Model for a Power Only Plant

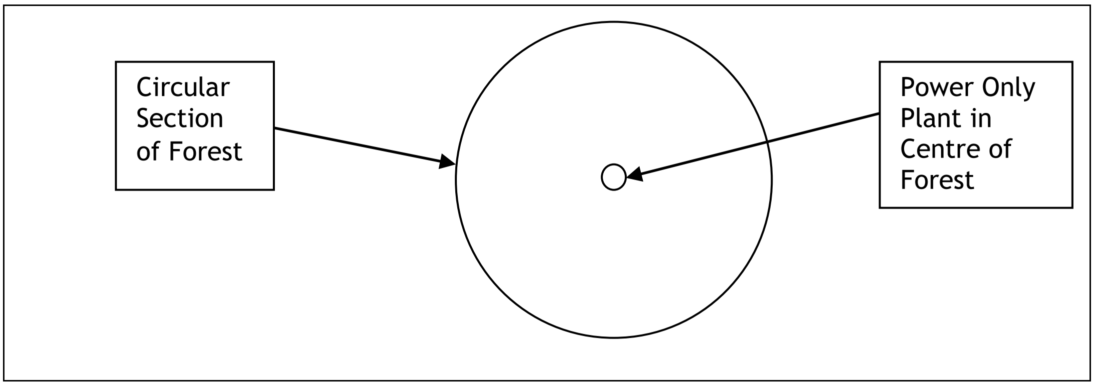
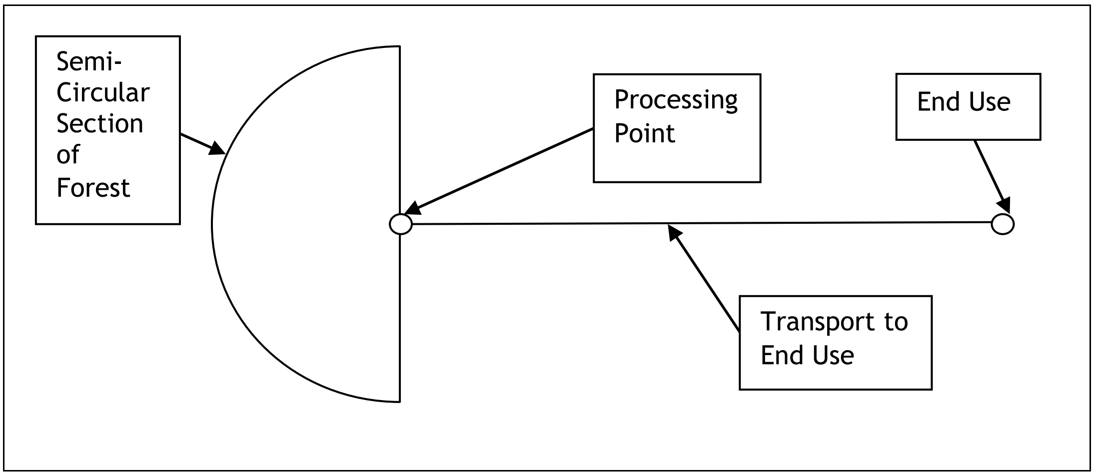


Figure 28 Idealised Model for Domestic, Commercial and Industrial Heating, and Commercial and Industrial Combined Heat and Power Plants



It can be seen from the modelling concepts illustrated in Figures 27 and 28 that the main influences on total GHG emissions associated with the use of wood for energy generation are transport distances. Indeed, a crucial feature of this modelling is that the transport distance for wood collection in the forest is linked to the scale of the end use based on the assumption that the average annualised yield of wood, in odt/ha.a, is evenly spread throughout the idealised forest. In effect, as the scale of a plant increases the round trip distance for collecting wood products from the forest increases. As a simplifying assumption to assist modelling, lorries can reach the wood products wherever they are available by the most direct route to and from the centralised power only plant or point for processing wood fuel for heat only and CHP plants. Mathematically, the average round trip distance for collecting wood in the circular forest for the centralised power only plant can be determined as follows:

$$d = (M/2\pi P)^{1/2} \qquad \text{(Equation 1)}$$

where, d = average round trip transport distance in the forest (km)

M = annual demand for forest products (odt/a)

P = average annualised yield of forest products (odt/ha.a)

Similarly, the average round trip distance for collecting wood in the semi-circular forest for a central heating and CHP wood fuel processing plant can be determined as follows:

$$d = (M/\pi P)^{1/2} \qquad \text{(Equation 2)}$$

where, d = average round trip transport distance in the forest (km)

M = annual demand for forest products (odt/a)

P = average annualised yield of forest products (odt/ha.a)

The annual demand for forest products of a wood-fired plant can be determined by its size or scale, represented by its installed output rating in MW, and its load factor, specified as its average annual energy output rating per installed output rating expressed as a percentage. In this modelling exercise, it was assumed that heat only, CHP and power only plants have typical load factors of 70%. The load factor is not the most critical consideration but it does affect the wood product collection transport distance in the forest and it influences the calculation of wood fuel delivery distance to dispersed domestic heating users (see below). Average values of thermal efficiencies and, in the case of CHP plants, heat-to-power ratio used in the modelling were derived from the ranges recorded in Appendix B. These values are summarised in Table 3.

Table 3 Average Values of Plant Design Specifications Used in Idealised Modelling for Wood Fuel from Roundwood and Forest Residues

Type of Plant	Thermal Efficiency (%)	Heat-to-Power Ratio
Domestic Heating with Wood Logs	85.5	not applicable
Domestic Heating with Wood Briquettes	86.5	not applicable
Domestic Heating with Wood Pellets	92.0	not applicable
Commercial and Industrial Heating with Wood Chips	90.0	not applicable
Commercial and Industrial Heating with Wood Chips Using Combined Heat and Power	70.0	2.8
Electricity Generation with Roundwood or Forest Residues	30.0	not applicable

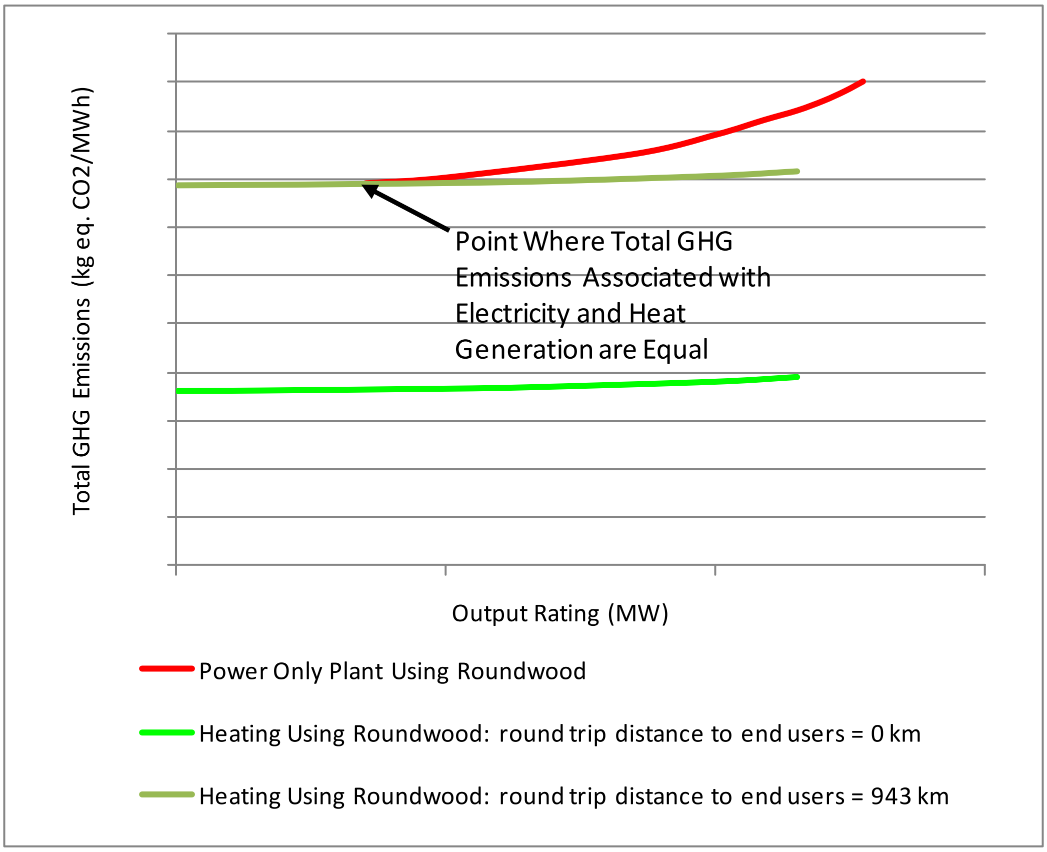
As indicated above, it was necessary to adopt simplifying assumptions for the supply of wood fuel to dispersed domestic users. In order to compare results on comparable scales, it was necessary to consider the collective rating, in MW, and annual wood fuel demand, in t/a, of a group of domestic heating appliances rather than their individual ratings and demands. This involved assuming that the average annual useful heat demand of an individual domestic user was 15,000 kWh/a. Again, this is not the most critical assumption in this idealised modelling exercise.

These assumptions and the idealised modelling enable variations in total GHG emissions, in kg eq. CO_2/MWh, for different types of energy end use using the same forest product (roundwood or forest residue) to be plotted against the scale of the end use application, in MW. The form of these results is provided in the example shown in Figure 29. This illustrates the variations in total GHG emissions with scale for a given wood fuel used for both heating and power only generation. In particular, the delivery distance for heating wood fuel can be increased until the estimated total GHG emissions of this application overlap those of power only generation. As demonstrated in Figure 29, this point of overlap has been chosen at the lowest total GHG emissions for the power only plant. This occurs at the lowest part of the scale range which is 5 MW. Overlaps could be considered at higher scales of power only plants. However, by choosing the lowest part of the power only plant scale range, robust conclusions can be drawn from this idealised modelling.

Specifically, such modelling can be used to determine the *upper* limit to the delivery distance for wood fuel in heating and CHP applications so that total GHG emissions per MWh do not exceed those of *any* power only plant that uses the same source of wood fuel. In effect, such analysis explores the trade-off, in terms of total GHG emissions, between the low thermal efficiency of power only plants (30%) relative to those of heating and CHP applications (54% to 94%), and the maximum delivery distances for wood fuel used in heat and CHP plants. This enables the issue addressed here to be re-phrased as; "what is the maximum distance for delivering wood fuel to heat and CHP plants at which their total GHG emissions equal those of power only plants using the same source of wood?" The corollary of this is that it is possible to determine conditions, in terms of delivery distances, for which wood-fired heat and CHP plants always have total GHG emissions lower than those of power only plants.

Subsequent variations, comparing the total GHG emissions associated with using roundwood and forest residues in heat and CHP plants, with those of power only plants were produced by idealised modelling and assembled in a workbook (SG RO Idealised Modelling 03.xls). This workbook, which also contains the results for total primary energy (fossil fuel) inputs, was used to generate graphical outputs that are reproduced in Appendix F. These variations show that that total GHG emissions for the power only plants vary relatively more strongly with scale than those for heat only and CHP plants. Furthermore, wood fuel for heat and CHP plants has to be transported considerable distances to end users for subsequent total GHG emissions to equal the lowest values for power only plants (at 5 MW electrical output rating representing the lowest end of the scale for such plants); 78.9 kg eq. CO_2/MWh for a roundwood-fired power only plant and 32.5 kg eq. CO_2/MWh for a forest residue-fired power only plant.

Figure 29 Example of Variation of Total Greenhouse Gas Emissions with Scale from an Idealised Model: Heating and Power Only Generation



Based on the variations presented in Appendix F, it is possible to estimate maximum delivery distances for wood fuel used in heat and CHP applications. These delivery distances, expressed as maximum round trip distances and their respective maximum radii of supply, are summarised in Table 4. This indicates that roundwood pellets for domestic heating and roundwood chips for commercial and industrial heating and CHP generation could be supplied nationally across Scotland before their total GHG emissions exceed those of an idealised power only plant[4]. All other forest wood fuel applications could be supplied on a regionally within Scotland. This includes using roundwood logs and briquettes, and forest residue pellets for domestic heating and forest residue chips for commercial and industrial heating and CHP generation. It should be recalled that these estimates of maximum radii of supply for particular heating and CHP wood fuels are based on comparison with an idealised power only plant which uses the same source of wood from the forest; heating and CHP wood fuel from roundwood or forest residues is compared with using roundwood or forest residues, respectively, in a power only plant. Additionally, it must be reiterated that these findings were derived assuming a direct comparison between 1 MWh of heat with 1 MWh of electricity.

Table 4 Wood Fuel Delivery Distances for Heat Only and Combined Heat and Power Plants Using Roundwood and Forest Residues; Idealised Modelling Equating Total Greenhouse Gas Emissions to a 5 MW Power Only Plant

Wood Fuel and End Use	Maximum Round Trip Distance (km)	Maximum Radius of Supply (km)
Roundwood Logs for Domestic Heating	943	471.5
Roundwood Briquettes for Domestic Heating	670	335.0
Roundwood Pellets for Domestic Heating	3,575	1,787.5
Roundwood Chips for Commercial and Industrial Heating	1,225	612.5
Roundwood Chips for Commercial and Industrial Heating by a Combined Heat and Power Plant	1,450	725.0
Forest Residue Pellets for Domestic Heating	995	497.5
Forest Residue Chips for Commercial and Industrial Heating	453	226.5
Forest Residue Chips for Commercial and Industrial Heating by Combined Heat and Power Plant	755	377.5

3.3.3 *Idealised modelling for waste wood fuel*

Idealised modelling for energy generation from clean and unclean waste wood is simpler than that for wood fuels derived from forest products. This consists of locating power only plants at the point where waste wood becomes available. This means that no transportation is required to supply the wood fuel which is only chipped before combustion. As no wood fuel collection is involved, results for the power only plant do not vary with scale. An average value for the thermal efficiency of a clean or unclean waste wood-fired power only plant was taken to be 31% (see Appendix A). This resulted in total GHG emissions of 19.4 kg eq CO_2/MWh and 56.1 kg eq. CO_2/MWh for power only plants of any size using clean and unclean waste wood, respectively.

In contrast, it was assumed that fuels derived from waste wood would have to be transported to domestic users for heating and, in some cases, to commercial and industrial user for heating and for CHP generation. The average values of the thermal efficiency and, in the case of CHP generation, the heat-to-power ratio for these end use energy applications were based on the ranges recorded in Appendix A and these are summarised in Table 5. As with the power only plants, the results for the waste wood-

[4] Given the concentration and location of potential wood fuel demand in Scotland, this conclusion can be extended to cover the possible supply of wood fuel from forests in the North of England.

fired heating and CHP applications do not vary with plant scale in such idealised modelling. Instead, the total GHG emissions depend principally on the distance for delivering wood fuel to end users.

Table 5 Average Values of Plant Design Specifications Used in Idealised Modelling for Clean and Unclean Waste Wood

Type of Plant	Thermal Efficiency (%)	Heat-to-Power Ratio
Domestic Heating with Clean Waste Wood Briquettes	86.5	not applicable
Domestic Heating with Clean Waste Wood Pellets	92.0	not applicable
Commercial and Industrial Heating with Clean Waste Wood Chips	90.0	not applicable
Commercial and Industrial Heating with Clean Waste Wood Chips Using Combined Heat and Power	70.0	2.8
Commercial and Industrial Heating with Unclean Waste Wood Chips	89.5	not applicable
Commercial and Industrial Heating with Unclean Waste Wood Chips Using Combined Heat and Power	70.0	2.8
Electricity Generation with Clean Waste Wood Chips	31.0	not applicable
Electricity Generation with Unclean Waste Wood Chips	31.0	not applicable

Hence, using the simplified workbook (SG RO Biomass Chains 12 NM.xls), it is possible to determine the waste wood fuel delivery distances for heating and CHP generation that result in total GHG emissions equal to those of power only plants using clean and unclean waste wood. These delivery distances, expressed as maximum round trip distances and their respective maximum radii of supply, are summarised in Table 6. Unlike results for wood fuels from forests, these delivery distances imply restrictions for the use of certain waste wood fuels relative to the idealised power only plants. Results indicate that clean waste wood chips for commercial and industrial CHP generation, and unclean waste wood chips for commercial and industrial heating and CHP generation can be delivered nationally across Scotland without exceeding the total GHG emission for using the same sources of wood for power only generation. However, clean waste wood pellets for domestic heating and clean waste wood chips for commercial and industrial heating can only be supplied on regionally, and clean waste wood briquettes must be supplied very locally (<50 km) to avoid associated total GHG emissions exceeding those of a power only plant using clean waste wood. Once again, it has to be pointed out that these findings were derived assuming a direct comparison between 1 MWh of heat with 1 MWh of electricity. In general, the outcomes from the idealised modelling results are partly due to the relatively low estimates of total GHG emissions associated with all waste wood applications. This, in turn, is a consequence of the RED methodology which excludes GHG emissions from activities and processes prior to the generation of the waste wood.

Table 6 Wood Fuel Delivery Distances for Heat Only and Combined Heat and Power Plants Using Clean and Unclean Waste Wood; Idealised Modelling Equating Total Greenhouse Gas Emissions with Those of a Power Only Plant

Wood Fuel and End Use	Maximum Round Trip Distance (km)	Maximum Radius of Supply (km)
Clean Waste Wood Briquettes for Domestic Heating	38	19.0
Clean Waste Wood Pellets for Domestic Heating	710	355.0
Clean Waste Wood Chips for Commercial and Industrial Heating	555	277.5
Clean Waste Wood Chips for Commercial and Industrial Heating by a Combined Heat and Power Plant	1,005	502.5
Unclean Waste Wood Chips for Commercial and Industrial Heating	1,535	767.5
Unclean Waste Chips for Commercial and Industrial Heating by Combined Heat and Power Plant	1,965	982.5

4 Relative heat and electricity pricing

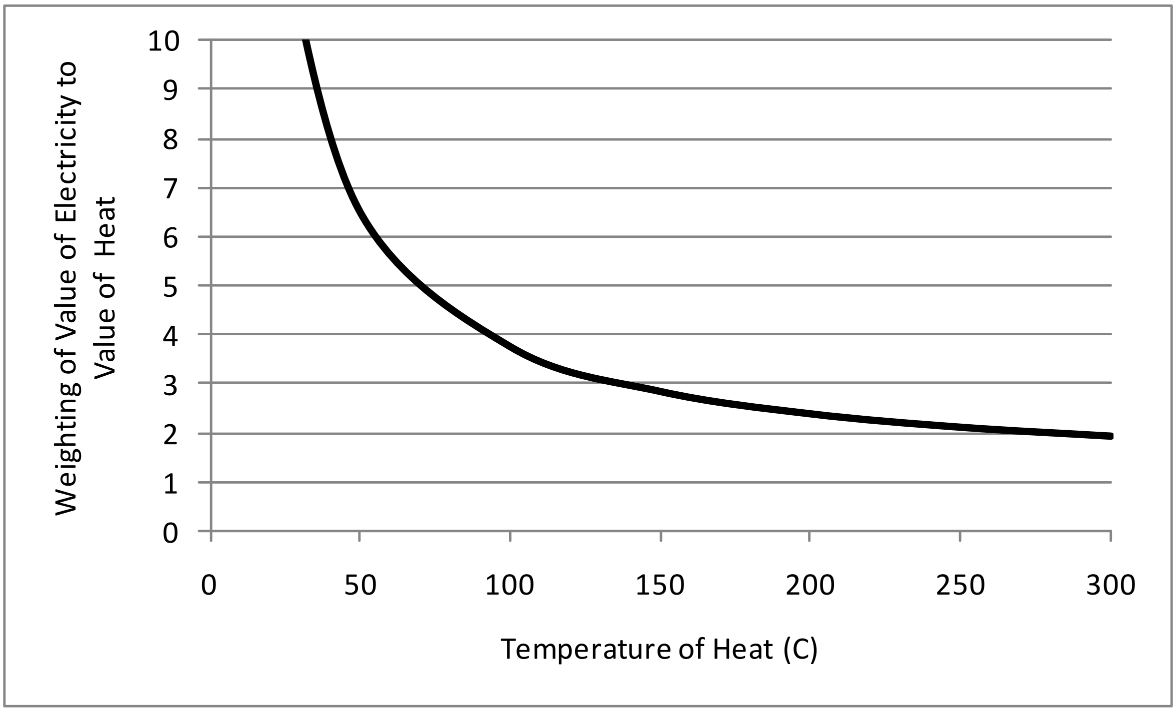
As frequently emphasised, the results and findings presented in Section 3 are based on the direct comparison of 1 MWh of heat with 1 MWh of electricity. In effect, this is equivalent to assuming that the price of delivered heat is equal to the price of delivered electricity. As such, this has implications for setting the level of any financial incentives that would prioritise the use of wood fuel in heating and CHP applications over its use in power only generation. This is because such incentives would alter the price of delivered heat relative to that of electricity. However, before these implications are examined further, it is helpful to explore how electricity is "valued" relative to heat in existing methods for assessing the total GHG emissions of CHP plants which produce both these forms of energy.

Electricity and heat are co-products generated by CHP plants and, as such, procedures are required to allocate GHG emissions between them. It is generally recognised that electricity is a more versatile and, potentially, more "valuable" form of energy than heat. However, it has to be appreciated that there is no universally accepted basis for comparing 1 MWh of electricity with 1 MWh of heat. The process of providing a basis for comparison is often referred to as "weighting". The approach adopted for in the guidelines for the UK Emissions Trading Scheme (ETS) is to give a weighting of 2.0 times to 1 MWh of electricity relative to 1 MWh of heat (Ref. 9). Whilst there appears to be no formal justification for this weighting, it has, on occasions, been supported by evidence on the relative economic value of electricity and heat.

British Standards Institution Publicly Available Specification (PAS) 2050 for GHG emission calculations of goods and services also addresses the allocation of total GHG emissions between electricity and heat from CHP plants (Ref. 10). This results, effectively, in specifying a weighting value of 2.5 for electricity relative to heat for boiler-based CHP plants of the type that would currently be used with wood fuels. However, no explicit justification is provided for this particular weighting.

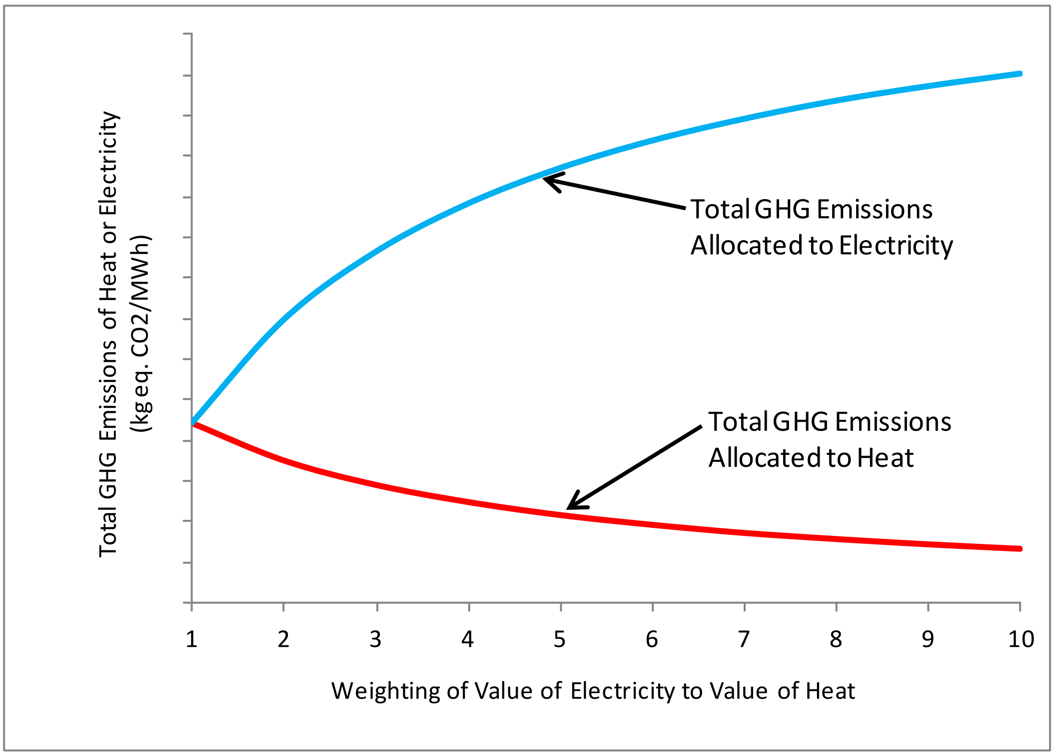
The report which provides the basis for extending the RED to biomass heat and/or electricity generation uses exergy, as determined by the Carnot efficiency, as a means of weighting electricity relative to heat (Ref. 6). The Carnot efficiency depends on the difference between the absolute temperature, in Kelvin (K), of the heat supplied and a base temperature of 273 K (assuming surroundings at 0 ^{o}C) divided by the absolute temperature of the heat supplied. As a consequence, the effective weighting value of electricity relative to heat varies with the temperature of the heat supplied by the CHP plant. This variation is illustrated in Figure 30.

Figure 30 Variation of Weighting of the Value of Electricity to the Value of Heat for Combined Heat and Power Generation Based on Exergy



The choice of weighting for the value of electricity to the value of heat affects the estimated total GHG emissions associated with electricity and heat generated by a CHP plant. An example of this is illustrated in Figure 31 and Appendix G contains the results for CHP plants using roundwood chips, forest residue chips, and clean and unclean waste wood chips, respectively. For consistency, average values of 70% overall energy efficiency and 2.8 heat-to-power ratio were adopted in these results, based on the typical ranges documented in Appendix B. For roundwood and forest residues, the typical round trip distances in the forest, on public roads and between the chipping plant and the CHP plant of 16 km, 66 km and 80 km, respectively, were used. For clean and unclean waste wood, a typical value of 80 km for the round trip distance between the source of this wood fuel and the CHP plant was assumed.

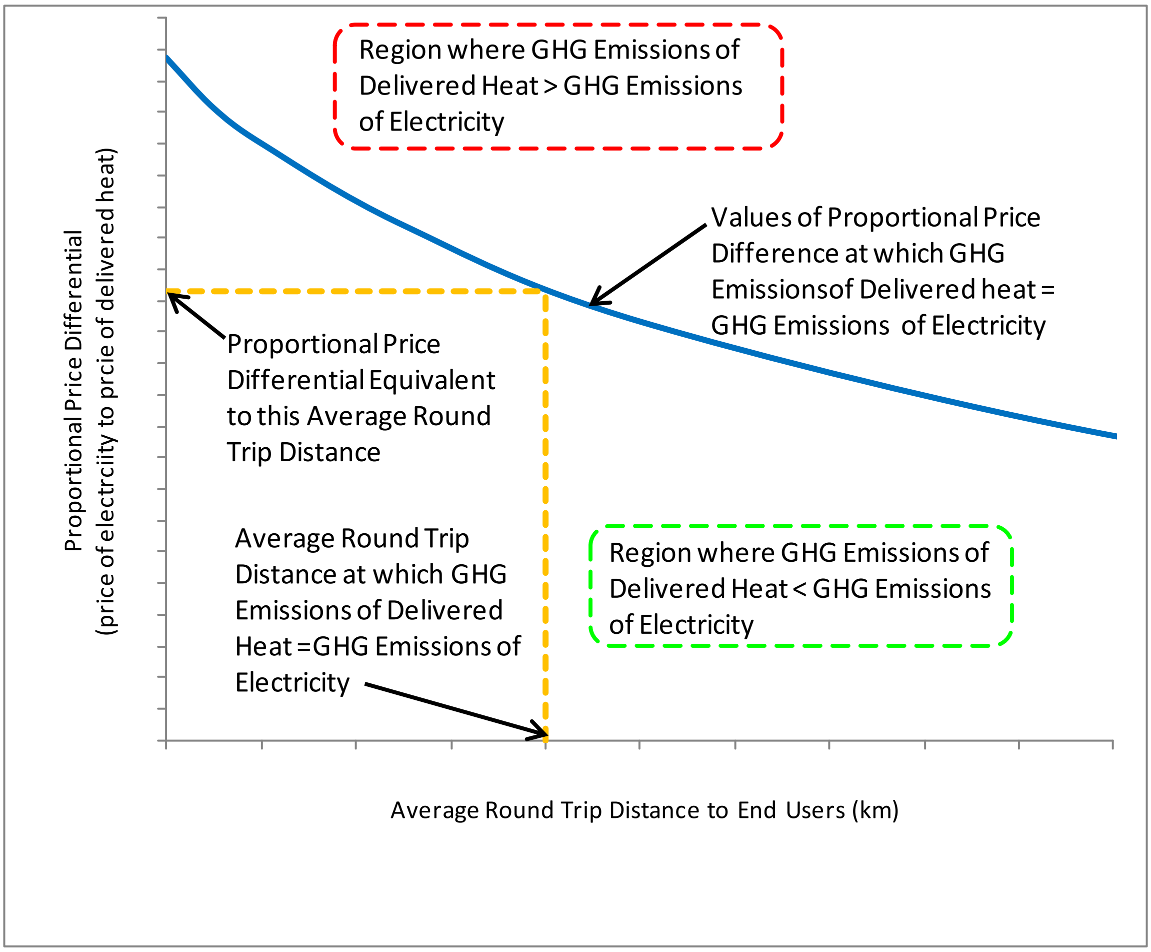
Figure 31 Example of the Effect of Weighting of Value of Electricity to Value of Heat on Total Greenhouse Gas Emissions for Heat and Electricity for a Combined Heat and Power Plant



Apart from the effect on estimated total GHG emissions of CHP plants, considerations over the weighting of the value of electricity to the value for heat have implications for the comparison of total GHG emissions associated with heat only and power only plants in this current context. In effect, this weighting could be used as a basis for comparing results for electricity and heat. Unfortunately, the different weighting values recommended by the ETS, PAS 2050 and the RED would seem to prevent this. However, this problem can be avoided by treating the weighting as a variable and investigating its effect on the total GHG emissions of heating and CHP plants relative to those of a power only plant. To assist with this approach, the weighting can be considered as a proportional price differential which is the ratio of the price of electricity relative to the price of delivered heat.

Using the simplified workbook (SG RO Biomass Chains 12 NM.xls) and the idealised modelling assumptions in Section 3, basic results, in the form of kg eq. CO_2/MWh of electricity, can be derived for power only plants using different sources of wood fuel. In particular, results for a 5 MW electrical output rating wood-fired power only plant, which is at the lowest end of the scale for such applications, are relevant in this context. Variations of estimated total GHG emissions associated with heat only and CHP plants using the same sources of wood fuel with average round trip transport distances to end users under idealised modelling conditions can be produced. The proportional price differential (weighting of value of electricity to value of heat) required to equate the total GHG emissions for the heat only or CHP plant with those of the power only plant using the same source of wood fuel can then determined. This enables the proportional price differential to be plotted against average round trip transport distance to end users of wood fuel for heating and CHP generation. An example of this variation is provided in Figure 32.

Figure 32 Example of Variation of Proportional Price Differential with Round Trip Transport Distance to End Users



Such variations enable a very specific question to be addressed; "what proportional price differential, as a ratio of the price of electricity to the price of delivered heat, is required to ensure that the total GHG emissions of heat and CHP plants using wood fuel supplied within a given radius of supply do not exceed those of a power only plant using the same source of wood fuel?" These variations establish a link between the proportional price differential and the maximum round trip distance for delivering wood fuel to heat and CHP plants. Setting a given value for the proportional price differential establishes the maximum round trip distance which wood fuel can be transported to heat and CHP plants so that their total GHG emissions are not higher than those of a power only plant which relies on the same wood source. Conversely, if a given radius of wood fuel supply is adopted for heat and CHP plants then it is possible to derive the proportional price differential that is required to prevent their total GHG emissions exceeding those of a power only plant. The subsequent variations for forest and waste wood fuels in different applications are presented in Appendix H.

Using the generalised specifications for the radii of supply in Table 2 with these variations, the relevant proportional price differentials for forest and waste wood fuel heating and CHP generation can be determined for local, regional and national (Scotland) delivery. These can be expressed as the maximum ratio of the price of electricity relative to the price of delivered heat for which the total GHG emissions of heating and CHP generation are less those of power only generation. The inverse of this proportional price differential is the minimum ratio of the price of delivered heat relative to the price of electricity. These results are summarised for forest wood fuels in Table 7 and waste wood fuels in Table 8.

These results show that there are substantial differences in proportional price differentials depending on the specific source of wood, the type of fuel and the energy end use application as well as the chosen maximum radius of supply to heat and CHP plants. The interpretation of the results in Tables 7 and 8 has significant implications for the level of price incentives which might be applied through policy to encourage the use of wood in certain applications. For example, if policy was intended to encourage the use of roundwood for pellets in domestic heating throughout Scotland rather than its use in power only generation, then, from a GHG emissions perspective, a financial adjustment would be required which results in a proportional price differential of no more than 1.58. Based on the inverse of this proportional price differential, the price of delivered heat relative to the price of electricity would have to be no lower than 0.63. In other words, the price of delivered heat in domestic applications from roundwood pellets sources in Scotland on a national scale would have to be not more than 37% lower than the price of electricity generated from Scottish roundwood.

Table 7 Proportional Price Differentials for Electricity and Delivered Heat Derived from Roundwood and Forest Residues Based on Total Greenhouse Gas Emissions

Option	Logistics of Wood Fuel Supply	Maximum Radius of Supply (km)	Maximum Round Trip Distance (km)	Maximum Proportional Price Differential (price of electricity/ price of delivered heat)	Minimum Inverse Proportional Price Differential (price of delivered heat/ price of electricity)
Domestic Heating by Roundwood Logs	Local	50	100	1.90	0.53
	Regional	200	400	1.43	0.70
	National	500	1,000	0.96	1.04
Domestic Heating by Roundwood Briquettes	Local	50	100	1.38	0.72
	Regional	200	400	1.14	0.88
	National	500	1,000	0.85	1.18
Domestic Heating by Roundwood Pellets	Local	50	100	1.97	0.51
	Regional	200	400	1.82	0.55
	National	500	1,000	1.58	0.63
Commercial/Industrial Heating by Roundwood Chips	Local	50	100	1.85	0.54
	Regional	200	400	1.50	0.67
	National	500	1,000	1.09	0.92
Commercial/Industrial CHP by Roundwood Chips	Local	50	100	2.34	0.43
	Regional	200	400	1.56	0.64
	National	500	1,000	0.95	1.05
Domestic Heating by Forest Residue Pellets	Local	50	100	1.44	0.69
	Regional	200	400	1.25	0.80
	National	500	1,000	0.99	1.01
Commercial/Industrial Heating by Forest Residue Chips	Local	50	100	1.68	0.60
	Regional	200	400	1.11	0.90
	National	500	1,000	0.66	1.52
Commercial/Industrial CHP by Forest Residue Chips	Local	50	100	2.80	0.36
	Regional	200	400	1.20	0.83
	National	500	1,000	0.54	1.85

Table 8 Proportional Price Differentials for Electricity and Delivered Heat Derived from Clean and Unclean Waste Wood Based on Total Greenhouse Gas Emissions

Option	Logistics of Wood Fuel Supply	Maximum Radius of Supply (km)	Maximum Round Trip Distance (km)	Maximum Proportional Price Differential (price of electricity/price of delivered heat)	Minimum Inverse Proportional Price Differential (price of delivered heat/ price of electricity)
Domestic Heating by Clean Waste Wood Briquettes	Local	50	100	0.89	1.12
	Regional	200	400	0.58	1.72
	National	500	1,000	0.34	2.94
Domestic Heating by Clean Waste Wood Pellets	Local	50	100	1.54	0.65
	Regional	200	400	1.20	0.83
	National	500	1,000	0.85	1.18
Commercial/Industrial Heating by Clean Waste Wood Chips	Local	50	100	1.74	0.57
	Regional	200	400	1.15	0.87
	National	500	1,000	0.69	1.45
Commercial/Industrial CHP by Clean Waste Wood Chips	Local	50	100	>10	<0.10
	Regional	200	400	2.72	0.37
	National	500	1,000	0.72	1.39
Commercial/Industrial Heating by Unclean Waste Wood Chips	Local	50	100	1.89	0.53
	Regional	200	400	1.60	0.63
	National	500	1,000	1.21	0.83
Commercial/Industrial CHP by Unclean Waste Chips	Local	50	100	3.25	0.31
	Regional	200	400	2.08	0.48
	National	500	1,000	1.24	0.81

In theory, the results in Tables 7 and 8 could be used to formulate the financial incentives necessary to promote the preferential or priority use of wood fuel in Scotland. However, there are a number of important considerations that would have to be taken into account. The most fundamental issue is that these findings are only based on total GHG emissions and policy usually has to accommodate a range of other relevant considerations. However, if GHG emissions are the main focus of policy measures, then it has to be recognised that a degree of sophistication will be required in their implementation. This will mean incorporating clear technical specifications, covering types of wood fuel, their end use applications and, in terms of heat and CHP plants, their intended delivery distances, for promoting priorities.

This raises consideration of the robustness of these results and findings for policy development and implementation. As stated previously (Section 3.3), the assumptions used in idealised modelling favour the use of wood fuel in power only generation over its use in heat and CHP plants. In particular, it has been assumed that power only plants will be located in the centre of forests and next to sources of waste wood production. Although this ensures essential robustness in the results, it should be noted that sensitivities to all possible variations in technical parameters, such as the thermal efficiencies of heat only, CHP and power only plants has not been addressed. However, it can be argued that subsequent variations are likely to be encompassed within the assumptions adopted in the idealised modelling, especially the combination of the favourable assumption about the location of power only plants and the generalised specification of delivery distances for wood fuel to heat and CHP plants. Finally, it is important to realise that the basic approach to the comparison of electricity to delivered heat adopted here, based on relative prices, contrasts with the use of exergy in the proposed extension of the RED to biomass heating and electricity generation (Ref. 6). However, the results contained in Appendix H can still be used with an approach based on exergy although this would mean that policy measures would have to take into account further technical details of wood fuel use. In particular, the temperature of heat production in specific applications would have to be accommodated.

5 Combined heat and power

In general, both typical and modelling results have indicated benefits, in reduced total GHG emissions, that can be derived from wood-fired CHP generation instead of using wood from the same source for power only generation. The main reason for this is the higher overall energy efficiency of CHP plants relative to power only plants. However, it is apparent that such general findings need to be qualified carefully. In Section 3, it was demonstrated, on the basis of direct comparison between 1 MWh of electricity and 1 MWh of heat, that heating from a typical range of CHP plants has lower total GHG emissions than power only plants that use the same source of wood fuel. With electricity from CHP plants, the comparison is less clear since there is some overlap in total GHG emissions associated with such plants and equivalent power only plants. The overlap is affected by the actual CHP design specifications, especially the overall energy efficiency and the heat-to-power ratio. In particular, CHP plants with relatively low overall energy efficiencies and heat-to-power ratios have associated total GHG emissions that fall within the range of those of power only plants.

Given the influence of these design specifications and the effects of other factors such as the distance for transporting wood fuel, there is no simple way of addressing the investigation of a possible threshold capacity for wood-fired CHP plants on the basis of total GHG emissions. From the idealised modelling in Section 3, it is apparent that, as overall energy efficiency falls, the total GHG emissions for a wood-fired CHP plant rise until, at a given wood fuel delivery distance, they equal the total GHG emissions of a power only plant of the same electrical output capacity. Hence, in order to maintain lower total GHG emissions than an equivalent power only plant, the radius for supplying wood fuel to a CHP plant shrinks as its overall energy efficiency decreases. In other words, whilst CHP plants with high overall energy efficiencies can be supplied with wood fuel regionally or nationally, those with lower overall energy efficiencies must rely on increasingly local supply.

The overall energy efficiency can also be linked to scale for CHP plants that use forest wood fuels, as demonstrated by idealised modelling in Section 3. Larger CHP plants will require greater areas for collecting wood fuel in forests, thereby increasing transport distances and associated GHG emissions. In contrast, this link is less clear for CHP plants that use waste wood fuel. This is because any relationship between the scale of such CHP plants and delivery distances will depend on the actual magnitude and distribution of sources of waste wood. In any case, detailed analysis of the relationship between the scale of wood-fired CHP plants and their total GHG emissions is further complicated by their other design specification, which is the heat-to-power ratio, and the weighting of the value of electricity to the value of heat. Hence, it is unlikely that a clear and simple rule for the threshold capacity of wood-fired CHP plants can be established with complete confidence.

In fact, other considerations may exert a greater influence on the practical designation of wood-fired CHP plants that are regarded as “acceptable”. One prominent consideration is the need to promote “good quality” CHP applications. The procedures for assessing CHP plants in this way are set out in the European Commission’s Cogeneration Directive (Ref. 14) and details are articulated in a relevant Programme for Quality Assurance of Combined Heat and Power (CHPQA) Guidance Note (Ref. 15). In particular, the quality of CHP is determined by its power efficiency and its Quality Index. The power efficiency is defined as:

η_{power} = $100(P_e/F)$ (Equation 3)

where η_{power} = power efficiency of the CHP plant (%)

P_e = total power output of the CHP plant (MWhe)

F = total fuel input of the CHP plant (MWh)

It should be noted that the subscript "e" with units of MWh or MW denotes energy in the form of electricity, whilst the subscript "t" specifies energy in the form of heat. The power efficiency can be expressed in terms of the overall energy efficiency and heat-to-power ratio of the CHP plant as follows

η_{power} = $\varepsilon/(1+R)$ (Equation 4)

where ε = overall energy efficiency of the CHP plant (%)

R = heat-to-power ratio of the CHP plant

It should be noted that the overall energy efficiency of the CHP plant is specified as:

E = $100(P_e + P_t)/F$ (Equation 5)

where P_e = total power output of the CHP plant (MWhe)

P_t = total qualifying heat output of the CHP plant (MWht)

The Quality Index is defined as:

QI = $(XP_e/F) + (YP_t/F)$ (Equation 6)

where QI = Quality Index of the CHP plant

X = power factor depending on the electrical output capacity of the CHP plant and its type of fuel

Y = heat supply factor depending on the electrical output capacity of the CHP plant and its type of fuel

The relevant values for the power and heat factors are reproduced in Table 9 (Ref. 15).

Table 9 Power and Heat Supply Factors for Wood-Fired Combined Heat and Power

Electrical Output Rating (MWe)	Power Factor, X	Heat Supply Factor, Y
≤ 1	329	120
>1 ≤ 25	315	120
> 25	220	120

The Quality Index can also be expressed in terms of the overall energy efficiency and heat-to-power ratio of the CHP plant as follows:

$$QI = \varepsilon(X + YR)/((1 + R)100) \quad \text{(Equation 7)}$$

For new plants, good quality CHP is specified as having a power efficiency equal to or greater than 20% and a Quality Index equal to or greater than 105. The implications for different scales of wood-fired CHP plants with different design specifications are illustrated in Figures 33 to 36. It can be seen that these rules restrict the combinations of overall energy efficiency and heat-to-power ratio of CHP plants that can be classified as good quality. This, in turn, determines whether such plants can meet the requirements of the ETS and Renewable Obligations. In particular, it should be noted from Figures 34 to 36 that, as the scale of a CHP plant, denoted by its electrical output rating, increases, its overall energy efficiency must also increase in order to achieve the Quality Index required by these regulations.

Figure 33 Values of Power Efficiency for Wood-Fired Combined Heat and Power Plants

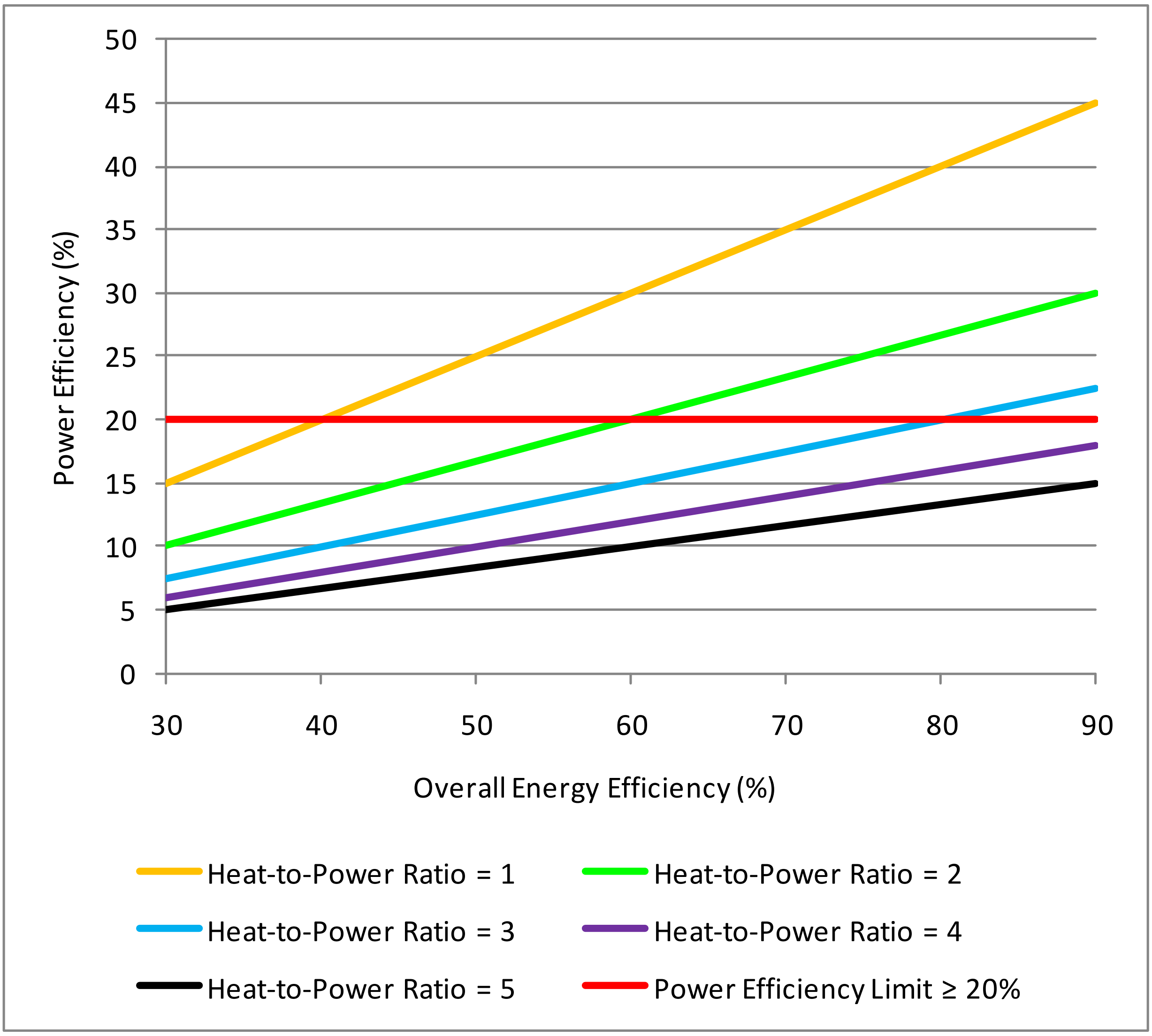


Figure 34 Values of Quality Index for Wood-Fired Combined Heat and Power Plants with an Electrical Output Rating Equal to or Greater than 1 MWe

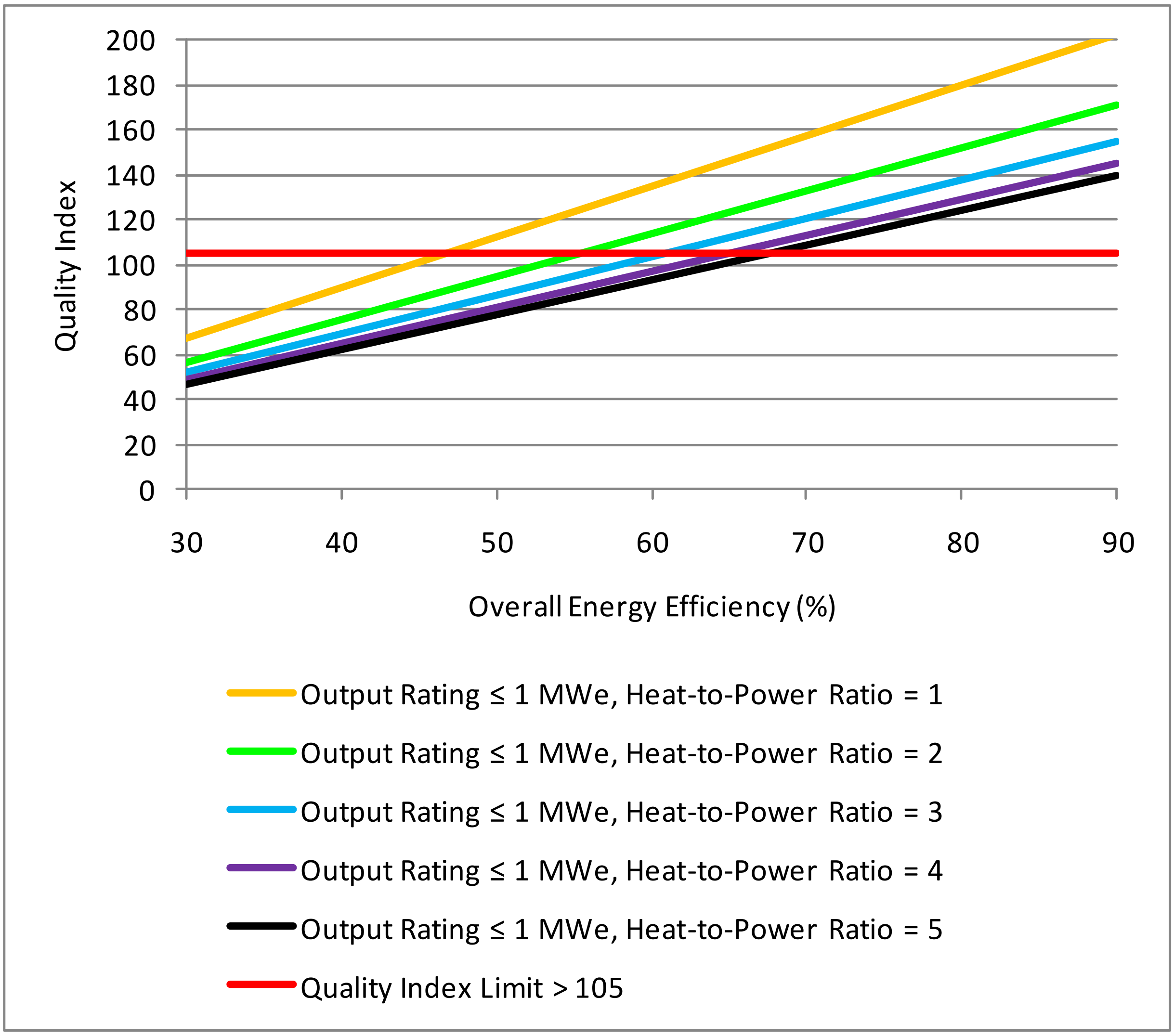


Figure 35 Values of Quality Index for Wood-Fired Combined Heat and Power Plants with an Electrical Output Rating Greater than 1 MWe and Equal to or Less than 25 MWe

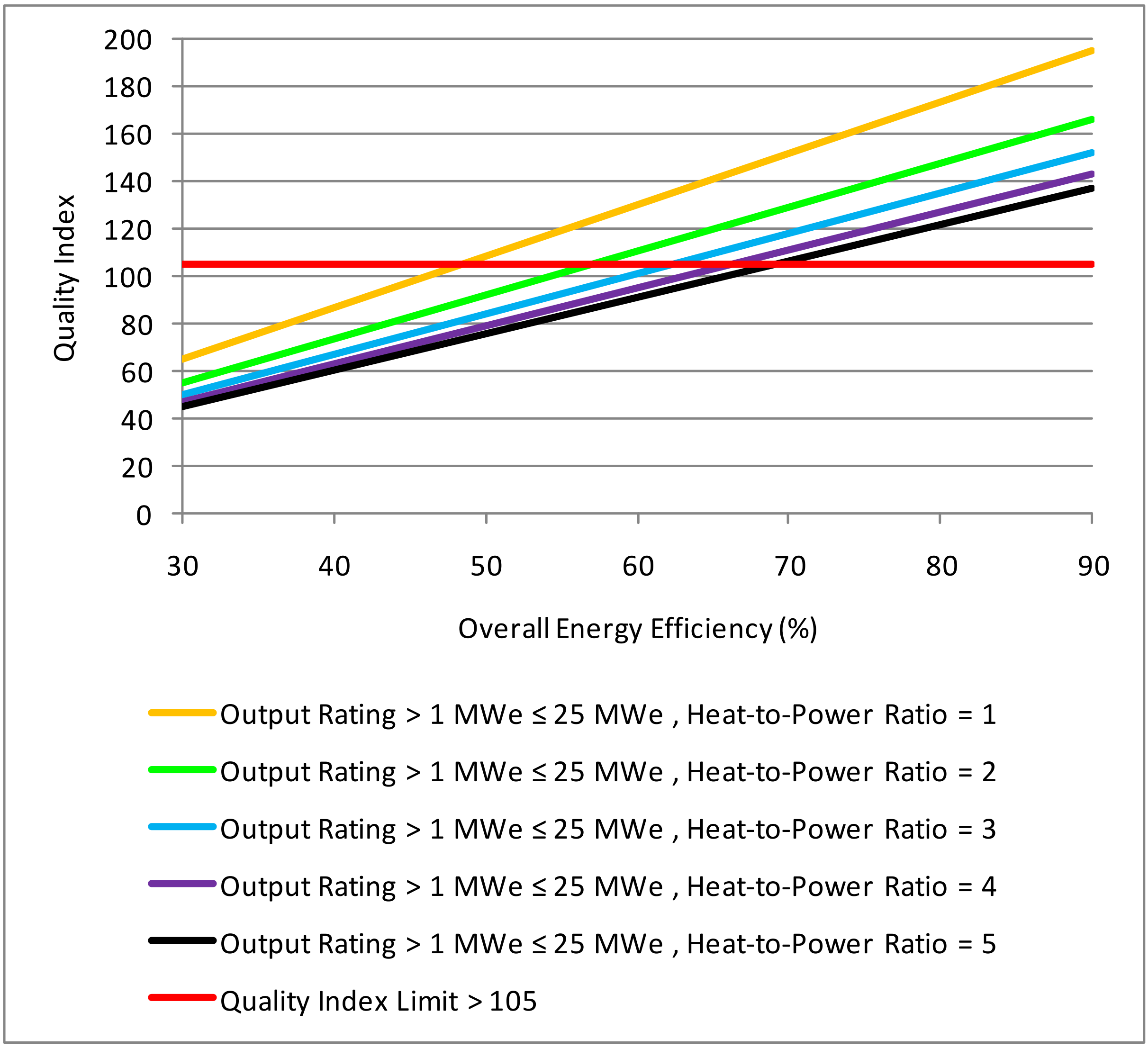
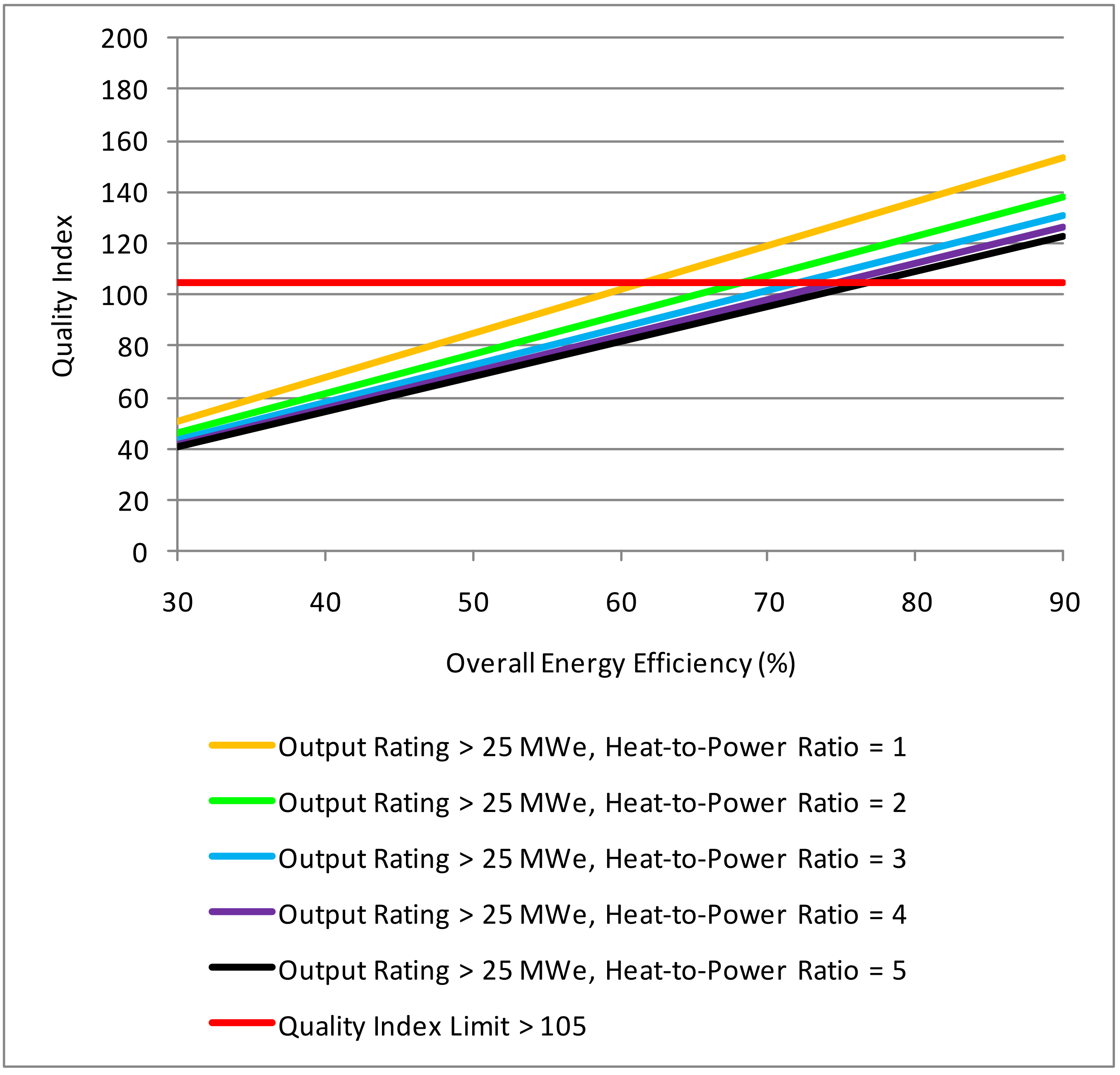


Figure 36 Values of Quality Index for Wood-Fired Combined Heat and Power Plants with an Electrical Output Rating Greater than 25 MWe



Another important consideration for the scale of CHP plants concerns their practical application in the UK. The majority of CHP plants are designed specifically to meet a given heating demand, with electricity production and possible export to the grid being a subsidiary factor, albeit one which can strongly influence its economics and financial justification. Commercial and industrial applications of CHP are often associated with the need to supply a given heat demand which, ideally, remains relatively constant throughout the year. Such applications are usually very specific to given commercial and industrial activities. Hence, it is the characteristics of these activities which tend to govern the scale of such CHP plants, which have a range of electrical output ratings, typically, from 0.4 MWe to 50 MWe. There are often many more opportunities for smaller scale rather than very large scale CHP development although, obviously, these have to be set within the context of economies of scale and scheme finances. Single, large and relatively constant heating demands are not numerous[5]. Some opportunities for very large scale CHP developments are presented by their connection to town- and city-wide district heating (DH) networks, as evidenced by such schemes in a number of European Union (EU) Member States. Such developments can have electrical output ratings of up to 400 MWe (Ref. 16).

However, there are very few large scale CHP/DH schemes in the UK. There are a number of fundamental reasons for this. A major consideration is the extent of the DH network as this has a basic influence on the economics of the CHP/DH scheme. This is determined by the heat load density which is the total annual or peak heating demand per unit area supplied. Apart from specific, localised areas, heat load densities in most UK town and cities are low compared with those in certain EU Member States, especially those in Northern Europe. Traditionally, this is related to preferences for living in high density apartments in city centres as opposed to lower density suburban areas. Other considerations relate to the historical adoption of DH, which assists its acceptance and provides existing legal, planning and logistical frameworks, and the general availability and widespread penetration of previously low cost heating fuels, especially natural gas. Hence, without vigorous promotion and concerted incentivisation of DH in the UK, in the form of financial support, modifications to the planning system, changes to legal requirements, etc., it seems the scale of wood-fired CHP plants will be limited mainly by the site-specific heating demands of certain commercial and industrial applications.

[5] One study found only two sites for very large scale, industrial CHP development in Scotland; St.Fergus with peak demands of 537 MWt of heat and 805 MWe of electricity, and Grangemouth with peak demand of 1,375 MWt of heat and 2,064 MWe of electricity (Ref. 17).

6. CONCLUSIONS

These conclusions are based on the typical results presented in Section 3.2, the idealised modelling results generated in Section 3.3, their extended exploration in terms of the relative valuation of heat and electricity in Section 4, and further consideration of CHP plants in Section 5.

The typical results in Section 3.2 represent the estimated total GHG emissions for using wood from Scottish forest and waste wood in heat, CHP and power only plants. These results are expressed as ranges based on realistic variations in key parameters such as the thermal efficiencies of these plants and the distances involved in supplying wood fuel in different forms from different sources. Typical results also reflect different scales of wood-fired applications which were based on the following actual data:

- typically, from 15 kWt to 320 kWt for domestic heating, from 50 kWt to 20 MWt for commercial and industrial heating, from 1.8 MWt to 125 MWt of heat and from 0.4 MWe and 50 MWe for electricity in CHP generation, and from 5 MWe to 350 MWe for dedicated power only generation,

These typical results are intended to address the basic question; "do wood-fired heat and CHP plants have lower total GHG emissions than those of power only plants that use the same source of wood fuel?" The following conclusions were formed from these typical results on the basis of comparing 1 MWh of electricity directly with 1 MWh of delivered heat:

- the use of forest wood fuels, derived from roundwood and forest residues, and clean and unclean waste wood fuels from Scottish sources in domestic, commercial and industrial heating, commercial and industrial CHP generation and power only generation has total GHG emissions that are approximately an order of magnitude lower than those of equivalent heat and/or electricity production from conventional fossil fuels,

- assuming typical ranges for wood fuel transport distances and for plant design specifications, total GHG emissions associated with all wood-fired heating applications, and heating from all CHP applications and electricity from some CHP applications are markedly lower than those for power only generation, and

- some overlap can occur in total GHG emissions associated with power only generation and the generation of electricity from wood-fired CHP plants which have combinations of large scale, low overall energy efficiency and large wood fuel delivery distances.

As a consequence of these typical results, it was apparent that further investigation of the trade-off between the thermal efficiency of wood-fired power only plants and delivery distances for wood-fired heat and CHP plants was required. This involved the use of idealised modelling to answer the question; "what is the maximum distance for delivering wood fuel to heat and CHP plants at which their total GHG emissions equal those of power only plants using the same source of wood?" To underpin the robustness of subsequent results and conclusions, such idealised modelling incorporated the favourable assumption that power only plants would be situated at the centre of a forest or next to a source of waste wood, thereby minimising transport distances, whereas necessary transportation of wood fuel was assumed for heat and CHP plants. The idealised modelling demonstrated that the advantage of heating and CHP generation using Scottish forest wood fuels over power only generation, in terms of lower total GHG emissions and with the direct comparison of 1 MWh of electricity with 1 MWh of delivered heat, could be maintained under the following conditions:

- the potential supply of roundwood pellets for domestic heating, and roundwood chips for commercial and industrial heating and CHP generation with wood fuel deliveries nationally (up to a distance of 500 km or, effectively, anywhere in Scotland), and

- the potential supply of roundwood logs, roundwood briquettes and forest residue pellets for domestic heating, and forest residue chips for commercial and industrial heating and CHP with wood fuel deliveries regionally (up to a distance of 200 km).

Idealised modelling also demonstrated that the advantage of heating and CHP generation using waste wood fuels over power only generation, in terms of lower total GHG emissions and with the direct comparison of 1 MWh of electricity with 1 MWh of heat, could be maintained under the following conditions:

- the potential supply of clean waste wood chips for commercial and industrial CHP generation, and unclean waste wood chips for commercial and industrial heating and CHP generation with wood fuel deliveries nationally (up to a distance of 500 km or, effectively, anywhere in Scotland),

- the potential supply of clean waste wood pellets for domestic heating and clean waste wood chips for commercial and industrial heating with wood fuel deliveries regionally (up to distance of 200 km), and

- the potential supply of clean waste wood briquettes for domestic heating with wood fuel deliveries on a very local basis (less than a distance of 50 km).

It was apparent that results and subsequent conclusions are affected by the basis for comparing 1 MWh of electricity with 1 MWh of delivered heat. Hence, different methods for weighting or valuing electricity relative to heat were examined. This led to a more detailed analysis in which the weighting is treated as a variable and investigating its effect on the total GHG emissions of heating and CHP plants supplied with wood fuel over different distances relative to the total GHG emissions of a power only plant that relies on the same source of wood. In this analysis, the relative weighting of electricity to heat was expressed as a proportional price differential consisting of the ratio of the price of electricity to the price of delivered heat. This enabled variations to be generated which addressed the specific question; "what proportional price differential is required to ensure that the total GHG emissions of heat and CHP plants using wood fuel supplied within a given radius of supply do not exceed those of a power only plant using the same source of wood fuel?" Using idealised modelling, a comparative baseline of total GHG emissions associated with power only generation and the assumed potential for delivery nationally (across Scotland), the following conclusions were formed on the price of delivered heat relative to the price of electricity derived from Scottish forest wood fuels:

- the price of delivered heat from roundwood pellets in domestic heating would have to be no more than 37% lower than the price of electricity from roundwood,

- the price of delivered heat from roundwood chips in commercial and industrial heating would have to be no more than 8% lower than the price of electricity from roundwood,

- the price of delivered heat from forest residue pellets in domestic heating would have to be at least 1% higher than that of electricity from roundwood,

- the price of delivered heat from roundwood logs in domestic heating would have to be at least 4% higher than the price of electricity from roundwood,

- the price of delivered heat from roundwood chips in commercial and industrial CHP generation would have to be at least 5% higher than the price of electricity from roundwood,

- the price of delivered heat from roundwood briquettes in domestic heating would have to be at least 18% higher than the price of electricity from roundwood,

- the price of delivered heat from forest residue chips in commercial and industrial heating would have to be at least 52% higher than the price of electricity from forest residues, and

- the price of delivered heat from forest residue chips in commercial and industrial CHP generation would have to be at least 85% higher than the price of electricity from forest residues.

Based on modelling, a comparative baseline of total GHG emissions associated with power only generation and the assumed potential for delivery nationally (across Scotland), the following conclusions were formed on the price of delivered heat relative to the price of electricity derived from Scottish waste wood fuels:

- the price of delivered heat from unclean waste wood chips in commercial and industrial CHP generation would have to be no more than 19% lower than the price of electricity from unclean waste wood,

- the price of delivered heat from unclean waste wood chips in commercial and industrial heating would have to be no more than 17% lower than the price of electricity from unclean waste wood,

- the price of delivered heat from clean waste wood pellets in domestic heating would have to be at least 18% higher than the price of electricity from clean waste wood,

- the price of delivered heat from clean waste wood chips in commercial and industrial CHP generation would have to be at least 39% higher than the price of electricity from clean waste wood,

- the price of delivered heat from clean waste wood chips in commercial and industrial heating would have to be at least 45% higher than the price of electricity from clean waste wood, and

- the price of delivered heat from clean waste wood briquettes in domestic heating would have to be at least 194% higher than the price of electricity from clean waste wood.

In theory, these conclusions could be used to formulate the financial incentives necessary to promote the preferential or priority use of wood fuel in Scotland. However, this needs to be qualified as follows:

- these conclusions are only based on total GHG emissions and actual policy measures may have to take into account a range of other relevant considerations,

- policy measures based exclusively on total GHG emissions considerations would have to incorporate technical specifications regarding types of wood fuel, their end use applications and intended delivery distances,

- whilst the robustness of these conclusions is based on favourable assumptions about the location of power only plants and the generalised specification of delivery distances for wood fuel to heat and CHP plants, other sensitivities to all possible variations in technical parameters, such as the thermal efficiencies of heat only, CHP and power only plants, may need to be taken into account, and

- the basic approach to comparing electricity with delivered heat using relative prices contrasts with the method based on exergy adopted by the proposed extension of the RED to biomass heating and electricity generation, although this could be addressed with the same type of analysis, albeit resulting in the need to account for more technical specifications, particularly the temperature of heat from wood-fired applications, in policy measures.

Due to the complex interplay of considerations over the design specifications of CHP plants, particularly the overall energy efficiency and the heat-to-power ratio, the weighting of the value of electricity relative to the value of heat and possible transport distances, it was not possible to determine a threshold capacity for wood-fired CHP generation, from the perspective of their total GHG emissions. However, typical results reinforced the need to promote “good quality” CHP which, in part, is based on higher overall energy efficiencies. It was also noted that upper scale of wood-fired CHP plants, in terms of their electrical output capacity rating, is likely to be set by certain commercial and industrial applications which will probably be very site specific. Higher scales of wood-fired CHP plants, normally associated with town- and city-wide DH network applications are unlikely to be realised unless such developments are vigorously promoted and coherently incentivised.

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