# Carbon impacts of using biomass in bio-energy and other sectors: energy crops

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# CONTENTS

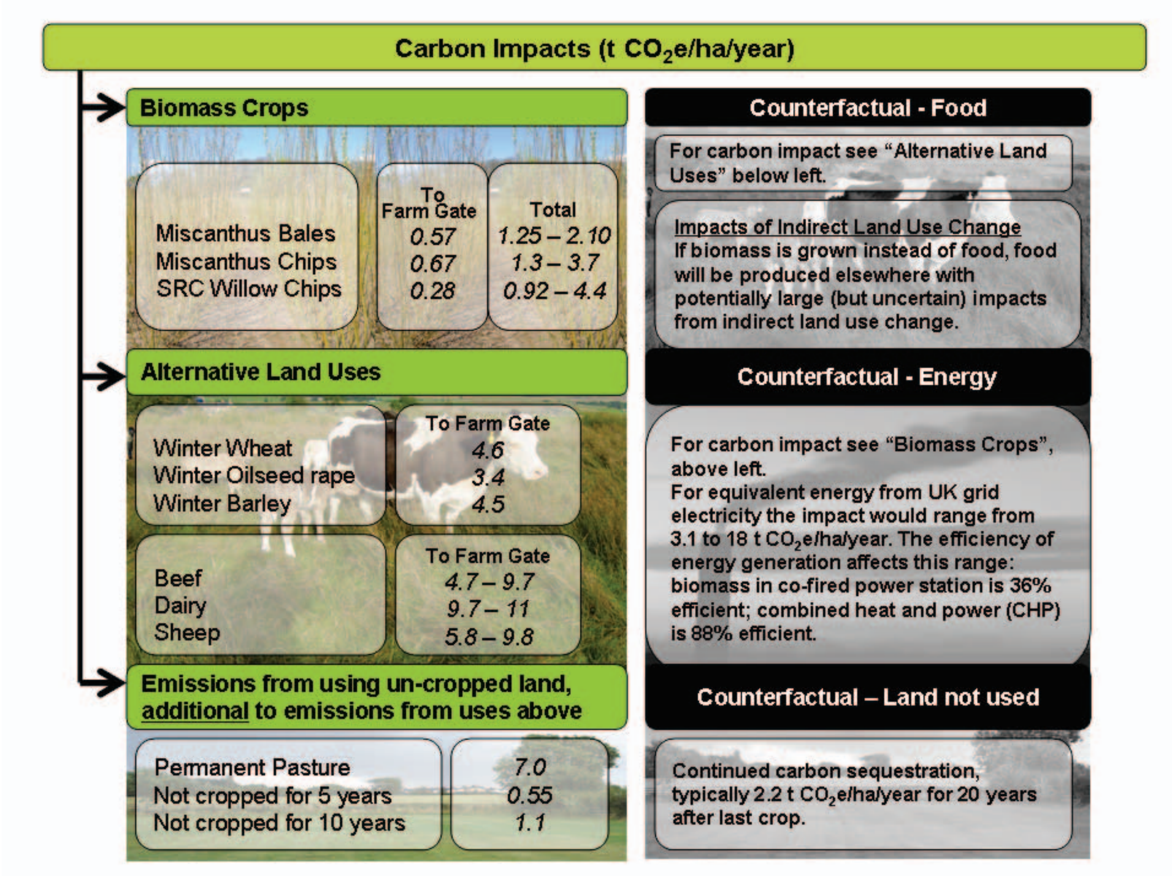


# ABBREVIATIONS

| | |
|---|---|
| ar | As received |
| $BEAT_2$ | Biomass Environmental Assessment Tool |
| CHP | Combined heat and power |
| CIP | Climate Information Portal |
| $CO_2e$ | Carbon dioxide equivalent |
| GHG | Greenhouse Gas |
| GWP | Global warming potential |
| ha | hectare |
| ILUC | Indirect land use change |
| LCA | Life cycle assessment |
| LUC | Land use change |
| odt | Oven dry tonnes |
| OSR | Oilseed rape |
| SRC | Short-rotation coppice |
| UKCIP | UK Climate Impacts Programme |
| UKCP09 | UK Climate Projections 2009 |
| t | tonne |

# EXECUTIVE SUMMARY

This study analysed the carbon impacts per hectare of growing and using energy crops and compared these impacts with those for key alternative land uses, see below:




## Key Points and Recommendations

Food production has a 5 to 40-fold higher carbon impact than biomass production, but food production will be displaced by biomass, not replaced.

Carbon impacts from indirect land use change (ILUC) when biomass crops replace other crops) are uncertain but potentially large[1].

The carbon impacts of producing and using biomass for energy generation should be considered in the context of the energy obtained and this is given in the main report.

The carbon impacts of importing biomass to the UK have been estimated for transporting miscanthus by road from France and by ship from Canada. Road transport is by far the most carbon intensive compared with shipping, despite the distances involved. The carbon impacts of transport from Bourgogne, France to Dover, UK are similar to the carbon impacts of miscanthus production.

The drivers for change of land use to biomass production are mainly economic and could be considered in any future work to estimate carbon impacts of alternative land uses.

[1] Indirect emissions were not assessed, but some comment is provided.

# 1. INTRODUCTION

This report presents numerical results from a study to analyse the carbon impacts of growing and using a selection of energy crops, and then compares these impacts with the carbon impacts associated with the most likely alternative land uses. Direct $CO_2e$ emissions were quantified and indirect $CO_2e$ emissions were considered broadly to give an overview of the issues for further consideration.

A summary of the carbon impacts analysed is given in Table 1.

**Table 1:** Results – location within the report.

| Carbon impact of using 1 ha of UK lowland land area | | Carbon Impacts |
|---|---|---|
| **Category** | **Breakdown** | |
| Biomass Crops | Miscanthus Bales/Chips/Pellets | Tables 3-4 |
| | SRC Willow Chips | Tables 5-6 |
| | Straw from Wheat | Tables 7-8 |
| Alternative land uses to biomass crops | Winter Oilseed Rape | Table 9 |
| | Winter Barley | |
| | Winter Wheat | |
| | Beef | |
| | Dairy | |
| | Sheep | |
| Land not currently used for crops | Permanent Pasture | Table 11 |
| | Previously cropped not cultivated idle for 5 years | |
| | Previously cropped land not cultivated for 10 years | |

# 2. CARBON IMPACTS OF BIOMASS CROPS

We present the carbon impacts of biomass crops in units of mass (kg or tonnes) $CO_2e$ per ha (Tables 1, 3 and 5) or per MWh (Tables 2, 4 and 6). Carbon impact values are given to two significant figures, reflecting the accuracy level for assessments of GHG emissions.

Types of biomass crop product use included:

- Heating (for SRC this was sub-divided into domestic heating and commercial and industrial heating),
- Combined heat and power (CHP)
- Electricity generation by co-firing,
- Electricity generation in a dedicated power plant

## 2.1 BEAT$_2$ Workbooks

The derivation of total GHG emissions associated with the production of bio-energy from energy crops was achieved using workbooks incorporated into the Biomass Environmental Assessment Tool (BEAT$_2$). These workbooks represent bio-energy chains based on miscanthus, SRC and straw. For miscanthus, workbooks were available for the production of fuel in the form of bales, chip and pellets. For SRC, it was assumed that the most common form of production would consist of chipping during harvesting, with subsequent use either directly as chips or by processing into pellets. It was also assumed that the most likely use of straw for bio-energy purposes would be in the form of bales. Where necessary, existing workbooks were extended to cover the combustion of these fuels to produce:

- heat in domestic, commercial and industrial applications,
- CHP in commercial and industrial applications,
- existing co-fired power-only plants, and
- electricity in new dedicated biomass power-only plants.

$BEAT_2$ workbooks were used to generate ranges of results in the form of total GHG emissions, broken down by GHG type ($CO_2$, $CH_4$ and $N_2O$) and by stage in the bio-energy chain). These results were converted into kilograms (kg) equivalent $CO_2$ using GWPs of 25 kg $CO_2$e/kg $CH_4$ and 298 kg $CO_2$e/kg $N_2O$ for a 100 year time horizon used in the Intergovernmental Panel on Climate Change Fourth Assessment Report.

More information on $BEAT_2$ workbooks can be found here: http://www.biomassenergycentre.org.uk/ , while a full list of results, with breakdown by activity, can be found in Appendix 1.

### 2.1.1 *Yield Assumptions*

The ranges of results were based on current values of yields for miscanthus and SRC grown in the UK, and the yield of straw from wheat production in the UK. The assumed range of annualised yield for miscanthus was between 11.0 and 12.0 oven dry tonnes per hectare (odt/ha/yr) or between 14.3 and 17.1 tonnes as received (ar) per hectare (t ar/ha/yr) with a moisture content of 30% by weight. For SRC, the assumed range of annualised yield was taken to be between 10.0 and 11.7 odt/ha/yr, or between 20.0 and 23.4 t ar/ha/yr at 50% moisture content. In the case of both miscanthus and SRC, it was assumed that no significant amounts of artificial nitrogen fertiliser were applied to these energy crops over the duration of their perennial cultivation.

The assumed range of straw yield was between 1.9 and 4.2 t ar/ha/yr at 25% moisture content. In terms of consequential LCA, the GHG emissions associated with the cultivation and harvesting of wheat grain were excluded from the collection and provision of wheat straw as a potential fuel for bio-energy production. Rather than account for possible allocation between straw and grain, which would be relevant in attributional LCA for regulatory purposes, the necessary approach for consistency with consequential LCA for policy analysis should be based on substitution. However, this would require evaluation of alternatives to grain since the focus here is on the use of straw. Hence, to avoid such complications, it was assumed that straw was, within the scope of this work, regarded as a waste product even though it has potential uses as a material. On this basis, the alternative to straw collection was assumed to be incorporation, the effects of which were included in this analysis. It should also be noted that GHG emissions associated entirely with the collection of straw, such as baling and carting, were accounted in calculations.

### 2.1.2 *Other Assumptions*

Other major factors that were also taken into account in these ranges were possible variations in drying methods, where relevant, transport distances and end use energy efficiencies. Drying options were only considered for providing miscanthus chips and pellets, and for SRC chips and pellets[2]. The range of GHG emissions adopted was based on natural drying and artificial drying using diesel fuel and electricity. In $BEAT_2$, electricity is used for air circulation and to operate handling machine to facilitate drying (and not as a source of heat) Transport distances were chosen to reflect possible local delivery, by assuming a minimum round trip distance of 100 kilometres, and nationwide delivery, by assuming a maximum round trip distance of 600 kilometres.

Plant size was not taken into account. The net thermal efficiencies for domestic SRC wood pellet-fired heating plants were assumed to range from 90% to 94%. For commercial and industrial heating plants fired by miscanthus bales, chips or pellets, SRC wood chips or pellets, and straw bales, net thermal efficiencies were taken to be between 88% and 90%. The combinations of specifications for CHP plants fired by miscanthus bales, chips or pellets, SRC wood chips, and straw bales consisted of overall net thermal efficiencies between 54% and 88%, with a typical heat-to-power ratio of 2.5:1. The net thermal efficiencies of power only co-firing with miscanthus chips or pellets, SRC wood chips or pellets, and straw bales were assumed to range from 30% to 36%. For dedicated power only plants fired by miscanthus bales, chips or pellets, SRC wood chips or pellets, and straw bales, net thermal efficiencies ranged from 25% to 36%. It should be noted that the GHG emissions associated with construction of new bio-energy plants were included in the calculations whereas those for existing co-fired plant were excluded. All calculations incorporated estimates of GHG emissions related to maintenance.

Some combinations of biomass crop products and energy generation do not occur, and this is indicated in the tables below as not applicable (N/A). For example, miscanthus bales cannot be used as a feedstock in a power station that is co-firing with fossil fuel (coal) and biomass fuel.

Two scenarios were modelled and exact details of the assumptions behind each scenario called “Low” and “High” are give in Appendix 1.

## 2.2 GHG Emissions

All of the outputs from $BEAT_2$ workbook are given in Appendix 1 and a summary of results presented in kg $CO_2e$ per ha per year is presented below with commentary as to the main findings.

The life cycle stages have been summarized into 3 main stages with an explanation of the life cycle stages in Table 2.

**Table 2:** Life Cycle Stage Summaries.

| Description | Stages |
|---|---|
| Farm | All activities up to the farm gate encompassing the stages of cultivation and harvesting and chipping |
| Processing | Farm gate to end of processing. This encompasses the following stages: transport to storage, bulk/batch drying and storage, milling and pelletising (if appropriate) |
| Other | Transport of crop to end of life. This encompasses the following stages; transport to plant, combustion, plant, start-up fuel, ash disposal and lime displacement |

[2] Only drying of miscanthus chips and SRC chips and pellets were taken into account when considering possible ranges of results. Straw is not normally dried and hence its drying was not accounted for. The ranges are based on the most extreme cases possible and diesel-fired chip and pellet driers do exist.

## 2.3 Miscanthus

### 2.3.1 *Miscanthus (kg $CO_2$e/ha/yr)*

There are three forms of miscanthus used for biomass in the UK; bales, chips and pellets. The largest carbon impacts arise from the carbon impacts of miscanthus pellets. This is due to the assumption that miscanthus crop is batch dried using diesel fuels and then converted to pellets.

Miscanthus bales have a lower carbon impact compared than chips and pellets because no further high-energy processes are needed before transport and combustion.

**Table 3:** Annual carbon impacts for miscanthus crop production and use, kg $CO_2$e per ha of crop production.

| kg $CO_2$e/ha/yr | | Heating | | CHP | | Co-firing | | Dedicated Power | |
|---|---|---|---|---|---|---|---|---|---|
| | | Low | High | Low | High | Low | High | Low | High |
| Miscanthus Bales | Farm | 570 | 570 | 570 | 570 | N/A | N/A | 570 | 570 |
| | Processing | 150 | 630 | 150 | 630 | N/A | N/A | 150 | 630 |
| | Use | 540 | 830 | 820 | 1000 | N/A | N/A | 530 | 820 |
| | Total | **1300** | **2000** | **1500** | **2200** | N/A | N/A | **1200** | **2000** |
| Miscanthus Chips | Farm | 670 | 670 | 670 | 670 | 670 | 670 | 670 | 670 |
| | Processing | 160 | 1800 | 150 | 1800 | 160 | 1400 | 150 | 1800 |
| | Use | 580 | 820 | 850 | 1200 | 480 | 1600 | 560 | 800 |
| | Total | **1400** | **3300** | **1700** | **3700** | **1300** | **2900** | **1400** | **3300** |
| Miscanthus Pellets | Farm | 670 | 670 | 670 | 670 | 670 | 670 | 670 | 670 |
| | Processing | 1900 | 2100 | 1900 | 2100 | 1900 | 2100 | 1900 | 2100 |
| | Use | 530 | 770 | 870 | 910 | 370 | 620 | 520 | 590 |
| | Total | **3100** | **3600** | **3500** | **3700** | **3000** | **3400** | **3100** | **3400** |

### 2.3.2 *Miscanthus (kg $CO_2$e per MWh)*

The carbon impact of miscanthus (kg $CO_2$e per MWh/ha) allow the efficiency of each method of energy generation to be taken into account. Heating emerges as the method with the lowest carbon impact per MWh/ha due the efficiency of conversion of fuel to heat; outputs are 37 MWh (miscanthus bales) to 40.1 MWh (miscanthus chips).

The lower energy outputs arise from miscanthus used in a dedicated power station. The outputs are 8.6 MWh for (miscanthus bales) to 9.3 MWh (miscanthus chips). These values are a quarter of the equivalent MWh outputs from heating (miscanthus bales 30.2 MWh and miscanthus chips 32.8 MWh). Consequently when each method of power generation is assessed on emissions per kg of $CO_2$e per MWh, heating has a far lower carbon impact (kg of $CO_2$e per MWh) than dedicated power.

**Table 4:** Annual carbon impacts for miscanthus crop production and use, kg $CO_2$e per MWh. *Energy production (MWh/ha) is given in italics.*

| **kg $CO_2$e per MWh *(MWh/ha)*** | | **Heating** | | **CHP** | | **Co-firing** | | **Dedicated Power** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| Miscanthus Bales | Farm | 15 | 19 | 16 | 31 | N/A | N/A | 38 | 66 |
| | Processing | 4.0 | 21 | 4.1 | 34 | N/A | N/A | 10 | 73 |
| | Use | 15 | 27 | 23 | 54 | N/A | N/A | 36 | 95 |
| | Total | **34** | **67** | **42** | **120** | **N/A** | **N/A** | **84** | **235** |
| *Total MWh/ha* | | *37.0* | *30.2* | *36.2* | *18.5* | *N/A* | *N/A* | *14.8* | *8.6* |
| Miscanthus Chips | Farm | 17 | 21 | 17 | 33 | 37 | 53 | 42 | 72 |
| | Processing | 4.0 | 56 | 3.9 | 91 | 8.6 | 110 | 9.6 | 200 |
| | Use | 15 | 25 | 22 | 59 | 26 | 130 | 35 | 86 |
| | Total | **35** | **100** | **43** | **180** | **70** | **230** | **87** | **350** |
| *Total MWh/ha* | | *40.1* | *32.8* | *39.2* | *20.1* | *18.1* | *12.6* | *16.0* | *9.3* |
| Miscanthus Pellets | Farm | 18 | 33 | 18 | 36 | 45 | 65 | 45 | 77 |
| | Processing | 52 | 100 | 53 | 110 | 130 | 210 | 130 | 250 |
| | Use | 14 | 37 | 24 | 49 | 25 | 61 | 35 | 67 |
| | Total | **84** | **170** | **96** | **200** | **200** | **330** | **210** | **390** |
| *Total MWh/ha* | | *37.4* | *20.6* | *36.5* | *18.8* | *14.8* | *10.3* | *14.9* | *8.7* |

## 2.4 SRC Willow

### 2.4.1 *SRC Willow (kg $CO_2$e per ha/yr)*

There are two main products of SRC willow used as biomass in the UK: wood chips and pellets. The highest carbon impact arises from heating (domestic and combustion) using pellets. This is because we assume that the crop will be batch dried using diesel fuel which is a very energy intensive method to dry crops. However it should be noted that the efficiency of each method of power generation needs to be taken into account as shown in Table 6.

**Table 5:** Annual carbon impacts for SRC willow crop production and use, kg $CO_2$e per ha of crop production.

| kg $CO_2$e per ha/yr | | Commercial and industrial heating | | Domestic Heating by Combustion | | Combined Heat and Power | | Power only generation by co-firing | | Dedicated Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| Chips | Farm | 280 | 280 | N/A | N/A | 280 | 280 | 280 | 280 | 280 | 280 |
| | Processing | 230 | 3100 | N/A | N/A | 230 | 3100 | 230 | 3100 | 230 | 3100 |
| | Use | 590 | 1000 | N/A | N/A | 760 | 1100 | 410 | 860 | 580 | 980 |
| | Total | **1100** | **4400** | N/A | N/A | **1300** | **4500** | **920** | **4300** | **1100** | **4400** |
| Pellets | Farm | 280 | 280 | 280 | 280 | N/A | N/A | 280 | 280 | 280 | 280 |
| | Processing | 530 | 4500 | 530 | 4500 | N/A | N/A | 530 | 4500 | 530 | 3100 |
| | Use | 690 | 990 | 1100 | 1300 | N/A | N/A | 360 | 710 | 580 | 1200 |
| | Total | **1500** | **5800** | **1900** | **6100** | N/A | N/A | **1200** | **5500** | **1400** | **4600** |

### 2.4.2 *SRC Willow (kg $CO_2$e per MWh)*

The carbon impacts (kg $CO_2$e per MWh/ha) allow the efficiency of each method of energy generation to be taken into account. The efficiency of heating rather than dedicated power generation is clear as the values (kg $CO_2$e /MWh per hectare) are lower than for power generation. For example for SRC willow chips, commercial and industrial heating (low value) results in 26 kg $CO_2$e per MWh/ha compared with 64 kg $CO_2$e per MWh/ha for dedicated power (low value).

**Table 6:** Annual carbon impacts for SRC willow crop production and use, kg $CO_2$e per MWh. Energy production (MWh/ha) is given in italics.

| **kg $CO_2$e per MWh *(MWh/ha)*** | | **Commercial and industrial heating** | | **Domestic Heating by Combustion** | | **Combined Heat and Power** | | **Power only generation by co- firing** | | **Dedicated Power** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| Chips | Farm | 6.6 | 7.9 | N/A | N/A | 6.7 | 13 | 17 | 28 | 16 | 28 |
| | Processing | 5.4 | 88 | N/A | N/A | 5.5 | 140 | 13 | 310 | 13 | 310 |
| | Use | 14 | 29 | N/A | N/A | 18 | 53 | 24 | 85 | 34 | 97 |
| | Total | 26 | 120 | N/A | N/A | 31 | 210 | 54 | 420 | 64 | 430 |
| *Total MWh/ha* | | *42.4* | *35.4* | N/A | N/A | *41.4* | *21.7* | *17.0* | *10.1* | *19.1* | *10.1* |
| Pellets | Farm | 5.8 | 7.0 | 5.6 | 6.8 | N/A | N/A | 15 | 25 | 15 | 28 |
| | Processing | 11 | 110 | 11 | 110 | N/A | N/A | 28 | 390 | 28 | 310 |
| | Use | 15 | 25 | 22 | 32 | N/A | N/A | 19 | 62 | 31 | 120 |
| | Total | 31 | 140 | 38 | 150 | N/A | N/A | 62 | 480 | 73 | 460 |
| *Total MWh/ha* | | *47.9* | *40.0* | *50.0* | *40.9* | N/A | N/A | *19.1* | *11.4* | *19* | *10.1* |

## 2.5 Straw from wheat

### 2.5.1 *Straw from wheat (kg $CO_2$e per ha/yr)*

The carbon impacts of straw from wheat are shown in Tables 6 and 7. The emissions from wheat "farm" stage only include the emissions from baling the straw and do not cover the nitrogen fertiliser and other inputs used for cultivating wheat. This is because the emissions from these inputs are allocated entirely to the wheat grain. The carbon impacts from straw are therefore lower than the GHG emissions from miscanthus and SRC willow which cover the full impact of cultivation for each crop.

**Table 7:** Annual carbon impacts for wheat bales production and use, kg $CO_2$e per ha of production.

| **kg $CO_2$e per ha/yr** | | **Heating** | | **CHP** | | **Dedicated Power** | |
|---|---|---|---|---|---|---|---|
| | | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| Straw Bales | Farm | 380 | 380 | 380 | 380 | 380 | 380 |
| | Processing | 41 | 92 | 41 | 92 | 41 | 92 |
| | Use | 120 | 110 | 220 | 150 | 140 | 120 |
| | Total | 540 | 580 | 640 | 620 | 560 | 590 |

### 2.5.2 *Straw from wheat (kg $CO_2$e per MWh)*

The total power (MWh) output from straw is considerably lower than the power outputs from miscanthus and SRC willow. The highest MWh value produced for straw bales used for heating is 10 MWh compared with 37 MWh for miscanthus bales used for heating.

**Table 8:** Annual carbon impacts for wheat bales production and use, kg $CO_2$e per MWh. Energy production (MWh/ha) is given in italics.

| **kg $CO_2$e per MWh *(MWh/ha)*** | | **Heating** | | **CHP** | | **Dedicated Power** | |
|---|---|---|---|---|---|---|---|
| | | **Low** | **High** | **Low** | **High** | **Low** | **High** |
| Straw Bales | Farm | 38 | 86 | 39 | 140 | 95 | 290 |
| | Processing | 4.1 | 21 | 4.2 | 34 | 10 | 71 |
| | Other | 12 | 25 | 22 | 57 | 36 | 92 |
| | Total | 54 | 130 | 65 | 230 | 140 | 450 |
| *Total MWh/ha* | | *10* | *4.4* | *9.8* | *2.7* | *4* | *1.3* |

# 3. ALTERNATIVE LAND USES

### 3.1.1 *Introduction*

To establish the alternative land uses to the biomass crops, the current spatial distribution of land for both miscanthus and SRC willow was identified and is shown in Figures 1 and 2. Alternative land uses were then identified using the ADAS 2010 landcover database.

### 3.1.2 *Methodology*

Defra provide regional SRC Willow and miscanthus crop areas as a percentage of total arable area from the 2010 Census returns. Using the ADAS 2010 Landcover database (1 $km^2$ resolution) the total arable area by region was summed, and the total area of SRC and miscanthus crop by region was derived.

Defra publish maps showing the location of SRC and miscanthus plantations by region. These maps were overlain with a 5 km grid and SRC and miscanthus plantations attributed to each square. For those squares containing SRC and/or miscanthus plantations, the total amount of arable land was summed, and the proportion of the land that is arable was derived. The proportion of arable land was used as the basis for distributing the total area of SRC and miscanthus to the 5km squares, such that the regional total matched the 2010 Census total.

### 3.1.3 *Miscanthus*

For miscanthus, a simple predictive model of yield was developed by ADAS, supported by yield assessment and crop physiological data from field sites (Price, et al., 2004). The model was applied in a GIS framework using weather data at a 5 km spatial resolution, allowing potential yield to be mapped across England and Wales for current climate conditions using UK CIP02 scenarios which are based on weather data from 1960 to 1990. The average model estimates of above ground dry matter yields at harvest for miscanthus on arable land in England and Wales are in the range 5.2 – 19.7 t $ha^{-1}$ $yr^{-1}$.

### 3.1.4 *SRC Willow*

For SRC, a map of potential yield was produced by Forest Research, and was based on yield estimates obtained at a network of 49 field experiments established across the UK. The yield model used to transform site specific yield estimates for five willow varieties into a national map. This took into account annual rainfall, seasonal rainfall, growing degree days, frost days, soil pH and soil texture, all based on 5km x 5km grid cells. Average yield estimates for the five willow varieties grown for two three-year cutting cycles in each 5 x 5 km grid square were calculated. The average model estimates of above ground dry matter yields at harvest for SRC on arable land in England and Wales are in the range 6 -14 t $ha^{-1}$ $yr^{-1}$ (Forest Research 1999) and personal communication 2011).

The modelled potential yield was multiplied by the area of SRC and miscanthus plantation respectively to give a total tonnage for the 5 km square for both SRC Willow and Miscanthus.

### 3.1.5 *Identification of alternative land uses*

The feedstock supply zones for identified biomass firing energy plants were used to determine alternative land uses. The ADAS 2010 Cropping and Livestock layers were overlain in a GIS environment and the agricultural land uses with the zones identified. Identification of the locations of production allowed comparison with existing land uses within the same 5 km squares using the ADAS 2010 landcover database. The top land uses by area were selected, including all agricultural uses covering more than 5% of the 5 km square area.

#### 3.1.6 *Short Rotation Coppice (SRC) – alternative land uses*

| **Arable** | **Livestock** |
|---|---|
| Winter wheat | Beef |
| Winter oilseed rape | Dairy |
| | Sheep |

#### 3.1.7 *Miscanthus – alternative land uses*

| **Arable** | **Livestock** |
|---|---|
| Wheat | Beef |
| Winter Barley | Dairy |
| Winter Oilseed Rape | |

#### 3.1.8 *Wheat – alternative land use*

As wheat straw is produced as a co-product of growing wheat grain, and the use of straw for biomass is unlikely to influence the area of the wheat crop, it is assumed that the alternative land use to wheat production is wheat production.

#### 3.1.9 *Summary – Alternative land uses*

Six alternative land uses were identified, including alternatives to SRC willow, miscanthus and wheat straw as shown below.

In addition to these alternative land uses identified using land use data, we have also included non-cropped land to allow consideration of the carbon impacts of land that is not cropped, and that could be cultivated to grow energy crops. The set of alternative land uses was as follows. The carbon impact of these land uses are discussed in Section 4.

| **Arable** | **Livestock** | **Other** |
|---|---|---|
| Wheat | Beef | Non-cropped land |
| Winter Barley | Dairy | |
| Winter Oilseed Rape | Sheep | |

**Figure 1:** Current miscanthus cultivation modelled – UKCIP02 results.

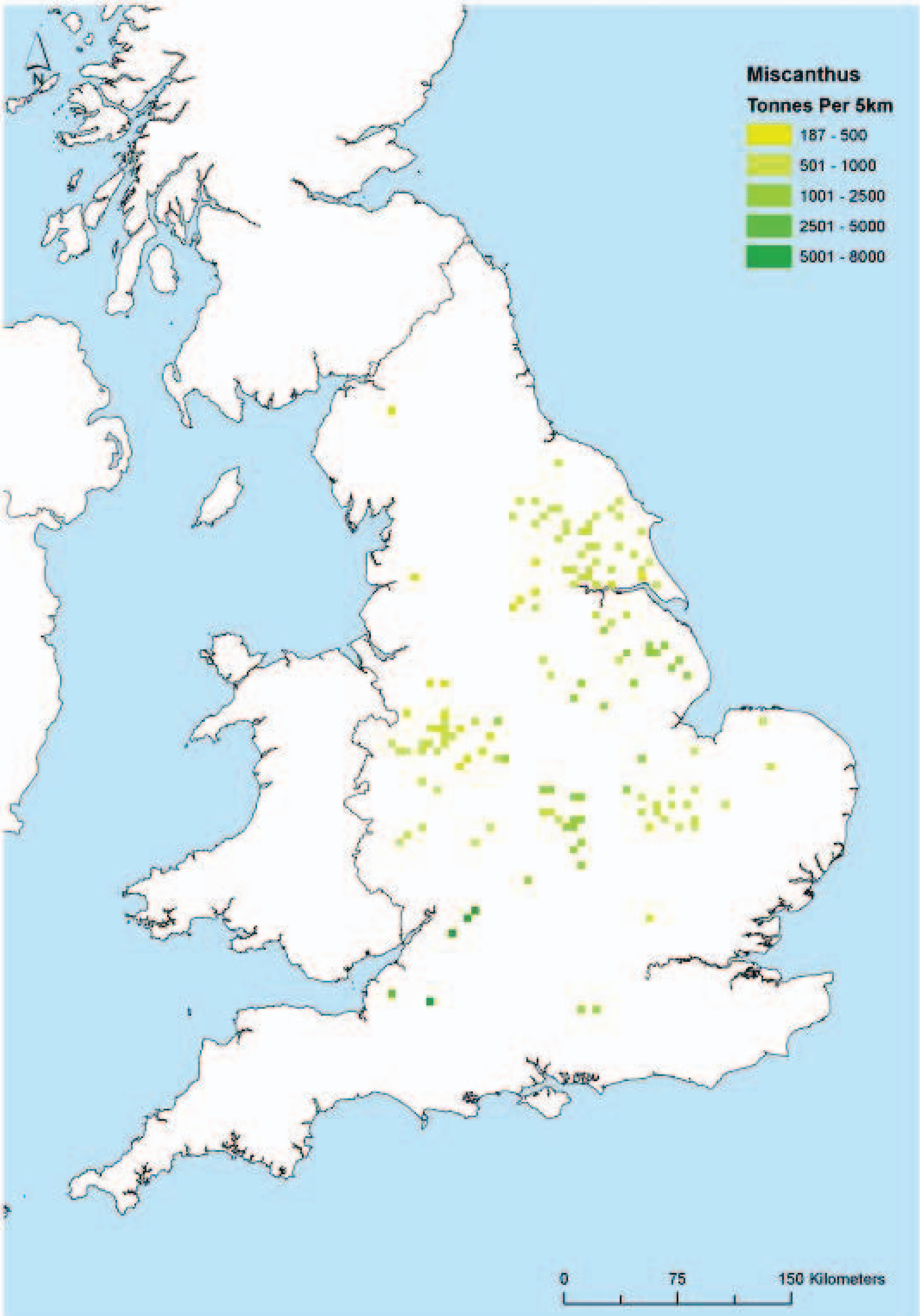
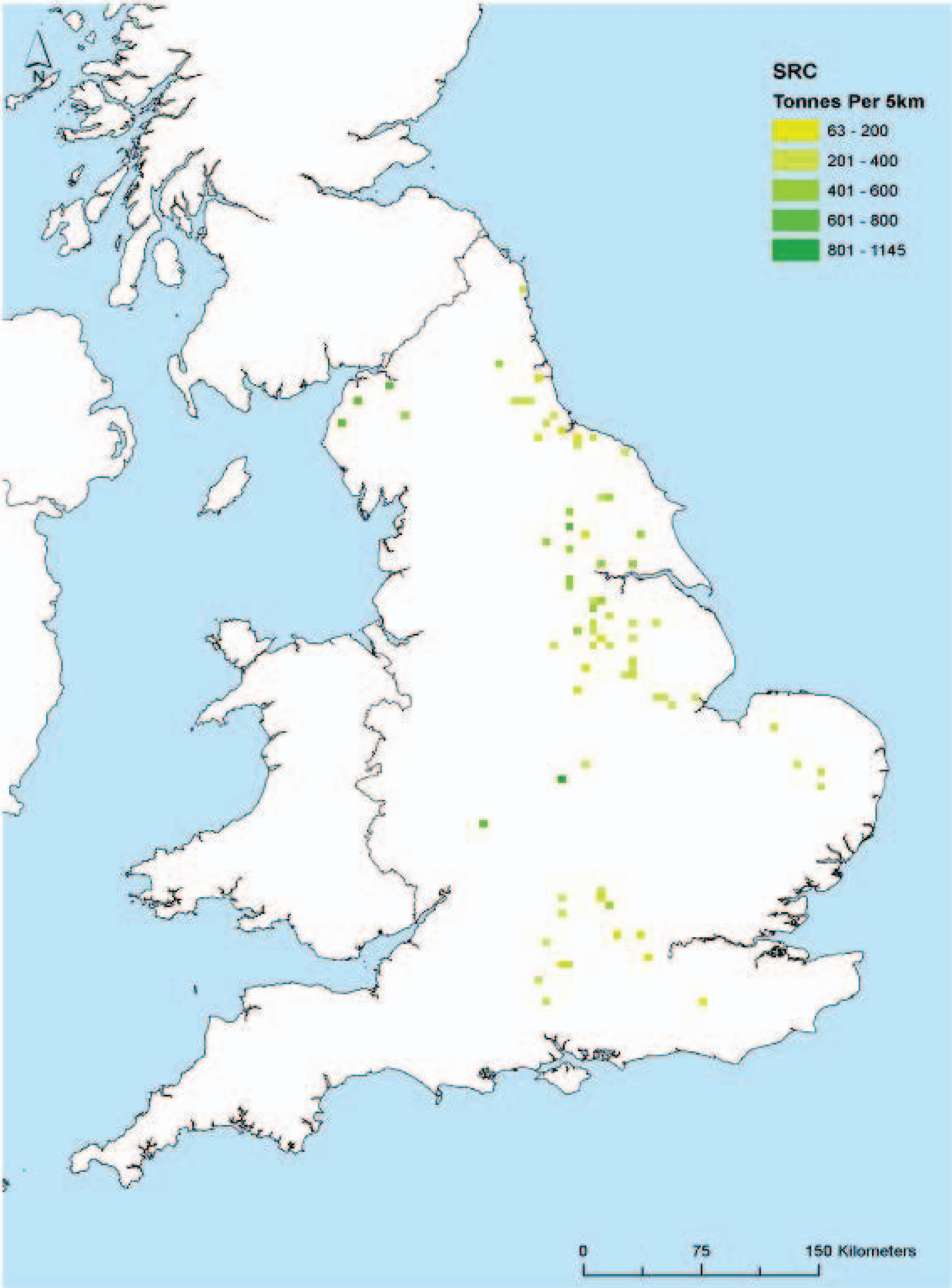


**Figure 2:** Current SRC Willow cultivation modelled– UKCIP02 Results.



## 3.2 2020 and 2050 Miscanthus and SRC crops - future yields and locations

### 3.2.1 *Miscanthus 2020 and 2050*

The predictive model of miscanthus yield that was used for the current scenario was used to predict future yields. The model was run using UKCIP modelling results (2002) for 2020 and 2050. A straight line interpolation between the values for 2020 and 2050 was performed to provide potential yields for 2030.

It was assumed that 10% of the arable land in each 5 km square would become available for energy crop cultivation[3]. The total potential tonnage of miscanthus as a feedstock for energy production was therefore derived by taking 10% of the arable land in the 5 km square and multiplying this by the modelled yields for 2020, 2030, and 2050 respectively.

The resultant feedstock layers were then used, in conjunction with the location and feedstock requirements of miscanthus fired power plants, to create supply zones around the power plants. These zones realistically represent the potential future areas of miscanthus cultivation as an energy crop. Initially, the power plant feedstock requirement was calculated by converting capacity in kWh to Gigajoules, and using a standard conversion of 13 Gigajoules of energy from each tonne of miscanthus (fresh weight), and a factor of 277.78 kWh per Gigajoule of energy using assumptions in the Environment Agency (2009) review.

Buffer zones around each plant were then grown by small incremental distances, until enough feedstock had been sourced to satisfy the capacity of all the plants in the simulation. Zones around plants that compete for the same feedstock were grown simultaneously such that the combined feedstock for both would be satisfied, and the supply zones merged. When an individual plant reached its feedstock requirement from the land in the designated supply zone, the supply zone stopped growing.

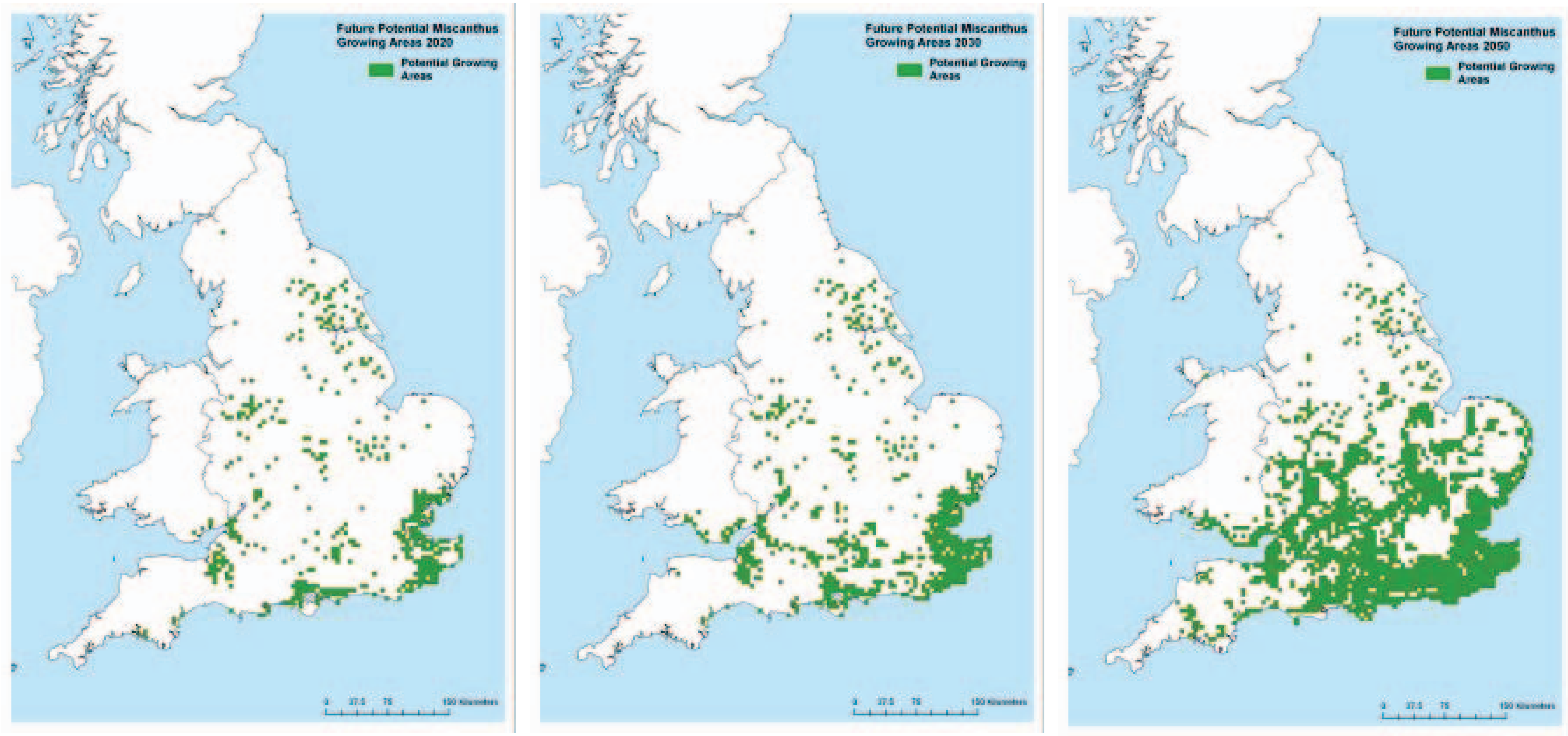
The maps in Figure 3 show the potential growing areas for miscanthus for 2020, 2030, and 2050. Areas where the modelled miscanthus yields exceeded 20 t/ha were designated potential growing areas, and are visualised in the maps as green 5 km squares.

### 3.2.2 *SRC Willow 2020 and 2050*

SRC Willow was not modelled as expert opinion from Forest Research indicates that climate will not be the driving factor for crop locations. Economics and the scale of the power stations are expected to have a greater influence on SRC production, but these factors were not modelled within this project. Competition from the heat market should also be considered when considering the future growth of SRC willow crop area. Currently there is no evidence that alternative land uses in future will be different from the main alternative land uses at present.

[3] This is based on the approach taken in the 2009 Bioenergy review. Please see References for further details of this work.

**Figure 3:** Predicted future yields of miscanthus – 2020, 2030, 2050.



# 4. CARBON IMPACTS OF ALTERNATIVE LAND USES

## 4.1 Methodology

The carbon impacts of alternative land uses (Table 7) were assessed using data from a previous Defra project (FO0404), in which carbon impacts of many food products were assessed. The values and production information from that work were impacts per product unit (e.g. 1 tonne of wheat), and these were used to calculate carbon impacts per ha of land.

### 4.1.1 *Cradle to Farm Gate approach*

The assessments used a lifecycle approach, up to the farm gate (i.e. excluding processing and use). Processing and use were excluded because (a) the values will vary very greatly depending on the chosen use and (b) it is assumed that food use will still occur if the land is used for biomass crops – the food crops will be grown elsewhere and use will be unchanged.

The arable carbon impact values are given as a single value rather than a range because upper and lower limits were not available from the data source.

The livestock values have been adjusted to include land used to grow the main feed crops, using results of Defra project FO0404 (Wiltshire et al., 2008), and expert knowledge of ADAS consultants to provide typical stocking rates for lowland farming systems. The range of carbon impact values derives from the range in stocking densities used in the calculations, and from consideration of relatively intensive and extensive farming systems.

### 4.1.2 *Adjustment to consider capital goods*

All values for agricultural land uses were adjusted to take account of emissions associated with production of capital goods (e.g. tractors and farm buildings). This was done to maintain consistency with the $BEAT_2$ method used for assessment of carbon impacts of growing and using the biomass crops, which included embedded emissions in capital goods. The adjustment was based on a published estimate of the contribution of capital goods to GHG emissions from agriculture (Frischknecht et al., 2007).

### 4.1.3 *Carbon Impacts of Energy Counterfactuals*

To provide additional context, carbon impacts of energy generation are given as additional counterfactuals to the biomass land uses because if the land is not used for growing biomass for energy, there will be an associated carbon impact from generating energy by another means. As an example, the other means in this case has been assumed to be UK grid average electricity for and the value 362 $kgCO_2e$ per MWh has been used. More detailed analysis to identify counterfactual energy production emissions from alternative energy sources is beyond the scope of this project.

## 4.2 Carbon Impacts

The carbon impacts (t $CO_2e$ per ha of land) are given in Table 9, for land uses that are alternatives to biomass crop production, and for biomass crop production and use, for comparison.

In Table 10 we present the carbon impacts of generating electricity (UK grid average) as additional counterfactuals to the biomass land uses. The counterfactual values are different depending on the biomass system that is replaced by an alternative land use (because biomass systems produce vary in the amount of energy produced), so values are presented for the miscanthus and SRC biomass systems considered in this project.

**Table 9:** Carbon impacts: Alternative land uses and Energy crop production (excluding processing and use).

| Land use | t $CO_2$e per ha of land | | | | | |
|---|---|---|---|---|---|---|
| | Production | | Processing and use[1] | | Total | |
| | Low | High | Low | High | Low | High |
| Alternative Land Uses | | | | | | |
| Winter wheat | 4.6 | | N/A | N/A | N/A | N/A |
| Winter OSR | 3.4 | | N/A | N/A | N/A | N/A |
| Winter barley | 4.5 | | N/A | N/A | N/A | N/A |
| Beef | 4.7 | 9.7 | N/A | N/A | N/A | N/A |
| Sheep | 5.8 | 9.8 | N/A | N/A | N/A | N/A |
| Dairy | 9.7 | 11 | N/A | N/A | N/A | N/A |
| Energy crop production (excluding processing and use) | | | | | | |
| Miscanthus bales | 0.57 | 0.57 | 0.68 | 1.5 | 1.3 | 2.1 |
| Miscanthus chips | 0.67 | 0.67 | 0.63 | 3.0 | 1.3 | 3.7 |
| Miscanthus pellets | 0.67 | 0.67 | 2.5 | 3.1 | 3.2 | 3.8 |
| SRC chips | 0.28 | 0.28 | 0.64 | 4.1 | 0.92 | 4.4 |
| SRC pellets | 0.28 | 0.28 | 4.4 | 5.5 | 4.7 | 5.8 |

[1] The range is derived from the range of energy crop uses, and the consequent range of energy generation carbon impact values.

**Table 10:** Carbon impacts for provision of energy using biomass, and for an example of alternative energy generation: ranges of emissions values for energy crop production and use, and for energy from national grid electricity at a value of 362 kg CO2e/MWh.

| Land use | t $CO_2$e /ha/yr | | T $CO_2$e to replace energy from 1 ha using a fossil fuel (example counterfactual for UK grid average energy generation) | |
|---|---|---|---|---|
| | Low | High | Low | High |
| Miscanthus bales | 1.3 | 2.2 | 3.1 | 13 |
| Miscanthus chips | 1.3 | 3.7 | 3.4 | 15 |
| Miscanthus pellets | 3.1 | 3.7 | 3.1 | 14 |
| SRC willow chips | 0.92 | 4.5 | 3.7 | 15 |
| SRC willow pellets | 1.2 | 6.1 | 3.7 | 18 |

The carbon impacts of non cropped land were also estimated, as indicative values for the UK only. In this context, uncropped land means either (1) land that is not used for agricultural production, is not cultivated, and is growing vegetation (e.g. land in an agri-environment scheme), or (2) permanent pasture. Carbon impacts of non-cropped land (Table 11) were considered by estimating the additional contribution to the carbon impacts of growing a biomass crop on land that was not cropped immediately before the use for a biomass crop. Three scenarios were considered to indicate the range of possible values:

1. Land cropped, then un-cropped for 5 years, then used for a biomass crop;
2. Land cropped, then un-cropped for 10 years, then used for a biomass crop;
3. Permanent pasture is cultivated and used for a biomass crop.

We applied a typical rate of carbon sequestration from a recent review (0.6 t/C/ha/year; Dawson & Smith, 2007), for scenarios 1 and 2, for the period between the previous crop and the biomass crop.

For emissions associated with cultivation of permanent pasture, we used land use change values given in PAS 2050:2011.

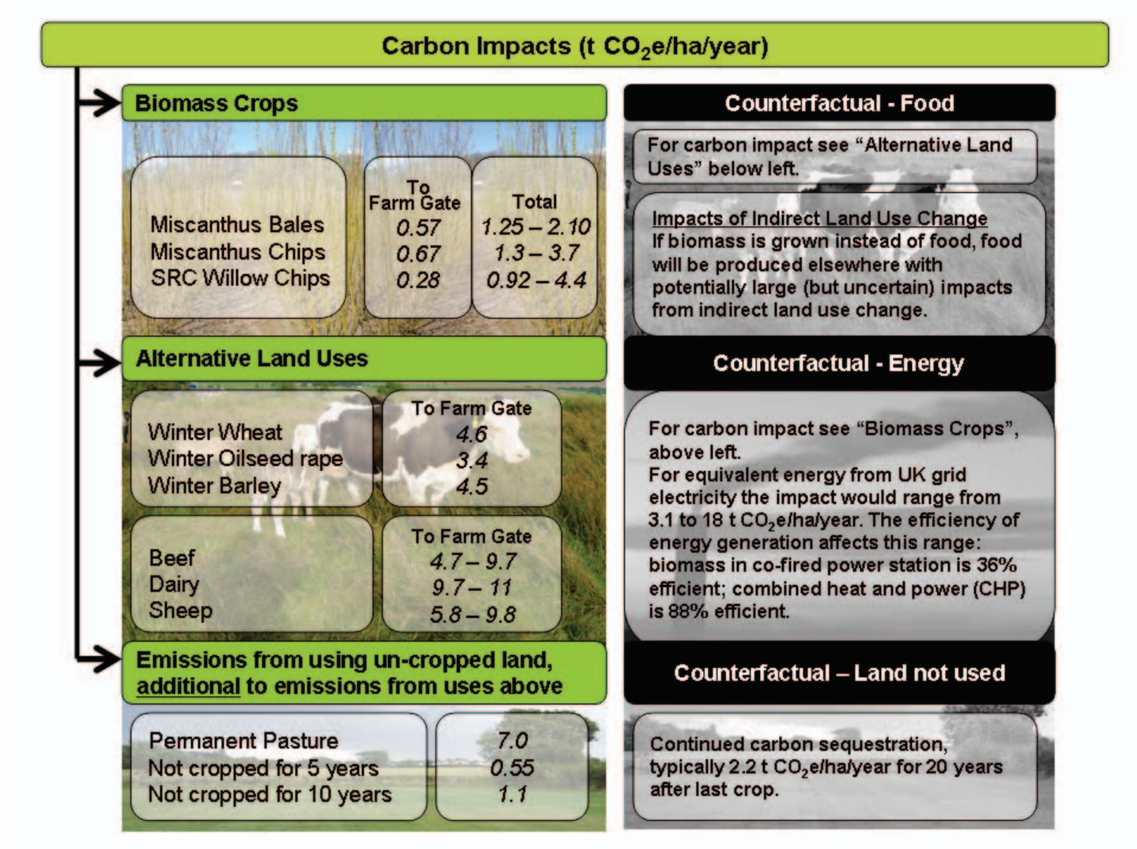
For each scenario we assumed that emissions associated with cultivation and loss of soil carbon are allocated to the land use over a period of 20 years after cultivation. This approach is in line with most accepted methods for estimation of carbon impacts from growing crops.

**Table 11:** Carbon impacts of non-cropped land.

| Scenario | t $CO_2$e/ha, additional to other emissions from biomass crop production |
|---|---|
| 1. Previously cropped land not cultivated for 5 years | 0.55 |
| 2. Previously cropped land not cultivated for 10 years | 1.1 |
| 3. Permanent pasture | 7.0 |

## 4.3 Results Summary

**Figure 4:** Results Summary Diagram.



# 5. EUROPEAN CASE STUDIES

## 5.1 Methodology

### 5.1.1 *Location of production and transport*

An international comparison of biomass feedstock carbon impacts was made using three case studies in European countries where there is significant biomass cultivation, based on the possibility that biomass crop products could be exported to the UK. Biomass energy plants were identified to indicate locations suitable for production of biomass crops. The chosen plants, located at Przechlewo in Poland, Bourgogne in France, and Sanguesa in Spain, are shown in Table 12 and Figure 5.

**Table 12:** European Case Studies.

| Name | Location | Feedstock |
|---|---|---|
| Sangüesa Biomass Power Plant | Navarra, Spain | Straw |
| Przechlewo Straw Biomass Power Plant | Przechlewo Poland | Straw |
| Bourgogne Power Plant | Aiserey France | Miscanthus |

The carbon impacts of the biomass crop production near these plants were assumed to be similar to carbon impacts for the same crops in the UK. Additional carbon impacts for transport to the UK were calculated based on standard emission factors for the most likely transport type and the distance to a UK port.

### 5.1.2 *Alternative land uses*

Alternative land uses were identified as additional background information. To do this, a notional 50 km radius buffer was created around the location of each of these three energy plants and the European land use database (CORINE) was then overlain, and the CORINE land uses within each of the buffers were identified.

It should be noted that the CORINE database used for the land cover for Europe does not have the same level of detail as the UK dataset used for other parts of this study, hence the broader terms used for describing land use.

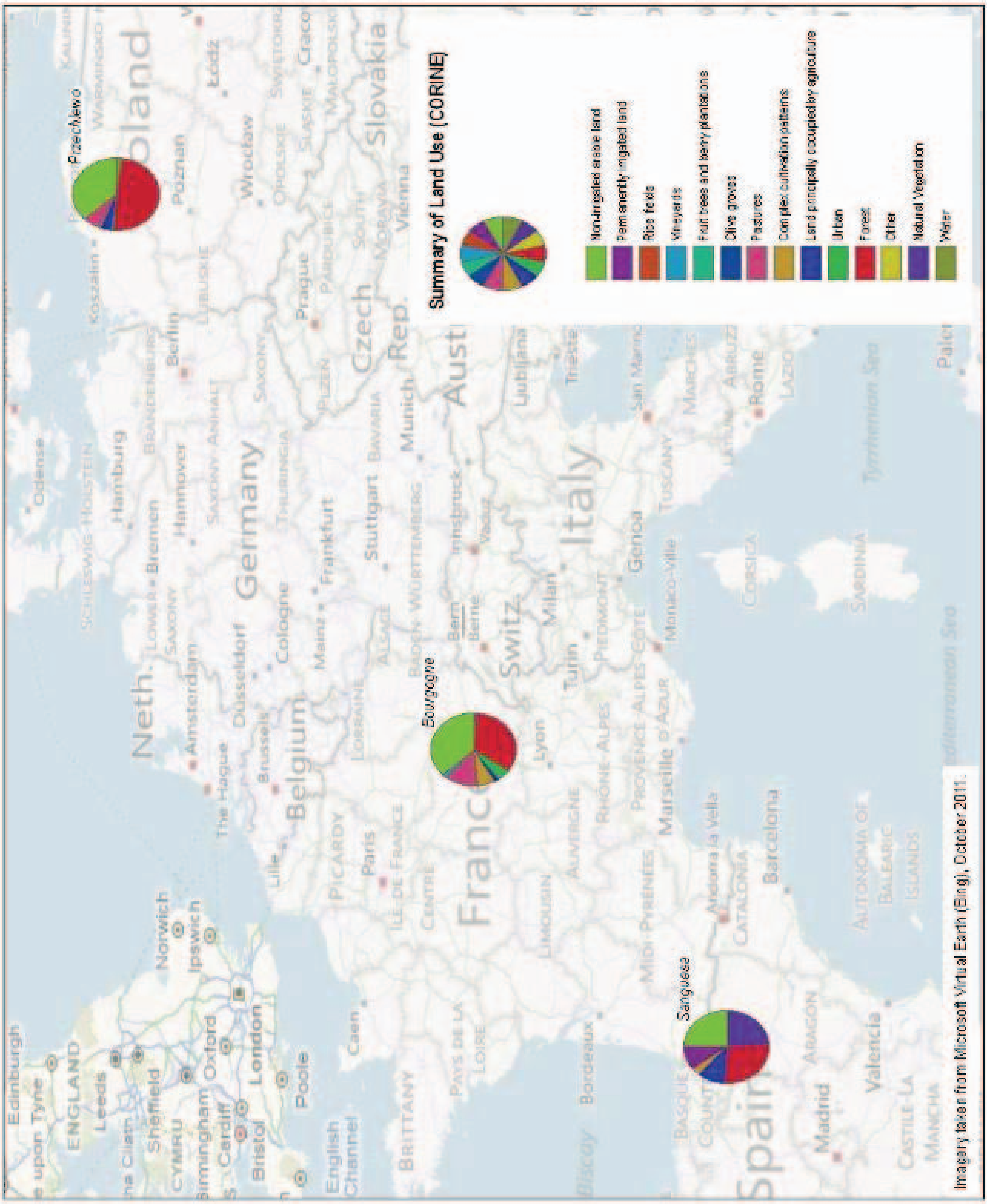
The most likely alternative land uses (i.e. the land uses with the highest proportions of the area within the 50 km radius buffers) are shown below.

**<u>Alternative Land Uses</u>**

| **Poland and France** | **Spain** |
|---|---|
| Non irrigated arable land (assumed to be predominantly wheat given that this was the feedstock for two of the case study plants) | Non irrigated arable land (assumed to be predominantly wheat given that this was the feedstock for two of the case study plants) |
| Forest | Forest |
| Pasture | Natural vegetation |

The carbon impacts of these alternative land uses are not have not been assessed within this study, although the carbon impacts of wheat production are likely to be similar in magnitude to impacts in the UK (Table 9) and natural vegetation is likely to sequester carbon at a rate highly dependent on the vegetation type and other local factors. The important carbon impacts in the context of this study are the impacts of biomass production, plus transport impacts, giving the comparison with biomass crop production in the UK, which imports could replace.

**Figure 5**: European Biomass Case Studies.



## 5.2 Carbon impacts of transport from importing biomass

### 5.2.1 *Carbon Impacts of transport from France to UK of biomass crops*

It is extremely unlikely that the UK will import wheat straw for energy generation because it has a low bulk density making it expensive to transport. Furthermore, wheat is currently the most prevalent UK arable crop with 1.79 million hectares of wheat cultivated in the UK in 2010 (Defra June Survey 2011), and not all of this straw is baled and used. Thus, further supplies of straw for energy generation could be sourced from the UK with lower transport costs than imports. Accordingly the emissions from transport from the two Polish and Spanish wheat straw plant case studies have not been assessed.

It is possible, but unlikely with current economic incentives, that miscanthus will be imported into the UK in significant quantities. Accordingly we have estimated transport emissions from the French miscanthus power plant (Bourgogne Power Plant) case study to the UK.

For additional context and to allow comparison of carbon impacts of transport by road with transport by sea we have calculated emissions from shipping miscanthus bales from Canada to the UK. Emissions from shipping are the only emissions that have been calculated in the case study of emissions from Canada.

Both transport carbon impacts have been calculated using Defra 2011 emission factors (Defra 2011).

### 5.2.2 *France – Transport Assumptions*

The assumptions for the French examples are for a one way journey by 17 tonne lorry assuming an average load of 52% (Defra 2011) from Bourgogne to Calais.

### 5.2.3 *Canada – Transport Assumptions*

The assumptions for Canada transport are for a one way journey of 5,744 km of a container ship from Toronto to Liverpool.

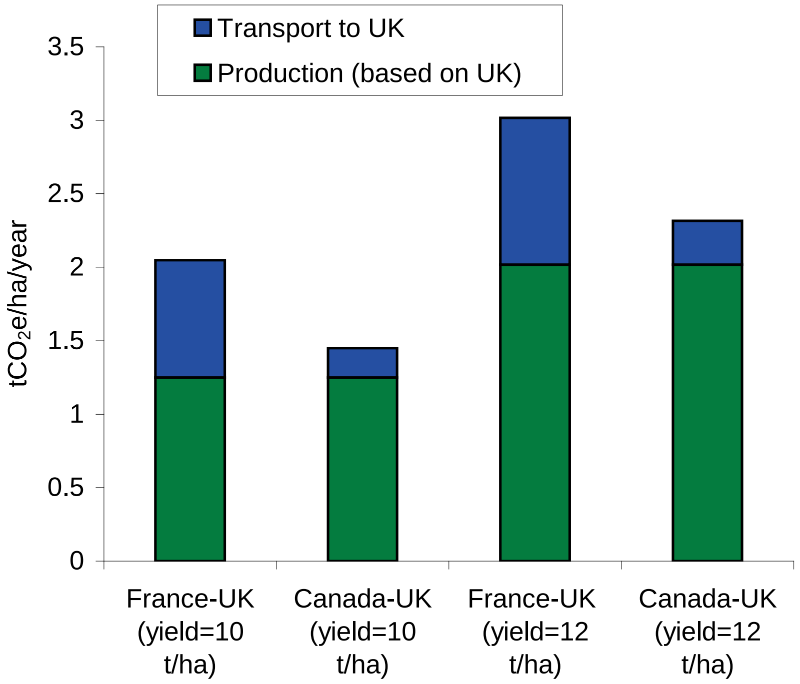
### 5.2.4 *Transport Results*

Figure 6 shows the breakdown and shows the total $CO_2$e impacts per hectare for two different journeys and the vast efficiencies of shipping compared to road transport are clearly shown. The distance from Canada to the UK is 10 times the distance from France to the UK yet the carbon impact of transport from Canada is around a quarter of the carbon impact of transport from France to the UK.

For imports from France, transport carbon impacts would be: 0.79 t $CO_2$e per hectare assuming a yield of 10 t/ha; and 0.95 t $CO_2$e per hectare assuming a yield of 12 t/ha.

For imports from Canada, transport carbon impacts would be: 0.2 t $CO_2$e per hectare assuming a yield of 10 t/ha; and 0.3 t $CO_2$e per hectare assuming a yield of 12 t/ha.

**Figure 6:** Carbon impacts of France–UK transport of biomass and Canada–UK transport of biomass.



# 6. DISCUSSION

The aim of this report was to identify the main alternative land uses to biomass crops grown within the UK and identify the carbon impacts of (a) biomass production and use for energy generation, and (b) alternative land uses.

Energy from biomass crops has a lower carbon impact (0.9 to 4.4 t $CO_2$e per ha/yr) than food crop production (3.1 to 11 t $CO_2$e per ha/yr). However, the ranges are large, and they overlap to some extent.

This headline result requires considerable qualification because the actual changes in land use when biomass crops are grown in place of food, or food production occurs in place of biomass crops, are very uncertain.

When biomass crops are grown in place of food, the food is likely to be grown elsewhere as market demand stimulates adequate production. It is not clear that the replacement area of food production will be the same as the area displaced because it is possible that increased competition for land will stimulate production efficiency and therefore higher yields, with replacement production on a smaller area of land. However, despite these uncertainties, it is highly likely that carbon impacts of the food production displaced by biomass crops will occur elsewhere and be on a similar scale to the displaced emissions.

A further qualification to the comparison between carbon impacts of energy from biomass crops and carbon impacts of food production is the possibility of indirect land use change (ILUC). This is land use change (LUC) that occurs as a consequence of changes elsewhere. When food production is displaced by another activity a chain of consequences may be triggered with very unpredictable changes in land use. Carbon impacts of LUC can be very high (e.g. 7 t $CO_2$e per ha/yr for change from permanent pasture to cropland). For any individual case, there is large uncertainty for whether or not ILUC will occur, and also the land types involved are highly uncertain.

When food production occurs in place of biomass crops the energy produced by use of biomass must be produced another way. If that energy production has the same carbon impact as national grid electricity, the carbon impacts will be greater (3.1 to 18 kg $CO_2$e per ha/yr) than the carbon impacts of generation using biomass (0.9 to 4.4 kg $CO_2$e per ha/yr). Again, the ranges are large and they overlap.

# REFERENCES AND DATA SOURCES


Acciona Energia (2011) Sangüesa Biomass Power Plant Project Navarra, Spain Available from http://www.accionaenergia.com/activity_areas/biomass/installations/plantasanguesa/planta-de-biomasa-de-sangueesa-(25-mw).aspx?id=1&desde=

Bourgogne Pellets (2010) Available from http://www.bourgogne-pellets.fr/la-societe

Dawson, J.J.C., Smith, P. (2007). Carbon losses from soil and its consequences for land-use management. Science of the Total Environment 382, 165-190.

Defra, (2007). Opportunities and optimum sitings for energy crops. (Accessed October 2011). Available from http://archive.defra.gov.uk/foodfarm/growing/crops/industrial/energy/opportunities/index.htm

Defra (2010) June Survey “County level crops areas/livestock numbers/labour force 2010” spreadsheet Available from http://www.defra.gov.uk/statistics/foodfarm/landuselivestock/junesurvey/junesurveyresults/

Defra (2011) “2011 Guidelines to Defra/DECC’s GHG conversion factors for company reporting” Available from http://www.defra.gov.uk/environment/economy/business-efficiency/reporting/

Environment Agency (2009) “Bioenergy Review – Mapping Work”. Bristol: Environment Agency. Available from http://publications.environment-agency.gov.uk/PDF/SCHO0809BQUQ-E-E.pdf

European Environment Agency, (2011). CORINE Land Cover 2006 raster data - version 15. Available from http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1

European Commission Energy (2011) Case study on Przechlewo Straw Biomass Power Plant Available from http://www.managenergy.net/resources/289

Forest Research, 1999. *Yield models for energy coppice of poplar and willow*. Project NF0407 for Defra. Available from: http://randd.defra.gov.uk/Document.aspx?Document=nf0407_4251_FRP.pdf [accessed 1 October 2011].

Frischknecht R, Althaus H-J, Bauer C, Doka G, Heck T, Jungbluth N, Kellenberger D, Nemecek T (2007) ‘The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services.’ Int J LCA, DOI: http://dx.doi.org/10.1065/lca2007.02.308

Garstang, J., et al. (2009)  Bioenergy Review. Environment Agency publication. Available from http://publications.environment-agency.gov.uk/PDF/SCHO0809BQUQ-E-E.pdf

Ofgem (2011) Figures see http://www.ofgem.gov.uk/Pages/MoreInformation.aspx? . docid=318&refer=Sustainability/Environment/RenewablObl/FuelledStations

Price L., Bullard, M., Lyons, H., Anthony, S. and Nixon, P., 2004. Identifying the yield potential of Miscanthusx giganteus: an assessment of the spatial and temporal variability of M. x giganteus biomass productivity across England and Wales. Biomass and Bioenergy, 26 (1) 3-13.

Wiltshire, J. et al. (2008). Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food. Technical annex to the final report for Defra project FO0404.

# Appendix 1

**DECC CARBON IMPACTS OF USING BIOMASS IN BIO-ENERGY AND OTHER SECTORS**

**Preliminary Greenhouse Gas Emissions Results for Energy Crops** (28.10.11)

| | |
|---|---|
| Main Sources of Results: | $BEAT_2$ workbooks (modified where necessary) |
| Global Warming Potentials: | 25 kg eq. $CO_2$/kg $CH_4$ |
| | 298 kg eq. $CO_2$/kg $N_2O$ |

**Miscanthus**

Miscanthus Bales at Farm Gate

Basic Assumption:

Nitrogen fertiliser application rate = 0 kg N/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00633 | 294 |
| Harvesting and Baling | 270 | 0.124 | 0.00423 | 274 |
| **Totals** | **559** | **0.258** | **0.01056** | **568** |

Assumption for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Cultivation | 16.9 | 0.00784 | 0.000370 | 17.2 |
| Harvesting and Baling | 15.8 | 0.00725 | 0.000247 | 16.0 |
| **Totals** | **32.7** | **0.01509** | **0.000617** | **33.2** |

Assumption for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Cultivation | 20.2 | 0.00937 | 0.000443 | 20.6 |
| Harvesting and Baling | 18.9 | 0.00867 | 0.000296 | 19.1 |
| **Totals** | **39.1** | **0.01804** | **0.000739** | **39.7** |

Miscanthus Chips at Farm Gate

Basic Assumption:

Nitrogen fertiliser application rate = 0 kg N/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 299 | 0.134 | 0.00633 | 304 |
| Harvesting and Chipping | 370 | 0.173 | 0.00591 | 376 |
| **Totals** | **669** | **0.307** | **0.01224** | **680** |

Assumption for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Chipping losses = 7%

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/t (ar) | Methane<br>kg $CH_4$/t (ar) | Nitrous Oxide<br>kg $N_2O$/t (ar) | Total Greenhouse Gases<br>kg eq. $CO_2$/t (ar) |
| Cultivation | 18.8 | 0.0084 | 0.000398 | 19.1 |
| Harvesting and Chipping | 23.3 | 0.0109 | 0.000371 | 23.7 |
| **Totals** | **42.1** | **0.0193** | **0.000769** | **42.8** |

Assumption for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Chipping losses = 7%

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/t (ar) | Methane<br>kg $CH_4$/t (ar) | Nitrous Oxide<br>kg $N_2O$/t (ar) | Total Greenhouse Gases<br>kg eq. $CO_2$/t (ar) |
| Cultivation | 22.5 | 0.01008 | 0.000476 | 22.9 |
| Harvesting and Chipping | 27.8 | 0.01301 | 0.000444 | 28.3 |
| **Totals** | **50.3** | **0.02309** | **0.000920** | **51.2** |

Commercial and Industrial Heating by Combustion: Miscanthus Bales

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 37.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00632 | 294 |
| Harvesting and Baling | 270 | 0.126 | 0.00425 | 274 |
| Transport to Storage | 111 | 0.070 | 0.02640 | 121 |
| Natural Drying in Storage | 26 | 0.043 | 0.00259 | 28 |
| Transport to Plant | 87 | 0.054 | 0.02048 | 94 |
| Combustion | 0 | 0.296 | 0.73937 | 228 |
| Plant | 77 | 0.113 | 0.00451 | 81 |
| Start-Up Fuel | 61 | 0.164 | 0.22680 | 133 |
| Ash Disposal | 3 | 0.002 | 0.00070 | 3 |
| Lime Displacement | - 4 | -0.009 | -0.00018 | - 4 |
| **Totals** | **920** | **0.993** | **1.03124** | **1252** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 30.2 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00635 | 295 |
| Harvesting and Baling | 270 | 0.125 | 0.00423 | 274 |
| Transport to Storage | 559 | 0.352 | 0.13241 | 607 |
| Natural Drying in Storage | 22 | 0.036 | 0.00212 | 24 |
| Transport to Plant | 433 | 0.273 | 0.10278 | 470 |
| Combustion | 0 | 0.248 | 0.61820 | 190 |
| Plant | 56 | 0.082 | 0.00323 | 59 |
| Start-Up Fuel | 50 | 0.134 | 0.18546 | 109 |
| Ash Disposal | 2 | 0.002 | 0.00060 | 2 |
| Lime Displacement | - 3 | -0.008 | -0.00030 | - 4 |
| **Totals** | **1679** | **1.378** | **1.05508** | **2026** |

Commercial and Industrial Heating by Combustion: Miscanthus Chips

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 40.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00633 | 295 |
| Harvesting and Chipping | 370 | 0.173 | 0.00593 | 376 |
| Transport to Storage | 115 | 0.073 | 0.02728 | 125 |
| Natural Drying in Storage | 27 | 0.044 | 0.02644 | 36 |
| Transport to Plant | 77 | 0.048 | 0.01827 | 84 |
| Combustion | 0 | 0.321 | 0.80128 | 239 |
| Plant | 108 | 0.160 | 0.00641 | 114 |
| Start-Up Fuel | 66 | 0.178 | 0.24579 | 144 |
| Ash Disposal | 2 | 0.002 | 0.00521 | 4 |
| Lime Displacement | - 3 | -0.007 | -0.00016 | - 3 |
| **Totals** | **1052** | **1.126** | **1.11634** | **1414** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 32.8 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00632 | 295 |
| Harvesting and Chipping | 370 | 0.173 | 0.00593 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13695 | 627 |
| Batch Drying and Storage | 1160 | 0.994 | 0.02538 | 1192 |
| Transport to Plant | 387 | 0.243 | 0.09168 | 420 |
| Combustion | 0 | 0.268 | 0.66983 | 206 |
| Plant | 68 | 0.100 | 0.00400 | 72 |
| Start-Up Fuel | 54 | 0.146 | 0.20095 | 118 |
| Ash Disposal | 2 | 0.001 | 0.00046 | 2 |
| Lime Displacement | - 2 | -0.006 | -0.00013 | - 2 |
| **Totals** | **2906** | **2.417** | **1.14107** | **3306** |

Commercial and Industrial Heating by Combustion: Miscanthus Pellets

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 37.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.135 | 0.00632 | 295 |
| Harvesting and Chipping | 370 | 0.172 | 0.00590 | 376 |
| Transport to Storage | 115 | 0.071 | 0.02728 | 125 |
| Bulk Drying and Storage | 1446 | 3.337 | 0.06487 | 1549 |
| Milling | 42 | 0.090 | 0.00127 | 45 |
| Pelletising | 205 | 0.531 | 0.00732 | 221 |
| Transport to Plant | 74 | 0.045 | 0.01753 | 80 |
| Combustion | 0 | 0.299 | 0.74738 | 230 |
| Plant | 78 | 0.114 | 0.00456 | 82 |
| Start-Up Fuel | 62 | 0.166 | 0.22907 | 134 |
| Ash Disposal | 2 | 0 | 0.00052 | 2 |
| Lime Displacement | - 3 | -0.007 | -0.00015 | - 3 |
| **Totals** | **2681** | **4.903** | **1.11187** | **3136** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 30.6 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00633 | 294 |
| Harvesting and Chipping | 370 | 0.174 | 0.00593 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13695 | 627 |
| Bulk Drying and Storage | 1209 | 2.790 | 0.05428 | 1295 |
| Milling | 35 | 0.076 | 0.00104 | 37 |
| Pelletising | 172 | 0.443 | 0.00614 | 185 |
| Transport to Plant | 371 | 0.235 | 0.08805 | 403 |
| Combustion | 0 | 0.250 | 0.61125 | 188 |
| Plant | 64 | 0.094 | 0.00373 | 67 |
| Start-Up Fuel | 51 | 0.136 | 0.18750 | 110 |
| Ash Disposal | 2 | 0 | 0.00043 | 2 |
| Lime Displacement | - 2 | -0.006 | -0.00012 | - 2 |
| **Totals** | **3138** | **4.690** | **1.10151** | **3582** |

Combined Heat and Power Generation by Combustion: Miscanthus Bales

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Combined Heat and Power Plant: Heat = 31 MW

Electricity = 12.5 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 88%

Output: Heat = 25.8 MWh/ha.a

Electricity = 10.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00615 | 295 |
| Harvesting and Baling | 270 | 0.124 | 0.00434 | 274 |
| Transport to Storage | 111 | 0.070 | 0.02639 | 121 |
| Natural Drying in Storage | 26 | 0.043 | 0.00253 | 28 |
| Transport to Plant | 86 | 0.055 | 0.02061 | 94 |
| Combustion | 0 | 0.296 | 0.73933 | 228 |
| Plant | 489 | 0.001 | 0.00002 | 489 |
| Start-Up Fuel | 4 | 0.009 | 0.00001 | 4 |
| Ash Disposal | 3 | 0.002 | 0.00072 | 5 |
| Lime Displacement | - 4 | -0.009 | -0.00036 | - 4 |
| **Totals** | **1275** | **0.725** | **0.79974** | **1534** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Combined Heat and Power Plant: Heat = 20 MW

Electricity = 8 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 54%

Output: Heat = 13.2 MWh/ha.a

Electricity = 5.3 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00631 | 295 |
| Harvesting and Baling | 270 | 0.124 | 0.00427 | 274 |
| Transport to Storage | 559 | 0.352 | 0.13244 | 607 |
| Natural Drying in Storage | 22 | 0.036 | 0.00223 | 24 |
| Transport to Plant | 434 | 0.273 | 0.10276 | 465 |
| Combustion | 0 | 0.247 | 0.61825 | 190 |
| Plant | 348 | 0.001 | 0.00002 | 348 |
| Start-Up Fuel | 4 | 0.008 | 0.00001 | 4 |
| Ash Disposal | 3 | 0.002 | 0.00056 | 3 |
| Lime Displacement | - 3 | -0.008 | -0.00019 | - 3 |
| **Totals** | **1927** | **1.169** | **0.86666** | **2207** |

Combined Heat and Power Generation by Combustion: Miscanthus Chips

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Combined Heat and Power Plant: Heat = 31 MW

Electricity = 12.5 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 88%

Output: Heat = 27.9 MWh/ha.a

Electricity = 11.3 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00635 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00591 | 376 |
| Transport to Storage | 115 | 0.072 | 0.02730 | 125 |
| Batch Drying and Storage | 27 | 0.044 | 0.00266 | 29 |
| Transport to Plant | 77 | 0.049 | 0.01825 | 84 |
| Combustion | 0 | 0.320 | 0.80102 | 247 |
| Plant | 513 | 0.001 | 0.00002 | 513 |
| Start-Up Fuel | 4 | 0.009 | 0.00001 | 4 |
| Ash Disposal | 2 | 0.002 | 0.00055 | 2 |
| Lime Displacement | - 3 | -0.007 | -0.00016 | - 3 |
| **Totals** | **1394** | **0.797** | **0.86191** | **1671** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Combined Heat and Power Plant: Heat = 20 MW

Electricity = 8 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 54%

Output: Heat = 14.4 MWh/ha.a

Electricity = 5.7 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00633 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00591 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13696 | 627 |
| Batch Drying and Storage | 1160 | 0.995 | 0.02539 | 1192 |
| Transport to Plant | 386 | 0.243 | 0.91678 | 665 |
| Combustion | 0 | 0.268 | 0.66995 | 206 |
| Plant | 310 | 0.001 | 0.00001 | 310 |
| Start-Up Fuel | 2 | 0.004 | 0 | 2 |
| Ash Disposal | 2 | 0.001 | 0.00044 | 2 |
| Lime Displacement | - 2 | -0.006 | -0.00012 | - 2 |
| **Totals** | **3094** | **2.177** | **1.76165** | **3672** |

Combined Heat and Power Generation by Combustion: Miscanthus Pellets

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Combined Heat and Power Plant: Heat = 31 MW

Electricity = 12.5 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 88%

Output: Heat = 26.0 MWh/ha.a

Electricity = 10.5 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00632 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00592 | 376 |
| Transport to Storage | 115 | 0.072 | 0.02730 | 125 |
| Bulk Drying and Storage | 1446 | 3.338 | 0.06491 | 1549 |
| Milling | 42 | 0.091 | 0.00124 | 45 |
| Pelletising | 206 | 0.531 | 0.00735 | 222 |
| Transport to Plant | 74 | 0.047 | 0.01754 | 80 |
| Combustion | 0 | 0.299 | 0.74744 | 230 |
| Plant | 561 | 0.001 | 0.00002 | 561 |
| Start-Up Fuel | 4 | 0.010 | 0.00001 | 4 |
| Ash Disposal | 2 | 0.001 | 0.00051 | 2 |
| Lime Displacement | - 3 | -0.007 | -0.00015 | - 3 |
| **Totals** | **3106** | **4.690** | **0.87841** | **3485** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Combined Heat and Power Plant: Heat = 20 MW

Electricity = 8 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 54%

Output: Heat = 13.4 MWh/ha.a

Electricity = 5.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00632 | 295 |
| Harvesting and Chipping | 370 | 0.173 | 0.00591 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13697 | 627 |
| Bulk Drying and Storage | 1209 | 2.791 | 0.05428 | 1295 |
| Milling | 35 | 0.078 | 0.00011 | 37 |
| Pelletising | 172 | 0.444 | 0.00613 | 185 |
| Transport to Plant | 371 | 0.234 | 0.08803 | 403 |
| Combustion | 0 | 0.250 | 0.62509 | 193 |
| Plant | 316 | 0.008 | 0.00001 | 316 |
| Start-Up Fuel | 2 | 0.004 | 0 | 2 |
| Ash Disposal | 2 | 0.001 | 0.00043 | 2 |
| Lime Displacement | - 2 | -0.005 | -0.00011 | - 2 |
| **Totals** | **3342** | **4.476** | **0.92317** | **3729** |

Power Only Generation by Co-firing: Miscanthus Chips

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 18.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00632 | 295 |
| Harvesting and Chipping | 370 | 0.173 | 0.00596 | 376 |
| Transport to Storage | 116 | 0.072 | 0.02727 | 126 |
| Natural Drying in Storage | 27 | 0.044 | 0.00271 | 29 |
| Transport to Plant | 87 | 0.055 | 0.02059 | 95 |
| Combustion | 0 | 0.361 | 0.90302 | 278 |
| Grinding Electricity and Plant Spares | 67 | 0.156 | 0.00217 | 72 |
| Ash Disposal | 3 | 0.001 | 0.00054 | 3 |
| **Totals** | **960** | **0.996** | **0.96858** | **1274** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Thermal Efficiency of Power Plant = 30%

Output: Electricity = 12.6 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00629 | 295 |
| Harvesting and Chipping | 370 | 0.173 | 0.00592 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13694 | 627 |
| Batch Drying and Storage | 782 | 0.994 | 0.02542 | 814 |
| Transport to Plant | 435 | 0.274 | 0.10334 | 473 |
| Combustion | 0 | 0.302 | 0.75519 | 232 |
| Grinding Electricity and Plant Spares | 56 | 0.131 | 0.00176 | 60 |
| Ash Disposal | 2 | 0.001 | 0.00050 | 2 |
| **Totals** | **2512** | **2.373** | **1.0356** | **2879** |

Power Only Generation by Co-firing: Miscanthus Pellets

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 14.8 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00632 | 295 |
| Harvesting and Chipping | 371 | 0.173 | 0.00591 | 377 |
| Transport to Storage | 115 | 0.073 | 0.02729 | 125 |
| Bulk Drying and Storage | 1447 | 3.338 | 0.06491 | 1550 |
| Milling | 42 | 0.091 | 0.00126 | 45 |
| Pelletising | 206 | 0.533 | 0.00736 | 222 |
| Transport to Plant | 74 | 0.047 | 0.01760 | 80 |
| Combustion | 0 | 0.296 | 0.73877 | 228 |
| Grinding Electricity and Plant Spares | 57 | 0.133 | 0.00183 | 61 |
| Ash Disposal | 2 | 0.002 | 0.00046 | 2 |
| **Totals** | **2604** | **4.820** | **0.87171** | **2985** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Thermal Efficiency of Power Plant = 30%

Output: Electricity = 10.3 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00632 | 294 |
| Harvesting and Chipping | 371 | 0.173 | 0.00591 | 377 |
| Transport to Storage | 578 | 0.364 | 0.13695 | 628 |
| Bulk Drying and Storage | 1210 | 2.791 | 0.05427 | 1296 |
| Milling | 35 | 0.076 | 0.00105 | 37 |
| Pelletising | 172 | 0.446 | 0.00615 | 185 |
| Transport to Plant | 372 | 0.235 | 0.08832 | 404 |
| Combustion | 0 | 0.247 | 0.61779 | 190 |
| Grinding Electricity and Plant Spares | 25 | 0.112 | 0.00153 | 28 |
| Ash Disposal | 2 | 0.002 | 0.00038 | 2 |
| **Totals** | **3054** | **4.580** | **0.91867** | **3441** |

Power Only Generation (Dedicated) by Combustion: Miscanthus Bales

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 14.8 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00636 | 294 |
| Harvesting and Baling | 270 | 0.125 | 0.00429 | 274 |
| Transport to Storage | 111 | 0.070 | 0.02647 | 121 |
| Natural Drying in Storage | 26 | 0.043 | 0.00251 | 28 |
| Transport to Plant | 86 | 0.054 | 0.02056 | 93 |
| Combustion | 0 | 0.296 | 0.73943 | 228 |
| Plant | 212 | 0 | 0.00001 | 212 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 3 | 0.002 | 0.00074 | 3 |
| Lime Displacement | - 4 | -0.009 | -0.00015 | - 4 |
| **Totals** | **993** | **0.715** | **0.80022** | **1249** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 8.6 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00636 | 295 |
| Harvesting and Baling | 270 | 0.124 | 0.00421 | 274 |
| Transport to Storage | 559 | 0.352 | 0.13251 | 607 |
| Natural Drying in Storage | 22 | 0.036 | 0.00215 | 24 |
| Transport to Plant | 434 | 0.273 | 0.10288 | 471 |
| Combustion | 0 | 0.247 | 0.61834 | 190 |
| Plant | 157 | 0 | 0.00001 | 157 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.002 | 0.00060 | 2 |
| Lime Displacement | - 3 | -0.008 | -0.00017 | - 3 |
| **Totals** | **1731** | **1.160** | **0.86689** | **2017** |

Power Only Generation (Dedicated) by Combustion: Miscanthus Chips

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 16.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 290 | 0.134 | 0.00633 | 295 |
| Harvesting and Chipping | 370 | 0.174 | 0.00591 | 376 |
| Transport to Storage | 115 | 0.072 | 0.02729 | 125 |
| Natural Drying in Storage | 27 | 0.044 | 0.00266 | 29 |
| Transport to Plant | 77 | 0.049 | 0.01827 | 84 |
| Combustion | 0 | 0.320 | 0.80115 | 247 |
| Plant | 230 | 0.001 | 0.00001 | 230 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.001 | 0.00052 | 2 |
| Lime Displacement | - 3 | -0.007 | -0.00014 | - 3 |
| **Totals** | **1108** | **0.788** | **0.86200** | **1385** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 9.3 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00633 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00592 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13695 | 627 |
| Batch Drying and Storage | 1160 | 0.994 | 0.02538 | 1192 |
| Transport to Plant | 386 | 0.244 | 0.09166 | 419 |
| Combustion | 0 | 0.261 | 0.66995 | 206 |
| Plant | 170 | 0 | 0 | 170 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.001 | 0.00045 | 2 |
| Lime Displacement | - 2 | -0.006 | -0.00013 | - 2 |
| **Totals** | **2952** | **2.165** | **0.93651** | **3284** |

Power Only Generation (Dedicated) by Combustion: Miscanthus Pellets

Assumptions for Low Case:

High Yield = 12 t (oven dry)/ha.a

= 17.1 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 14.9 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00632 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00592 | 376 |
| Transport to Storage | 115 | 0.073 | 0.02730 | 125 |
| Bulk Drying and Storage | 1446 | 3.337 | 0.06490 | 1549 |
| Milling | 42 | 0.091 | 0.00125 | 45 |
| Pelletising | 205 | 0.531 | 0.00733 | 220 |
| Transport to Plant | 74 | 0.047 | 0.01755 | 80 |
| Combustion | 0 | 0.299 | 0.74750 | 230 |
| Plant | 214 | 0 | 0 | 214 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.001 | 0.00051 | 2 |
| Lime Displacement | - 3 | -0.007 | -0.00015 | - 3 |
| **Totals** | **2754** | **4.679** | **0.87848** | **3132** |

Assumptions for High Case:

Low Yield = 11 t (oven dry)/ha.a

= 14.3 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Bulk Drying with Electricity

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 8.7 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 289 | 0.134 | 0.00633 | 294 |
| Harvesting and Chipping | 370 | 0.173 | 0.00591 | 376 |
| Transport to Storage | 577 | 0.364 | 0.13695 | 627 |
| Bulk Drying and Storage | 1209 | 2.791 | 0.05427 | 1295 |
| Milling | 35 | 0.076 | 0.00105 | 37 |
| Pelletising | 172 | 0.444 | 0.00613 | 185 |
| Transport to Plant | 371 | 0.234 | 0.08804 | 403 |
| Combustion | 0 | 0.250 | 0.06251 | 24 |
| Plant | 159 | 0 | 0 | 159 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.001 | 0.00043 | 2 |
| Lime Displacement | - 2 | -0.005 | -0.00012 | - 2 |
| **Totals** | **3182** | **4.462** | **0.36150** | **3400** |

**Short Rotation Coppice**

SRC Wood Chips at Farm Gate

Basic Assumptions:

Nitrogen fertiliser application rate = 0 kg N/ha.a

Chip harvesting

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205.1 | 0.0286 | 0.029389 | 214.6 |
| Harvesting and Chipping | 65.4 | 0.0167 | 0.000460 | 66.0 |
| **Totals** | **270.5** | **0.0453** | **0.029849** | **280.6** |

Assumption for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Cultivation | 8.7 | 0.00122 | 0.00126 | 9.1 |
| Harvesting and Chipping | 2.8 | 0.00071 | 0.00002 | 2.8 |
| **Totals** | **11.5** | **0.00193** | **0.00128** | **11.9** |

Assumption for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Cultivation | 10.3 | 0.00143 | 0.00147 | 10.8 |
| Harvesting and Chipping | 3.3 | 0.00083 | 0.00002 | 3.3 |
| **Totals** | **13.6** | **0.00226** | **0.00170** | **14.1** |

Commercial and Industrial Heating by Combustion: Wood Chips from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 42.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Transport to Plant | 109 | 0.069 | 0.026 | 118 |
| Combustion | 0 | 1.695 | 0.508 | 194 |
| Plant | 120 | 0.181 | 0.007 | 127 |
| Start-Up Fuel | 70 | 0.188 | 0.260 | 152 |
| Ash Disposal | 2 | 0.001 | 0 | 2 |
| Lime Displacement | - 2 | -0.006 | 0 | - 2 |
| **Totals** | **778** | **2.346** | **0.874** | **1097** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 35.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 2119 | 1.767 | 0.044 | 2176 |
| Transport to Plant | 561 | 0.354 | 0.133 | 609 |
| Combustion | 0 | 1.449 | 0.435 | 166 |
| Plant | 105 | 0.154 | 0.006 | 111 |
| Start-Up Fuel | 59 | 0.157 | 0.217 | 128 |
| Ash Disposal | 1 | 0.001 | 0 | 1 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **3981** | **4.470** | **1.070** | **4411** |

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 47.9 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Milling | 42 | 0.115 | 0.001 | 45 |
| Pelletising | 241 | 0.651 | 0.009 | 260 |
| Transport to Plant | 86 | 0.054 | 0.021 | 93 |
| Combustion | 0 | 0.096 | 0.766 | 231 |
| Plant | 187 | 0.274 | 0.293 | 281 |
| Start-Up Fuel | 79 | 0.213 | 0.011 | 88 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| Lime Displacement | 0 | -0.001 | 0 | 0 |
| **Totals** | **1114** | **1.620** | **1.174** | **1504** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 40.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 3243 | 2.592 | 0.061 | 3326 |
| Milling | 36 | 0.098 | 0.001 | 39 |
| Pelletising | 206 | 0.556 | 0.007 | 222 |
| Transport to Plant | 440 | 0.277 | 0.104 | 478 |
| Combustion | 0 | 0.082 | 0.655 | 197 |
| Plant | 160 | 0.235 | 0.010 | 169 |
| Start-Up Fuel | 66 | 0.178 | 0.245 | 143 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| Lime Displacement | 0 | -0.001 | 0 | 0 |
| **Totals** | **5289** | **4.610** | **1.318** | **5796** |

Domestic Heating by Combustion: Wood Pellets from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.03 MW

Load Factor of Heating Plant = 25%

Thermal Efficiency of Heating Plant = 94%

Output: Heat = 50 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Milling | 42 | 0.115 | 0.001 | 45 |
| Pelletising | 241 | 0.651 | 0.009 | 260 |
| Transport to Plant | 86 | 0.054 | 0.021 | 94 |
| Combustion | 0 | 0.096 | 0.766 | 231 |
| Plant | 486 | 0.714 | 0.029 | 512 |
| Start-Up Fuel | 120 | 0.323 | 0.446 | 261 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| Lime Displacement | 0 | -0.002 | 0 | 0 |
| **Totals** | **1454** | **2.209** | **1.345** | **1909** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.03 MW

Load Factor of Heating Plant = 25%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 40.9 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 3242 | 2.579 | 0.061 | 3325 |
| Milling | 36 | 0.099 | 0.001 | 39 |
| Pelletising | 206 | 0.556 | 0.007 | 222 |
| Transport to Plant | 440 | 0.277 | 0.104 | 478 |
| Combustion | 0 | 0.082 | 0.655 | 197 |
| Plant | 416 | 0.610 | 0.024 | 438 |
| Start-Up Fuel | 98 | 0.264 | 0.365 | 213 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| Lime Displacement | 0 | -0.001 | 0 | 0 |
| **Totals** | **5576** | **5.059** | **1.452** | **6134** |

Combined Heat and Power Generation by Combustion: Wood Chips from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Combined Heat and Power Plant: Heat = 31 MW

Electricity = 12.5 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 88%

Output: Heat = 29.5 MWh/ha.a

Electricity = 11.9 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.106 | 0.040 | 183 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Transport to Plant | 109 | 0.069 | 0.026 | 118 |
| Combustion | 0 | 0 | 0 | 0 |
| Plant | 637 | 0.002 | 0 | 637 |
| Start-Up Fuel | 1 | 0.002 | 0 | 1 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| Lime Displacement | - 2 | -0.006 | 0 | 0 |
| **Totals** | **1224** | **0.284** | **0.099** | **1261** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Combined Heat and Power Plant: Heat = 20 MW

Electricity = 8 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 54%

Output: Heat = 15.5 MWh/ha.a

Electricity = 6.2 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 2119 | 1.767 | 0.043 | 2176 |
| Transport to Plant | 561 | 0.354 | 0.133 | 609 |
| Combustion | 0 | 0 | 0 | 0 |
| Plant | 536 | 0.001 | 0 | 536 |
| Start-Up Fuel | 1 | 0.002 | 0 | 1 |
| Ash Disposal | 2 | 0.002 | 0 | 2 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **4355** | **2.714** | **0.411** | **4544** |

Power Only Generation by Co-firing: Wood Chips from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Thermal Efficiency of Electricity Plant = 36%

Output: Electricity = 17.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0.001 | 66 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Transport to Plant | 109 | 0.069 | 0.026 | 118 |
| Combustion | 0 | 0.085 | 0.678 | 204 |
| Grinding Electricity and Plant Spares | 84 | 0.197 | 0.003 | 90 |
| Ash Disposal | 2 | 0.002 | 0.001 | 2 |
| **Totals** | **674** | **0.571** | **0.782** | **921** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Thermal Efficiency of Electricity Plant = 25%

Output: Electricity = 10.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0.001 | 66 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 2119 | 1.767 | 0.044 | 2176 |
| Transport to Plant | 561 | 0.354 | 0.133 | 609 |
| Combustion | 0 | 0.072 | 0.580 | 175 |
| Grinding Electricity and Plant Spares | 72 | 0.168 | 0.002 | 77 |
| Ash Disposal | 2 | 0.002 | 0 | 2 |
| **Totals** | **3892** | **2.956** | **0.995** | **4262** |

Power Only Generation by Co-firing: Wood Pellets from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Thermal Efficiency of Electricity Plant = 36%

Output: Electricity = 19.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.065 | 0.004 | 43 |
| Milling | 42 | 0.115 | 0.002 | 45 |
| Pelletising | 241 | 0.651 | 0.009 | 260 |
| Transport to Plant | 86 | 0.054 | 0.020 | 93 |
| Combustion | 0 | 0.096 | 0.767 | 231 |
| Grinding Electricity and Plant Spares | 37 | 0.076 | 0.001 | 39 |
| Ash Disposal | 0 | 0.001 | 0 | 0 |
| **Totals** | **885** | **1.211** | **0.872** | **1174** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage = road

Round Trip Transport Distance to Storage = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Thermal Efficiency of Electricity Plant = 25%

Output: Electricity = 11.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.026 | 889 |
| Batch Drying and Storage | 3242 | 2.580 | 0.061 | 3325 |
| Milling | 36 | 0.098 | 0.001 | 39 |
| Pelletising | 206 | 0.556 | 0.007 | 222 |
| Transport to Plant | 440 | 0.277 | 0.104 | 478 |
| Combustion | 0 | 0.082 | 0.656 | 198 |
| Grinding Electricity and Plant Spares | 32 | 0.065 | 0.001 | 34 |
| Ash Disposal | 0 | 0 | 0 | 0 |
| **Totals** | **5094** | **4.251** | **0.885** | **5464** |

Power Only Generation (Dedicated) by Combustion: Wood Chips from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 17.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.064 | 0.004 | 43 |
| Transport to Plant | 109 | 0.070 | 0.026 | 118 |
| Combustion | 0 | 0.085 | 0.678 | 204 |
| Plant | 243 | 0.541 | 0.008 | 260 |
| Start-Up Fuel | 2 | 0.004 | 0 | 2 |
| Ash Disposal | 2 | 0.002 | 0 | 2 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **833** | **0.914** | **0.785** | **1090** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 10.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 2119 | 1.767 | 0.044 | 2176 |
| Transport to Plant | 561 | 0.354 | 0.133 | 609 |
| Combustion | 0 | 0.072 | 0.580 | 175 |
| Plant | 184 | 0.410 | 0.006 | 196 |
| Start-Up Fuel | 1 | 0.002 | 0 | 1 |
| Ash Disposal | 2 | 0.001 | 0 | 2 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **4003** | **3.194** | **0.998** | **4379** |

Power Only Generation (Dedicated) by Combustion: Wood Pellets from SRC Chip Harvesting

Assumptions for Low Case:

High Yield = 11.7 t (oven dry)/ha.a

= 23.4 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 19.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 169 | 0.107 | 0.040 | 184 |
| Natural Drying in Storage | 40 | 0.064 | 0.004 | 43 |
| Milling | 42 | 0.115 | 0.002 | 45 |
| Pelletising | 241 | 0.651 | 0.009 | 260 |
| Transport to Plant | 109 | 0.070 | 0.026 | 118 |
| Combustion | 0 | 0.085 | 0.678 | 204 |
| Plant | 243 | 0.541 | 0.008 | 260 |
| Start-Up Fuel | 2 | 0.004 | 0 | 2 |
| Ash Disposal | 2 | 0.002 | 0 | 2 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **1116** | **1.680** | **0.796** | **1395** |

Assumptions for High Case:

Low Yield = 10.0 t (oven dry)/ha.a

= 20.0 t (as received)/ha.a (at 50% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Batch Drying with Diesel Fuel

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 10.1 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Cultivation | 205 | 0.029 | 0.029 | 214 |
| Harvesting and Chipping | 65 | 0.017 | 0 | 65 |
| Transport to Storage | 868 | 0.547 | 0.206 | 943 |
| Batch Drying and Storage | 2119 | 1.767 | 0.044 | 2176 |
| Transport to Plant | 561 | 0.354 | 0.133 | 609 |
| Milling | 36 | 0.098 | 0.001 | 39 |
| Pelletising | 206 | 0.556 | 0.007 | 222 |
| Combustion | 0 | 0.072 | 0.580 | 175 |
| Plant | 184 | 0.410 | 0.006 | 196 |
| Start-Up Fuel | 1 | 0.002 | 0 | 1 |
| Ash Disposal | 2 | 0.001 | 0 | 2 |
| Lime Displacement | - 2 | -0.005 | 0 | - 2 |
| **Totals** | **4245** | **3.802** | **1.006** | **4640** |

**Wheat Straw**

Basic Assumption:

Straw treated as a residue (no allocation between wheat grain and straw)

No account taken of subsequent effects of straw removal relative to incorporation and impact on subsequent crops.

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| **Totals** | **373** | **0.153** | **0.00503** | **378** |

Assumption for Low Case:

High Yield = 4.2 t (as received)/ha.a (at 25% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Baling and Carting | 88.8 | 0.0364 | 0.00120 | 90.1 |
| **Totals** | **88.8** | **0.0364** | **0.00120** | **90.1** |

Assumption for High Case:

Low Yield = 1.9 t (as received)/ha.a (at 25% moisture content by weight)

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/t (ar) | Methane kg $CH_4$/t (ar) | Nitrous Oxide kg $N_2O$/t (ar) | Total Greenhouse Gases kg eq. $CO_2$/t (ar) |
| Baling and Carting | 196.3 | 0.0805 | 0.00265 | 199.1 |
| **Totals** | **196.3** | **0.0805** | **0.00265** | **199.1** |

Commercial and Industrial Heating by Combustion: Straw Bales

Assumptions for Low Case:

High Yield = 4.2 t (as received)/ha.a (at 25% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 90%

Output: Heat = 10.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| Transport to Storage | 30 | 0.019 | 0.00714 | 33 |
| Natural Drying in Storage | 7 | 0.012 | 0.00070 | 8 |
| Transport to Plant | 23 | 0.015 | 0.00549 | 25 |
| Combustion | 0 | 0.199 | 0.11964 | 41 |
| Plant | 19 | 0.028 | 0.00110 | 20 |
| Start-Up Fuel | 16 | 0.044 | 0.06117 | 35 |
| Ash Disposal | 2 | 0.001 | 0.00036 | 2 |
| Lime Displacement | - 2 | -0.005 | -0.00010 | - 2 |
| **Totals** | **468** | **0.466** | **0.20053** | **540** |

Assumptions for High Case:

Low Yield = 1.9 t (as received)/ha.a (at 25% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Heating Plant = 0.8 MW

Load Factor of Heating Plant = 65%

Thermal Efficiency of Heating Plant = 88%

Output: Heat = 4.4 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| Transport to Storage | 82 | 0.051 | 0.01936 | 89 |
| Natural Drying in Storage | 3 | 0.005 | 0.00031 | 3 |
| Transport to Plant | 63 | 0.040 | 0.01492 | 68 |
| Combustion | 0 | 0.090 | 0.05414 | 18 |
| Plant | 8 | 0.012 | 0.00047 | 8 |
| Start-Up Fuel | 7 | 0.020 | 0.02706 | 16 |
| Ash Disposal | 1 | 0 | 0.00016 | 1 |
| Lime Displacement | - 1 | -0.002 | -0.00004 | - 1 |
| **Totals** | **536** | **0.369** | **0.12141** | **580** |

Combined Heat and Power Generation by Combustion: Straw Bales

Assumptions for Low Case:

High Yield = 4.2 t (as received)/ha.a (at 25% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Combined Heat and Power Plant: Heat = 31 MW

Electricity = 12.5 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 88%

Output: Heat = 6.9 MWh/ha.a

Electricity = 2.9 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| Transport to Storage | 30 | 0.019 | 0.00714 | 33 |
| Natural Drying in Storage | 7 | 0.012 | 0.00069 | 8 |
| Transport to Plant | 23 | 0.015 | 0.00550 | 25 |
| Combustion | 0 | 0.199 | 0.11967 | 41 |
| Plant | 150 | 0 | 0.00001 | 150 |
| Start-Up Fuel | 1 | 0.003 | 0 | 1 |
| Ash Disposal | 1 | 0.001 | 0.00026 | 1 |
| Lime Displacement | - 1 | -0.003 | -0.00008 | - 1 |
| **Totals** | **584** | **0.408** | **0.13822** | **636** |

Assumptions for High Case:

Low Yield = 1.9 t (as received)/ha.a (at 25% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Combined Heat and Power Plant: Heat = 20 MW

Electricity = 8 MW

Load Factor of Combined Heat and Power Plant = 55%

Thermal Efficiency of Combined Heat and Power Plant = 54%

Output: Heat = 1.9 MWh/ha.a

Electricity = 0.8 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| Transport to Storage | 82 | 0.051 | 0.01937 | 89 |
| Natural Drying in Storage | 3 | 0.005 | 0.00031 | 3 |
| Transport to Plant | 63 | 0.040 | 0.01492 | 68 |
| Combustion | 0 | 0.090 | 0.05414 | 18 |
| Plant | 67 | 0 | 0 | 67 |
| Start-Up Fuel | 1 | 0.002 | 0 | 1 |
| Ash Disposal | 1 | 0 | 0.00012 | 1 |
| Lime Displacement | - 1 | -0.002 | -0.00003 | - 1 |
| **Totals** | **589** | **0.339** | **0.09386** | **624** |

Power Only Generation (Dedicated) by Combustion: Straw Bales

Assumptions for Low Case:

High Yield = 4.2 t (as received)/ha.a (at 30% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 100 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 100 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 36%

Output: Electricity = 4.0 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide<br>kg $CO_2$/ha.a | Methane<br>kg $CH_4$/ha.a | Nitrous Oxide<br>kg $N_2O$/ha.a | Total Greenhouse Gases<br>kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00503 | 378 |
| Transport to Storage | 30 | 0.019 | 0.00714 | 33 |
| Natural Drying in Storage | 7 | 0.012 | 0.00068 | 8 |
| Transport to Plant | 23 | 0.015 | 0.00550 | 25 |
| Combustion | 0 | 0.080 | 0.19944 | 61 |
| Plant | 57 | 0 | 0 | 57 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 2 | 0.001 | 0.00036 | 2 |
| Lime Displacement | - 2 | -0.005 | -0.00012 | - 2 |
| **Totals** | **490** | **0.275** | **0.21803** | **562** |

Assumptions for High Case:

Low Yield = 1.9 t (as received)/ha.a (at 25% moisture content by weight)

Transport Mode to Storage/Fuel Processing = road

Round Trip Transport Distance to Storage/Fuel Processing = 600 km

Natural Drying

Transport Mode to End Use = road

Round Trip Transport Distance to End Use = 600 km

Net Output Rating of Power Plant = 25 MW

Load Factor of Power Plant = 85%

Thermal Efficiency of Power Plant = 25%

Output: Electricity = 1.3 MWh/ha.a

| Contribution | Greenhouse Gas Emissions | | | |
|---|---|---|---|---|
| | Carbon Dioxide kg $CO_2$/ha.a | Methane kg $CH_4$/ha.a | Nitrous Oxide kg $N_2O$/ha.a | Total Greenhouse Gases kg eq. $CO_2$/ha.a |
| Baling and Carting | 373 | 0.153 | 0.00504 | 378 |
| Transport to Storage | 82 | 0.052 | 0.01938 | 89 |
| Natural Drying in Storage | 3 | 0.005 | 0.00031 | 3 |
| Transport to Plant | 63 | 0.040 | 0.01493 | 68 |
| Combustion | 0 | 0.036 | 0.09024 | 28 |
| Plant | 23 | 0 | 0 | 23 |
| Start-Up Fuel | 0 | 0 | 0 | 0 |
| Ash Disposal | 1 | 0 | 0.00016 | 1 |
| Lime Displacement | - 1 | -0.002 | -0.00005 | - 1 |
| **Totals** | **544** | **0.284** | **0.13001** | **589** |