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To cite this article: Patricia Thornley 2008 Environ. Res. Lett. 3 014004

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Airborne emissions from biomass based power generation systems

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Received 28 November 2007
Accepted for publication 27 February 2008
Published 13 March 2008
Online at stacks.iop.org/ERL/3/014004

Abstract
Generating electricity from biomass generates airborne pollution from the thermal conversion facility, but also from the upstream activities required to produce, process and provide the biomass. It is important that this is recognized in environmental evaluations of biomass power plants. Previous work had shown that off-site emissions could be significant for at least two particular bioenergy plants, but had not examined the extent to which this was likely to be generally applicable for a range of technologies and feedstocks; nor identified which steps were most likely to cause significant pollution. A number of bioenergy systems were modelled over whole life cycle to evaluate direct airborne emissions for short rotation coppice and miscanthus energy crops. This showed that CO and hydrocarbon emissions arise predominantly at the thermal conversion plant but up to 44% of NO$_x$ and 70% of particulate emissions could be released upstream. Transportation is a minor contributor; with harvesting and tractor transport potentially most significant.

Keywords: biomass, life cycle, emissions, environmental impact, supply chain

1. Introduction
Biomass based power generation is an increasingly popular renewable energy technology. Many life cycle analyses of biomass systems show overall greenhouse gas benefits [1–5]. However production and provision of the biomass (such as wood or perennial grass crops) gives rise to other airborne emissions. Whole-system studies considering these for relatively large facilities have still found net environmental benefits, but noted the potential for significant impacts related to diesel machinery [6–8]. Two studies that thoroughly disaggregated key air pollutants [9, 10] found substantial off-site contributions; one noted this may be site specific [9] to small scale district heating with long distance transport of forestry residues, while the other [10] considered a 30 MWe (megawatts electrical) plant with energy crops immediately adjacent and found that crop production was a major source of non-greenhouse gas emissions.

This study extends these results by considering different technologies, feedstocks and scales, in order to establish the extent to which offsite emissions may contribute to overall environmental impact. Direct emissions associated with each step (including crop cultivation and transportation) are included; indirect emissions associated with production of other materials consumed in the system e.g. agrochemicals, steel, concrete are not.

2. Background
Four airborne pollutants have been considered for this study: carbon monoxide (CO), nitrogen oxides (NO$_x$), particulates and volatile organic compounds (VOCs).

Carbon monoxide is emitted by combustion processes and is one of the most common and evenly distributed air pollutants. It affects the transport of oxygen in the blood, which can affect the cardiovascular response to exercise or exertion, particularly in individuals already suffering from cardiovascular disease [11]. Levels tend to be higher in urban city environments, owing to the prevalence of vehicles, although emission levels in the UK fell by 71% between 1990 and 2005 [12], primarily due to the fitting of catalytic...
It has been assumed for the purposes of this work that a catalytic converter has been fitted to the exhaust of the reciprocating engine systems, in line with current best practice.

Nitrogen oxides (NO\textsubscript{x}) are acid gases and ozone precursors and can affect human health and vegetation. Nitrogen dioxide is believed to have both acute and chronic effects on airway and lung function, particularly in people with asthma. NO\textsubscript{x} emissions have reduced by 45% from 1990 to 2005. As in the case of CO this is mainly due to the impact of fitting catalytic converters to cars [13]. Further reductions in emissions are still required by 2010 under the EU National Emissions Ceiling Directive and the EC large combustion plant directive required a substantial reduction in total NO\textsubscript{x} emissions by 1998, with additional restrictions for plants above 50 MW from 2008.

Airborne particulate emissions can arise from a variety of sources, including combustion plants. Particulate air pollution is responsible for causing premature deaths in those with pre-existing lung and heart disease. It is one of the most significant forms of air pollution from a public health perspective and long term exposure even to low levels has been identified as a public health risk [14]. Particulate levels have increased slightly in each of the last two years, but there has been an overall downward trend since 1993, the first year for which UK data is available.

Eight different biomass based power generation systems are evaluated, which are summarized in table 1 and described below.

In system A (250 kWe SRC engine), a short rotation coppice (SRC) willow energy crop dries in the field to 30% moisture content, before transport to the plant by tractor and trailer, where it is dried to 15% using hot process air. The willow is gasified in a downdraught gasifier, producing a gas, which is cooled, filtered and cleaned in a cold scrubbing unit and passed to a gas engine, where it is burnt to generate electricity. This facility would be suitable for small scale farm installation.

System B (5 MWe SRC engine) is a larger twin fluidized bed gasifier using steam and air as oxidants. SRC willow is transported by tractor to covered storage, where it dries to 30% moisture, before being mechanically reclaimed and transported by articulated lorry to the plant. The willow is fed directly to the gasifier and the product gas cooled, filtered and scrubbed before being passed to a reciprocating engine, where it is burnt to directly generate electricity. As an indication of scale, this facility would require around 6 round-trips by delivery vehicles per delivery day and would support around 20 full time jobs.

System C (5 MWe SRC grate) uses short rotation coppice willow, supplied as in B, in a fixed bed grate. The feedstock is directly combusted, generating heat, which raises steam in a high pressure boiler, which generates electricity in a steam turbine on the same scale as system B.

System D (5 MWe misc engine) uses miscanthus, a perennial grass, grown as an energy crop in the same way and at the same scale that willow is used in system B. The miscanthus is harvested and baled in winter and carted 3 miles to a satellite bale store, from which it is offloaded, as required, for transport via 120 m\textsuperscript{3} articulated lorry to the plant.

System E (25 MWe SRC grate) is a fixed bed grate fired with SRC willow, like system C, but much larger. It’s scale is comparable to the largest dedicated biomass plants that have been built in the UK. This requires substantial feedstock storage and management facilities, with typically more than 30 deliveries per delivery day and supporting over 90 full time jobs.

System F (25 MWe misc grate) is the same as system E, but uses miscanthus, rather than SRC feedstock. This is baled and supplied as described for system D.

System G (25 MWe SRC press GCC) is an advanced technology pressurized gasification combined cycle system. Willow SRC feedstock arriving by lorry (after covered storage) is dried to 15% moisture using process flue gases, before feeding to a gasifier with sand and dolomite bed material and oxidant air. The product gas is cooled to 350°C, cleaned in a hot gas filter and combusted in a gas turbine, generating electricity. Heat recovered from the gas turbine exhaust gases in a heat recovery steam generator raises steam which generates electricity in a steam turbine. There are no working examples of this technology at this scale. Substantial research and development effort is being directed at key barriers, including achieving adequate gas cleanliness for the gas turbine.

System H (25 MWe misc press GCC) is the same as system G, but with a miscanthus feedstock.

### Table 1. Key properties of power plant systems studied.

<table>
<thead>
<tr>
<th>Electrical capacity (MWe)</th>
<th>Fuel</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Willow SRC</td>
<td>Downdraught gasifier and reciprocating engine</td>
</tr>
<tr>
<td>B</td>
<td>Willow SRC</td>
<td>Twin fluidized bed gasifier and reciprocating engine</td>
</tr>
<tr>
<td>C</td>
<td>Willow SRC</td>
<td>Fixed bed grate</td>
</tr>
<tr>
<td>D</td>
<td>Miscanthus</td>
<td>Twin fluidized bed gasifier and reciprocating engine</td>
</tr>
<tr>
<td>E</td>
<td>Willow SRC</td>
<td>Fixed bed grate</td>
</tr>
<tr>
<td>F</td>
<td>Miscanthus</td>
<td>Fixed bed grate</td>
</tr>
<tr>
<td>G</td>
<td>Willow SRC</td>
<td>Pressurized gasification combined cycle</td>
</tr>
<tr>
<td>H</td>
<td>Miscanthus</td>
<td>Pressurized gasification combined cycle</td>
</tr>
</tbody>
</table>
on common airborne pollutants, but comprehensive energy, greenhouse and economic analyses were also performed.

4. Energy crop production

Emissions are included for all agricultural operations required to establish, cultivate and harvest the energy crops. Each agricultural step has been classified as either cultivation or transportation and emission factors assigned based on work on operating agricultural vehicles in 2002 [15]. In the absence of more recent data, the NO_x and particulates figures have been amended for some engine sizes to ensure compliance with the EU stage 2 limits for off-road diesel engines legislation. The resultant levels are shown in table 2.

The total emissions for each agricultural step are then calculated by combining these emission rates with the engine size, vehicle work rate and area of land to be worked (determined by the biomass demand of the power generation plant).

5. Storage and provision

The model includes direct airborne emissions associated with tractor transport of feedstock to local satellite storage facilities, mechanical stockpiling, recovering and bulk transport to the power generation plant.

Account has been taken of varying moisture content and related density, transit volume, tortuosity factors for different road grades and requirements for storage at the plant. For the larger systems transport is via articulated lorry [16], compliant with Euro IV emission standards.

Vehicle emissions are calculated using formulae developed by the UK Highways Agency [17] for this purpose, with a nominal speed of 40 km h\(^{-1}\). The resultant figures (in table 3) are combined with the calculations for number of trips and mean length of trip to arrive at the overall emissions from transportation.

Transport emissions are directly linked to distance travelled, which depends on proximity of crops to the conversion plant. For the smallest plant it has been assumed that 50% of the surrounding area has been planted with the energy crop, since at this scale the plant and crop are likely to be owned by the same organisation. For the larger plants a much lower figure of 10% is used, resulting in longer journeys, but more realistic at this scale. Appropriate allowances have been made for dry matter losses related to storage and transfer of material in each supply chain. This affects the overall results, as upstream emissions related to a particular quantity of biomass are effectively being concentrated by subsequent dry matter losses.

6. Electricity production

Table 4 gives flue gas emission concentrations for each of the systems. These are based upon published data and actual experience as far as possible, as noted in the table. However, there is no practical experience available for biomass gasification combined cycle and so figures for these systems have had to be taken from the Environment Agency’s (the relevant regulatory body) guidance note. For all of the power generation systems a detailed process simulation model has been produced by project partners (University of Ulster), the mass-energy balance from which was used to convert the concentrations at reference oxygen levels in table 4 to actual quantities of pollutant emitted over entire system lifetime.

The detailed process modelling of the power generation plants has allowed an accurate assessment of plant efficiency

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**Table 2. Emission level assumptions for agricultural operation.**

<table>
<thead>
<tr>
<th>Engine rating (kW)</th>
<th>Emissions during soil cultivation (g kWh(^{-1}))</th>
<th>Emissions during transportation (g kWh(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
<td>NO_x</td>
</tr>
<tr>
<td></td>
<td>22–75</td>
<td>75–130</td>
</tr>
<tr>
<td>22–75</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>75–130</td>
<td>0.68</td>
<td>1.13</td>
</tr>
<tr>
<td>&gt;130</td>
<td>1.13</td>
<td>1.13</td>
</tr>
</tbody>
</table>

**Table 3. Emission levels calculated for Euro IV articulated lorry.**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emission level (g km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.6647</td>
</tr>
<tr>
<td>NO_x</td>
<td>6.8871</td>
</tr>
<tr>
<td>Particulates</td>
<td>0.0665</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

**Table 4. Emission levels of key pollutants from power generation systems studied.**

<table>
<thead>
<tr>
<th>Ref (\text{O}_2) (%)</th>
<th>CO (mg Nm(^{-3}))</th>
<th>NO_x (mg Nm(^{-3}))</th>
<th>Particulates (mg Nm(^{-3}))</th>
<th>Hydrocarbons (mg Nm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>150</td>
<td>350</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>150</td>
<td>350</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>250</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>150</td>
<td>350</td>
<td>20</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>250</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>250</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>G</td>
<td>15</td>
<td>20</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>15</td>
<td>20</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: Nm\(^3\) = the volume occupied by a gas at normal conditions of 1 atm pressure and 0°C.

Sources: A, B, D: based on Environment Agency PG1/12(04) guidance note, modified to take account of practical experience with CO catalyst from UK plants, results also consistent with published data for Gussing plant. C, E, F based on Environment Agency IPPC sector guidance note combustion activities, verified by practical data from Elenaw straw-burning plant. G, H: based only on Environment Agency IPPC Guidance Note S2 1.08: gasification of solid and liquid feedstocks, including gasification combined cycle as no real-life data could be established owing to a lack of built facilities.
and therefore this has provided an exact demand for biomass feedstock to match a specified plant output. This demand is used to fix the area of land required to produce sufficient feedstock, taking into account system losses. Combining the electrical output with capacity factors which have been verified by a group of experts from industry and academia allows calculation of total electrical output over lifetime. In order to make a sensible comparison across the very different plant technologies and scales the environmental emission figures have been expressed per unit of electrical output.

7. Uncertainty

This work quantifies off-site emissions for bioenergy systems to highlight potentially significant releases that would not be regulated in conjunction with the plant, but could impact on local air quality.

For biomass production assumptions have been made about the work rate and engine rating in conjunction with academic and industrial partners actually involved with commercial production to ensure that these are representative of industry norms, but the figures for a specific application will vary with terrain, vehicle specification etc. It is impossible to meaningfully assess uncertainty in this context.

Agricultural vehicle emissions profiles were very difficult to access and published results of practical measurements were used, but further experimental confirmation of the actual emissions from operating agricultural vehicles would certainly enhance the results.

Transportation emissions used Highways Agency data, recommended for use in environmental impact assessments and other statutory calculations. No uncertainty assessments are available for these, but variations in speed were the most likely source of error for such assessments. This depends on human behaviour and so is impossible to reliably quantify.

The power generation emissions are based on real-life averages during continuous operation as far as possible and so are considered to be accurate.

For each stage the data used is the most reliable, representative average that could be found; but the real-life variability of the activities preclude a numerical assessment of uncertainty. It also limits the predictive capacity of this work for particular applications, but does not diminish its usefulness in identifying areas where there are likely to be significant emissions and on which mitigation measures might be focused.

8. Results and discussion

Figure 1 illustrates the specific emissions over entire life cycle achieved by each system for each of the four pollutants considered.

It is not surprising that the two advanced gasification combined cycles offer lower levels of emissions; with the exception of hydrocarbon emissions, for which all the technologies are quite closely clustered. However, it is interesting to note that the small scale system, frequently preferred by local rural communities [18], generates higher emission levels than all the other systems for all four pollutants.

The distinction between the 5 and 25 MWe systems is less pronounced and less consistent, but there is practically no difference between emissions for a 5 MWe grate and a 25 MWe grate i.e. the increased transport and degradation in bulk storage do not cause overall emissions to increase substantially at the larger scale. There is a general trend that miscanthus systems have slightly higher specific emissions than SRC systems of the same size and technology. This is mainly due to carting bales of miscanthus to a satellite bale store. This is common practice for UK straw handling, but has quite a significant emissions burden. More lorry trips are also required for miscanthus deliveries compared to wood, owing to its lower bulk density, but the emissions impact of this is much less.

Figures 2–5 display graphically the partitioning of each type of pollutant across the stages: ‘Electricity production’, ‘Biomass preparation and provision’ and ‘Biomass production’.

Figure 2 shows that for CO emissions the dominant source is the electricity production plant and upstream contributions...
are minor. Hence in figure 1, the only variation in CO emissions is for technology, rather than crop or scale.

Figure 3 shows that between 4 and 44% of NO\textsubscript{x} emissions originate away from the power generation plant. Obviously the gasification combined cycles produce lower plant emission levels, increasing the relative importance of upstream emissions; but these results show that even for more established grate and engine technologies substantial emissions can occur away from the main production sites. The biomass preparation and provision element is generally relatively small for all systems, so these are not related to fuel transport, except for carting of miscanthus bales.

Figure 4 shows the breakdown for particulates. As for NO\textsubscript{x}, the fact that the proportion of off-site emissions is high for the two gasification combined cycles just reflects the fact that the power generation emissions have been minimized. Of more interest are the results for the established grate and engine technologies, for which a substantial proportion of the particulate emissions are off-site.

Figure 5 shows the results for hydrocarbon emissions. Generally biomass production contributes up to 10% of emissions and preparation and provision is negligible with the exception of miscanthus.

In figures 6 and 7 particulate emissions for the 25 MWe miscanthus grate and 25 MWe SRC grate are disaggregated by process step to establish which steps are responsible for the emissions of this pollutant, which is an important factor for local air quality.

Figure 6 shows that, for the miscanthus system, the dominant source of particulate emissions is carting and stacking of miscanthus bales. It has been assumed in the

modelling work that the miscanthus is baled and carted typically 5 km away, which is common practice for storage of agricultural straw bales. However, for energy crops the yield of baleable material is obviously much higher and this results in substantial emissions associated with moving these to a satellite bale store. In-field storage would be an alternative option that would eliminate most of these emissions. However, the practicality of this depends on being able to get large vehicles close to the supply points and it would inevitably result in higher losses during storage; the extent of which are not well understood at present. It may, therefore be worthwhile considering alternative strategies for collection, processing and transport of grasses material for energy applications.

For the SRC system, figure 7 shows that electricity production is much more dominant, but that there are also substantial particulate emissions associated with the harvesting and planting of the SRC feedstock.

Transport of feedstock to the plant is frequently perceived to be a major source of air pollution and is one reason the UK government are encouraging plants where the distance from feedstock to conversion plant is less than 16–40 km, depending on scale [19]. For lorry transport, the distances in this work ranged from 13 km (B and D) to 29–31 km (F and E). Despite longer distances systems E and F do not show significant emission related to biomass provision for any of the pollutants studied, with the exception of additional emissions related to tractor movements for carting and stacking of miscanthus bales. Therefore even when the distance from field to plant is quite large the environmental emissions associated with lorry haulage remain relatively small.

It must be remembered for all these results that if growth of energy crops for electricity production replaces other farming activities these would also have produced emissions that are not normally recorded; so these emissions are only,
effectively, additional where previously uncultivated land is devoted to energy crops.

9. Conclusions

A substantial proportion of the airborne emissions of NO_x and particulates from bioenergy systems fuelled by energy crops are likely to arise in activities upstream from the thermal conversion plant. Lorry transport does not make a significant contribution to overall emissions, although harvesting and tractor haulage can do. It is recommended that measurements of engine emissions during operation are made, as data in this area is lacking.

Acknowledgments

This work was funded by the Engineering and Physical Sciences Research Council as part of the Supergen Bioenergy programme. Consortium partners who have provided information include academic partners: Dr Y Huang, University of Ulster, Dr J Brammer and Mr J Rodgers of Aston University, Dr Andrew Riche of Rothamstead Research Institute, and industrial partners: Eon, Biomass Engineering, Rural Generation, Coppice Resources Limited and BiCal.

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