Integrated assessment of bioelectricity technology options

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Abstract

Power generation from biomass is a sustainable energy technology which can contribute to substantial reductions in greenhouse gas emissions. It is not, however, emission free and, when account is taken of airborne emissions, ecological and other impacts there is arguably greater potential for direct environmental impact than is the case for most other renewable energy technologies. The requirement to produce and supply biomass feedstock in rural areas also results in the systems having far-reaching impacts within local rural communities.

These factors make it particularly important to consider the whole system (including crop production and transport) and to choose an appropriate scale, technology and feedstock. The optimal system choice will take account of a number of factors, including technical performance, efficiency, greenhouse gas savings, environmental emissions, scale of facility, impact on transport networks, cost of electricity produced etc.

The work completed in work package 1 of the Supergen bioenergy consortium addresses the challenge of analysing, quantifying and comparing these factors for bioenergy power generation systems. A life cycle approach is used to analyse the technical, environmental, economic and social impacts of entire bioelectricity systems, with a number of life cycle indicators as outputs to facilitate cross-comparison.

These indicators are presented here for a selection of the systems studied along with outputs from stakeholder consultation of scenarios utilising these systems. The results provide definitive data relating to the systems and also illustrate the complexity of comparing different systems.

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Introduction
The UK now has a number of operating bioenergy systems for electricity production, which vary significantly in scale, technology, feedstock, and consequently also in their impacts and benefits.[1] Some projections suggest that the market for dedicated bioelectricity plants could more than double by 2010, resulting in a significant increase in the number of operating facilities. [2] Central government has not offered any guidance on preferred type and size of facilities for different applications, leaving the market open on a case by case basis. It is important therefore that information pertaining to the relevant impacts of entire bioenergy systems is available to support choices being made in relation to development of new bioenergy capacity. This work addresses that information need.

The principal UK driver for pursuing bioenergy expansion is reduction of greenhouse gas emissions to combat climate change and so environmental sustainability is a key element to be taken into account. Work that has been done recently in this area includes a review of the potential for significant environmental impacts from energy crop plantations, [3] and development of a framework for sustainability assessment of UK bioenergy plants, adopting a consistent systems methodology. [4]

However, the impacts of bioenergy facilities are more than just environmental. At national levels assessments have been carried out of the potential socio-economic impact of bioenergy system [5], but it is local circumstances, including rural social initiatives, which have, in many cases, driven development of small scale bioenergy facilities in the UK to date [6] and in other cases stalled or halted development. [7] Ultimately bioenergy facilities must be accepted by local communities for the industry to grow and so due recognition must be given to tangible local impacts in making decisions about new facilities.

In order to address the issues raised above, the work presented here:

- Assesses the entire system, from crop establishment to energy demand servicing
- Adopts a systems methodology with consistent boundaries and scope to facilitate comparison between technologies and design options
- Considers social and economic drivers as well as technical and environmental assessment
- Assesses local impacts prioritized by stakeholders

Background
Phase 1 of the Supergen bioenergy consortium work focused on entire bioenergy systems for electricity production using indigenous energy crops. Work package 1 carried out systems analysis covering the technical, environmental, economic and social impacts of those systems; the outputs of which are presented here.

A similar approach has been adopted by others to assess energy crop production [8, 9] and the economic cost of greenhouse gas savings via different bioenergy technologies [10, 11]. However, the Supergen assessment uses a life cycle assessment (LCA) methodology to carry out a broader assessment incorporating technical, economic, environmental and social dimensions. These have been condensed into a set of life-cycle indicators which reflect the most often cited concerns of stakeholders in relation to bioenergy. Similar assessments have previously been carried out in relation to
particular bioenergy plants [11, 12] and are being pursued by the TSEC group with a focus on the bioenergy chain [4], but this work attempts to use the approach to distinguish the relative merits of a range of different bioenergy conversion options (scale and technology) and aims to output results that are accessible to a non-specialist audience.

While these outputs facilitate cross-comparison, it is important to realise that it inevitably results in describing a system in terms of “apples and pears”, for example the extent to which increased rural employment might offset higher costs of electricity or transport movements depends on the site-specific application and the values of the person or institute making the judgement. Multi-criteria analysis (MCA) provides one framework whereby this cross-comparison can be made to identify preferred options. In the present study, MCA was used in a heuristic mode, in the sense of clarifying why stakeholders held particular opinions, and what those opinions consisted of, rather than any attempt to define an ‘optimal’ configuration for the system attributes ([13], [14][in][15][ibid]). The rationale for this is that while optimality may be considered a potential attribute of an uncontentious system, it is not a plausible attribute of a system that stakeholders view very differently.

**Methodology**
A number of modelling approaches have been combined in this work, as illustrated in figure 1. The thermodynamic performance of the conversion facility is essentially deterministic, so a high degree of accuracy can be achieved with detailed process modelling. This was done using the ECLIPSE process simulator to produce complete mass-energy balances and techno-economic analyses for most of the conversion systems, with the exception of the pyrolysis systems for which ASPEN was used. All the systems modelled have been based on real-world industrial experience as far as possible.

The same degree of determinism is not possible with the wider bioenergy chain because of practical and commercial variations and real-world sensitivities. Therefore the experience of the consortium has been used to define typical data for each stage in a bioenergy chain appropriate for the conversion system modelled. Key inputs have been gathered from industrial and agricultural experience within the consortium as well as published data where appropriate. A model has thereby been produced that uses interlinking spreadsheets to represent the entire bioenergy system, from energy crop production, through storage and provision to electricity production. The outputs from this model have been condensed into 42 extended LCA indicators for each system studied, which have formed the basis of information and scenarios presented to stakeholders for MCA evaluation.

**System scope**
The same system scope has been defined for each case studied, as follows:

**Agricultural elements**
Each system begins with fields previously used for grassland or arable cultivation. Pre-existing growth is eradicated and the field prepared as appropriate for the crop. Crop establishment is included and the cuttings, rhizomes or seeds used are considered as a material flow into the system with an embodied energy which represents the specialised cultivation of the material. All agrochemicals required are
Figure 1: Modelling approach to systems assessment

quantified as materials entering the systems with an associated energy and carbon cost. A particular agronomic regime is defined for each crop and scale of activity in consultation with partners and the wider industry. Simultaneous harvesting and chipping of short rotation coppice has been included, mowing and baling of miscanthus and baling of straw. At the end of the plantation lifetime it is returned to its original state by appropriate eradication of the energy crop.

**Transport and logistics**

Tables 1 and 2 summarize the assumptions about transport made in the base case models.

**Table 1: Transport and logistic assumptions for short rotation coppice**

<table>
<thead>
<tr>
<th>Short rotation coppice (winter harvest &amp; chip)</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Leave piles of chips in field to dry to 30% moisture content</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>&lt; 2 MWe</strong></td>
<td><strong>&gt; 2 MWe</strong></td>
<td></td>
</tr>
<tr>
<td>Transport to power plant by tractor/trailer</td>
<td>Transport to covered storage area by tractor/trailer</td>
<td></td>
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<tr>
<td></td>
<td>Reclaim from storage area with front-end loader</td>
<td></td>
</tr>
<tr>
<td><strong>&lt; 5 MWe</strong></td>
<td><strong>&gt; 5 MWe</strong></td>
<td></td>
</tr>
<tr>
<td>Transport to plant in 60 m³ rigid trucks</td>
<td>Transport to plant in 120 m³ articulated trucks</td>
<td></td>
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</table>
Table 2: Transport and logistic assumptions for miscanthus and straw

<table>
<thead>
<tr>
<th>Assumption</th>
<th>&lt; 2 MWe</th>
<th>2-5 MWe</th>
<th>&gt; 5 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscanthus: Winter harvest &amp; bale at 25% moisture content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cart 5 km to satellite bale store</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack up to 7 bales high</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport to plant by tractor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport to plant by 60 m³ rigid trucks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport to plant in 120 m³ articulated trucks</td>
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Appropriate account is taken of dry matter losses during processing and storage based on published data. Transport emissions are taken into account based on modified emission profiles for agricultural vehicles [16] and highways agency formulae for haulage vehicles [17].

**Electricity production**

The analysis incorporates consideration of power plant construction, operation and decommissioning. For construction the energy and carbon impacts are estimated, without a detailed breakdown of other environmental emissions. During power plant operation key material inflows are quantified, including start-up fuel, abstracted water and chemical process reagents as well as waste arisings, effluents and air borne pollutants. Power plant operation takes account of typical operating patterns for a plant of that type and size to estimate load factors, requirements for start-up fuel etc.

**Cases studied**

A total of 25 different systems were modelled, covering a range of technologies, feedstocks and scales. These are summarized in table 3.

**Analysis scope**

**Carbon balance**

The carbon balances incorporate greenhouse gas emissions (expressed as CO2 equivalent) associated with

- direct consumption of fossil fuel
- production of machinery wholly or partly used in the process
- production of the materials consumed in the process.
- Nitrous oxide emissions arising from fertiliser application and decomposition of fallen leaves

Soil carbon balances have not been included owing to their site-specific variability. However, the tillage associated with energy crops is generally much less than that associated with conventional arable farming; so if comparing to an arable farmland scenario there will be no significant increase in carbon emissions, but if comparing to grassland there will be increased carbon emissions which have not been included. In all cases the CO2 equivalent factor is calculated for the various greenhouse gases considered.

**Material balance**

Key materials tracked through each system are those identified as of importance or interest through stakeholder dialogue or required for calculations described elsewhere. These include the agrochemicals used in energy crop production, chemicals used in power production, materials required for crop establishment, sewage sludge being treated, ash and effluent arisings and airborne pollutants. Four key airborne
pollutants: CO, NOx, particulates and VOC’s, have been tracked across every step in the bioenergy system from field to power plant.

### Table 3: Bioenergy systems studied

<table>
<thead>
<tr>
<th>Biomass input (equiv)</th>
<th>250 KWe</th>
<th>2 MWe</th>
<th>5 MWe</th>
<th>25 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>PO</td>
<td>CHP</td>
<td>PO</td>
<td>CHP</td>
</tr>
<tr>
<td>Gasifier (reciprocating engine) - air drying, wood</td>
<td>1</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier (reciprocating engine) - no drying, wood</td>
<td>2</td>
<td>17</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Gasifier (reciprocating engine) - no drying, miscanthus</td>
<td>4</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier (atmospheric gasification combined cycle) - flue gas drying, wood</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier (pressurized gasification combined cycle) - flue gas drying, wood</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier (pressurized gasification combined cycle) - flue gas drying, miscanthus</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion (circulating fluidized bed) - no drying, wood</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion (grate) – wood</td>
<td>20</td>
<td>9</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Combustion (grate) – miscanthus</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion (grate) – straw</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrolysis (reciprocating engine) – wood</td>
<td>13</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrolysis (gas turbine) – wood</td>
<td>14</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-combustion, 5% of 500 MWe (PF) – wood</td>
<td></td>
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</tbody>
</table>

**Economic assessment**

Detailed techno-economic assessment has been carried out of each thermal conversion facility modelled. The capital cost of equipment has been assimilated from a combination of process modelling, in-house data and industry information. This has been adjusted to reflect total development cost in line with existing UK experience and this is represented in the specific investment presented here. Operating costs have been calculated based on an understanding of staffing patterns, plant consumables and typical maintenance and administrative requirements. Fuel requirements originating from the process modelling have been costed based on typical current prices for the relevant feedstocks in the UK. Electricity production has also been assessed from the process modelling and benchmarked assessments of capacity factor based on past plant performance. This allows assessment of total annual income and expenditure, which is then discounted based on standard economic techniques. For this analysis the selling price of electricity has then been varied to achieve zero net present value for the project: effectively a break-even selling price for the electricity.

Each system has also been analyzed in terms of its job creation utility. Actual manhours expended in energy crop cultivation, harvesting and processing have been calculated. For the power plants manning and shift patterns have been developed specific to each plant technology and size and estimates made of the manpower.
required to undertake the relevant development and construction work. Previous work completed by Mott McDonald on behalf of the DTI [18] has then been used to quantify the supply chain employment impact of each bioenergy system and finally the jobs created by induced economic activity associated with the new bioenergy system have been calculated in association with HM Treasury’s green book guidelines. [19] Further detail on the employment aspects of the systems studied is reported elsewhere. [20]

**Results**

The results presented here comprise graphical representations of some of the key technical, economic, environmental and social indicators, as well as information gleaned from stakeholder consultation using multi criteria assessment techniques based on the same indicators. For ease of comparison and comprehension by a non-specialist audience the indicators have been normalised across the 25 systems studied so that the total impact of any parameter summed over the 25 systems adds up to 100 units. In many cases the results have been presented per unit of electrical output, as a convenient means of comparing different sized systems. However, due account has also been taken of all heat output from CHP systems by incorporating a carbon saving referenced to oil heating alternatives in carbon balances and a cash value per unit of heat output in economic analyses.

**Technical assessment**

The parameter used most often to assess the technical performance of thermochemical conversion systems is efficiency. The results for this (fig. 2) show that the advanced pressurized gasification systems offer the potential for highest efficiency. However, the third best performing system is not another advanced system, but the most proven, co-firing technology. Small systems and CHP systems do not generally perform well against this indicator.

Of the CHP systems (fig. 3) the best performers against the efficiency criteria are the 2 and 5 MWe grates. By contrast the 25 MWe grate is actually the least efficient of the CHP systems, although it must be recognised that it is delivering higher grade heat, which cannot be recognised with most analysis measures. The pyrolysis CHP systems also compare poorly with the direct-fired alternative on this measure.

Many new applications will be seeking to minimize risk of technology failure and a relatively crude assessment of technology novelty is given in figure 4, as assessed by an expert group. Generally the more efficient systems have less attractive novelty ratings and (fig. 5) less attractive capacity factors, but there are a few exceptions. Co-firing is well-proven and very efficient, while pyrolysis systems carry relatively high technology risks and yet do not offer significant efficiency benefits.

**Environmental assessment**

**Greenhouse gases**

The systems analyzed all showed substantial reductions in greenhouse gas emissions compared to conventional grid electricity, even when the entire production, processing, transport and conversion chain is taken into account. Typically a 90% reduction can be achieved per unit of electricity generated. Figure 2 shows substantial efficiency variations between systems but figure 6 shows that the variation between different bioenergy systems for carbon savings is actually very small and
does not follow variations in plant efficiency. It is possible to expend considerable efforts in carbon footprinting these systems, but the results show that larger systems, including co-firing, are generally better at reducing CO2 than comparable smaller systems. High efficiency advanced gasification technologies do not offer consistent and convincing CO2 benefits, but gasification allows very small scale systems to compete on a par with larger technologies. The results for CO2 savings from CHP systems in figure 7 show a similar close clustering of results, with variations between systems being substantially less than efficiency variations in figure 3.

Figure 2: Electrical efficiency

Figure 3: CHP Efficiency

Figure 4: Technology novelty

Figure 5: Capacity factor
Another way of considering greenhouse gas reductions is not in terms of the energy delivered but the savings made by each unit of biomass energy that is available at the point of harvest. This should identify the most efficient ways of making use of a limited biomass resource. As shown in figure 8, the CHP systems show clear advantages compared to all other technologies. Next the advanced technology, large scale gasification systems score best, with small scale gasification being generally on a par with small and large scale grates.

There is increasing concern in the media, government and scientific press about potential land-use conflicts arising from expansion of bioenergy and, in particular, biofuel production. It is therefore particularly instructive to consider greenhouse gas benefits as a function of land intensity. Figure 9 shows that the high yield, low moisture content of miscanthus results in very positive results for this feedstock judged against this parameter. Straw performs very poorly in terms of this indicator; however, it is of course closely associated with a second productive use of the same land, namely cereal production.
Airborne emissions

Four airborne pollutants have been considered for the purposes of this work. These are CO, NOx, particulates and VOC’s. The results show the total emissions of each of these pollutants across the entire production, processing and utilisation chain, including all emissions from agricultural vehicles for energy crop production, transport and direct electricity production. A brief overview is given here and more detail is reported elsewhere. [21], where it is demonstrated that the contribution of dedicated haulage vehicles to overall emissions is negligible even with long supply distances, that upstream activities can be particularly significant when considering NOx and particulates and that small scale systems frequently have worse emission profiles than large scale ones.

The results for CO in figure 10 show that best performance (per unit electricity generated) is achieved for the advanced technology gasification and fluidised bed systems. This reflects a combination of the low level of emissions from these systems and their relatively high efficiency. In general the smaller systems perform significantly worse than larger ones; with the small-intermediate grates and gasifier-engine combinations having highest emission levels. This is caused by a combination of: lower efficiencies and higher emission levels from the thermal conversion plant.

The results for NOx in figure 11 again demonstrate the environmental advantages of the advanced technologies, with small grate, pyrolysis and even small gasification systems performing worst. Upstream NOx emissions are quite significant for this parameter and all small scale systems perform relatively poorly in terms of NOx emissions.

Particulate emissions in figure 12 are also more likely to have a greater proportion of the overall emissions generated upstream in both agricultural activities and short-range haulage and transportation. For this reason we again see the smaller systems generally performing worse than the larger systems on this measure. Also, particulate emissions are easily arrested from most large scale facilities by the use of bag-filters, but these are impractical and uneconomic at smaller scales.

VOC emissions in figure 13 are dominated by the releases from the thermal conversion plant, with transport and crop production/processing playing only a minor role. These emissions are generally related to the requirement to maintain good combustion conditions in terms of temperature, turbulence and residence time. For pf facilities designed for coal-burning this is easily achieved and emissions are the lowest of any of the systems studied.
Taking an overview of all 4 emissions categories: for large scale systems advanced gasification systems perform best, while fluidised beds do not offer significant emissions benefits compared to grates. However, co-firing system generally performs quite well for all airborne emissions studied. For smaller scale applications emissions are generally higher than for large scale and gasification technologies do not confer significant emissions benefits.

**Figure 10: CO per unit of electricity generated**

**Figure 11: NOx per unit of electricity generated**

**Figure 12: Particulates per unit of electricity generated**

**Figure 13: VOC's per unit of electricity generated**

**Waste produced**
Quantities of bottom ash, fly ash and routinely produced effluent have been estimated for each of the systems studied and are displayed in figures 14-16 respectively. These
are only produced at the thermal conversion plant, so results depend only on the technology, feedstock and process efficiency. Straw generally performs worse than miscanthus and wood respectively and grate systems have higher levels of bottom ash; with advanced systems lower. For fly ash (which is much more toxic and more of an issue for disposal than bottom ash) pf firing scores badly because of the technology: pulverisation facilitates good combustion conditions for low levels of NOx, but results in higher levels of fly ash. The small engine systems perform best, as the fly ash material is effectively removed with the effluent, of which they generate much higher quantities.

**Economics**

The principle economic measure presented is the break even electricity selling price: the price for electricity which covers all of the generator’s costs, including the cost of repaying the initial investment at commercial rates. It provides a useful indicator of the currently most cost-effective options, but learning curves and feedstock cost variations may alter the relative positions of technologies as time progresses and variations in the cost of feedstock may also significantly affect the ranking of different biomass technology options.
The base case results from the Supergen studies assume a feedstock cost of £50/odt for SRC wood chips, straw and miscanthus, in line with prevailing market prices. Figure 17 shows that at these levels, the most financially attractive option is co-firing, because of low initial capital investment and a very high efficiency. The next most attractive options are the wood and miscanthus grates, which are proven technologies where the lower capital investment compensates financially for the very much lower efficiency offered. However, it should be noted that the difference between the figures for the grate systems and the advanced gasification combined cycle systems is very small. So, at these feedstock prices, only a relatively small reduction in capital cost via learning curves is required to make advanced gasification technologies the preferred option for electricity price.

The three most expensive options in figure 17 are all small scale CHP systems and this reflects the very low load factor ascribed to these systems: typically around 40% for small scale systems in the UK following heating load profiles. It could also be argued that the break-even cost of electricity for these systems is critically dependent on the price charged for heat. A current market value for heat has been used in the analysis and an increase in this would reduce the BESP for the CHP systems, making them more competitive.

Generally biomass CHP systems offer potential for substantial carbon reductions but are not as economically attractive, except with higher heat prices or load factors: more likely in industrial than domestic applications.

Figure 18 shows the specific investment per unit of installed capacity and it is interesting to note that the large-scale advanced gasification technologies are not substantially more expensive than small scale facilities generally, although advanced pyrolysis technologies do entail substantial investment costs, possibly because of the small scale studied here.

Biomass CHP systems also suffer from high specific investment costs, particularly at small scales, as illustrated in figure 18. This is a significant barrier to their deployment, which cannot be addressed by raising the value of heat, and so will not be resolved in the longer term by projected trends in energy prices. It is also the case that the additional cost of CHP operation is generally a well-proven, established area, for which further cost reductions through innovation and technology development are not likely to be significant. On the contrary much of this cost is associated with the uniqueness of the application, which is necessary in order to maximise load factor. This seems to suggest that there is little prospect of achieving greater uptake of biomass CHP without addressing the issue of upfront capital cost. It is possible that some inroads could be made by standardisation of equipment for a narrow range of applications (similar to the approach being taken by the Carbon Trust in their heat acceleration project). The alternative appears to be fairly substantial support or subsidy of the initial capital investment.

A third economic measure included here is the job creation potential for the different technologies. The figures presented here summarize more extensive work which assessed the direct jobs required in agriculture, transportation and conversion, as well as indirect supply chain work and induced economic effects. [20] The summary results in figure 19 demonstrate that CHP projects have greater job creation potential than
other bioenergy schemes, which is consistent with their higher electricity production costs. Co-firing has particularly low employment generation effects, but otherwise the employment creation level does not vary substantially with technology or scale.

**Sustainability**

There is increasing concern about food-fuel debates mainly with respect to biofuels, but with increasing relevance to other bioenergy systems. The efficiency of land use is critical in these arguments and the land take per unit of electricity produced is displayed in figure 20. The best performing systems are the miscanthus ones – this crop has a higher yield and lower moisture content than SRC, resulting in significantly lower land requirements per unit of electricity produced. This reflects the figures on CO2 savings quoted earlier. CHP systems perform worst on this measure, reflecting the focus on electricity rather than CO2.
Vehicle traffic is frequently cited as a cause for concern with regard to new biomass developments. Biomass is unique in providing storable and therefore reliable renewable energy on demand, but consequently the resource must be transported to the point of use and this can create sustainability conflicts. It has been established above that neither the energy consumption, greenhouse gas emissions nor the environmental pollutants associated with transportation are particularly significant within the overall bioelectricity assessment. However, the facilities are still increasing traffic congestion, resulting in an additional and very visible burden that would not otherwise be there. Some assessment of traffic generation is therefore appropriate.

Traffic impacts (beyond the greenhouse gases and airborne pollutants already considered above) can broadly be classified as environmental (noise levels, habitats etc.) or personal (infringement of peace and quiet, visual disturbance, local noise etc.). Different measures are appropriate for capturing the distinct concerns these raise. A good measure relating to nuisance is the number of vehicles related to the bioenergy plant passing a defined point in unit time. This is shown in figure 21 and shows a huge variation from the best performing small gasification facilities to the worst offending large grates. Other points worth noting from this graph are that miscanthus generally requires more journeys than SRC and that the higher efficiencies associated with advanced technologies can be a significant benefit. A 44% reduction in vehicles can be obtained by changing from a 25 MWe wood grate to a 25 MWe wood gasification combined cycle.

A more relevant measure of transport disturbance from an environmental perspective is the number of delivery vehicle-kms travelled per unit of electricity generated. This is shown in figure 22 and has a significantly narrower results span than the previous measure, but the same pattern as the previous measure: with smaller engines and advanced technologies performing best, while grates and CHP both score poorly against this measure.
Stakeholder opinion
Two forms of stakeholder consultation were carried out in relation to the above LCA and techno-economic work. The first, in the Yorkshire and Humber region, used preliminary results, configured in the form of regional scenarios, in an MCA process with stakeholders and in focus groups with informed members of the rural public who were already involved in an energy options project led locally by the North York Moors National Park Authority [22]. Use of the region’s wood resource for small and medium sized CHP and heat plants was found to be more attractive to these groups than use of the same resource for large or small electric power plants. Key reasons mentioned by stakeholders and the informed public groups were the higher energetic efficiency of CHP and heat relative to electricity, and perceptions of better performance in terms of local employment, local environmental impact and associated social benefits. There was also a common feeling that small scale electric power plants were, to date, less technologically proven. The efficiency and employment arguments are backed up by the results above, for small and medium scale CHP plants; but the perceptions related to environmental impact are contrary to the results above.

The second consultation, in NW England, used a largely complete version of the techno-economic and LCA results in a simple spreadsheet model that enabled users to partially modify regional SRC scenarios (Upham and Speakman, 2007). Stakeholders were asked to allocate the region’s agricultural and set aside land, by grade, to the different power and CHP plant types. The sheet then output the energy supply, environmental and agricultural employment implications and stakeholders were asked for their reactions and whether they wanted to make changes in their choice of land allocation.

It should be noted, first, that most stakeholders objected strongly to the electrical remit that had been imposed by the study. Nonetheless there was quite a high degree of consensus on the land types likely to be allocated to SRC: grade 3 was considered most likely and grade 1 least likely. However, stakeholders held widely differing views of which technologies should dominate in 2030. Among stakeholders expressing a preference for larger power plants, this was due to economies of scale and the relatively high power potential that such plants afford. However, stakeholders also anticipated significant problems with the transportation of willow, unless most could be located close to the power plants. In their view, rail and water transport have to be considered as means of transport and innovative ways of using these networks will be needed to capitalise on the use of existing infrastructure.
There was some scepticism of the small scale (250 kWe) gasifier power plants due to concerns over emissions, plant efficiencies and the ability of the rural network to cope with the transmission of power. By contrast figures 9-12 show that the technology is comparable in terms of emissions to other small scale facilities and figure 1 shows its efficiency as not significantly lower than comparable sized systems. Perhaps more importantly, figures 5 and 16 show that the low efficiency does not result in lower levels of carbon savings or higher electricity costs. To focus solely on efficiency of the thermal conversion plant can therefore be somewhat misleading. It may be that lack of familiarity with the small-scale gasification systems is resulting in erroneous assumptions about their performance.

Those who preferred larger plants did so because of economies of scale and the relatively high power potential these plants could afford. The evidence from figure 16 in large part supports this. However, these respondents also anticipated significant road transport problems with such facilities, which appear from figures 19 and 20 to be not as significant as might have been imagined.

NW stakeholders were also asked to rate the significance of particular modelled variables. In aggregate they rated carbon savings most highly, followed by transport impacts, the number of agricultural jobs supported and emissions. These issues have been common priorities with stakeholders and the public throughout our UK-focussed bioenergy research, in addition to siting issues, and should be priorities for stakeholder communication.

Conclusions
1. Traditional technical parameters such as thermal conversion efficiency are not a good guide to overall bioenergy system performance in terms of carbon saved or land use efficiency
2. Carbon savings per unit of electricity generated by the very different systems studied are actually quite closely clustered, with only small distinctions from one system to the next.
3. CHP systems generally offer higher carbon savings than power only
4. Higher yielding miscanthus results in higher carbon savings per unit of land used than SRC.
5. Smaller facilities generally produce higher levels of emissions per unit of electrical output.
6. CHP variants do not perform well in terms of the economic parameters: per unit of electricity produced or in terms of requirements for higher initial investment. They are also the least likely systems to benefit from learning curve cost-reductions.
7. Large scale advanced gasification technologies are expensive on a specific investment basis, but not significantly more so than small scale plants generally.
8. The number of jobs created per unit of bioelectricity is fairly constant across technologies and greater for CHP than power-only schemes, reflecting the higher cost of the CHP schemes
9. Miscanthus and CHP systems offer much higher land-use efficiency than SRC and power only schemes.
10. The number of vehicle journeys is minimized with smaller plants, SRC feedstocks and advanced technologies.

11. Small and large gasification systems both perform well in terms of minimizing transport activity per unit of output, while traditional grates and CHP score worse.

12. Gasification facilitates a reduction in emissions for large plants, compared to other available technologies but this is not necessarily the case for small plants where switching to gasification allows small scale plants to compete in terms of efficiency, carbon and economics, but does not necessarily improve airborne emissions.

13. PF co-firing systems generally perform very well against emissions, cost and carbon categories.
References

18. MottMcDonald, Renewable supply chain gap analysis. 2004, DTI.


