Extended Life Cycle Analysis of Bioenergy Plant

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Abstract – A life cycle analysis has been performed of two contrasting bioenergy systems: from crop establishment, cultivation and harvesting; through fuel preparation and transport to thermal conversion and electricity production. Quantitative energy balances are presented for a fluidised bed combustion plant and a gasifier with reciprocating engine, both utilising short rotation coppice. The methodology for extending the life cycle approach to account for wider environmental, social and economic factors is explained. Ongoing work that applies the same calculation framework to a range of biomass technologies and fuels is described.

1. Introduction
Presently the UK has 160 MWe dedicated biomass generating capacity in 14 plants. (Ofgem, 2004) All are designed to utilise animal, agricultural or forestry wastes, except for the 11 MWe Arbre plant, which was intended to utilise energy crops, but is not operational. Following the end of the Non Fossil Fuel Obligation support mechanism, there has been a development hiatus; the last biomass plant having been commissioned almost 3 years ago. Despite numerous planned projects and government grant awards, only one biomass plant is currently under construction in the UK.

The UK government has encouraged development of energy crops, (RCEP, 2004) but current national production amounts to only 16,000 tpa. (Forest Research 2003) There have also been various strategic reports produced on the prospects for UK bioenergy, evaluating the technical and economic status of different technologies e.g. (Oxera, 2002). However, the wider environmental and socio-economic impacts from significant bioenergy expansion have been less thoroughly examined to date.

2. Background
The Supergen bioenergy programme is a UK research-council funded R&D programme that addresses the complete bioenergy chain from biomass in the field or forest, through handling, preparation and utilisation for electricity generation. As well as technical and economic analysis, it incorporates environmental and social assessment of the full life cycle of bioenergy power production, including stakeholder evaluation of bioenergy impacts.

3. Methodology
3.1 General methodology
The methodology used in this work is illustrated in figure 1 and combines several conventional assessment
techniques in a single framework to consistently and comprehensively evaluate the entire bioenergy system.

Figure 1: Methodology for extended life cycle analysis

Data relating to biofuel production is obtained from UK growers and research work and provides inputs to a spreadsheet model of production of a specific biofuel in the UK under different conditions. For some crops the input data will be directly obtained from field trials funded within the Supergen programme. Published data and information from bioenergy project developers is also used in detailed spreadsheet models of fuel processing and provision. Process simulation software is then used to perform detailed technical evaluations of thermal conversion plants for different biomass fuels from fuel receipt at the station gate to electricity export.

The outputs of the biofuel production model, the fuel processing and provision assessment and the process modelling are then consolidated to carry out a complete life cycle assessment (LCA) of the entire bioenergy system. This approach allows considerable depth of evaluation with regard to technical and agricultural variables; while facilitating a comprehensive, consistent analysis of different bioenergy systems.

The LCA methodology has been extended to account for bioenergy impacts considered relevant by stakeholders in the following areas.

- Energy balance
- Carbon balance
- Materials balance
- Economic impacts
- Environmental impacts
- Social impacts

Therefore it includes quantification of traditional LCA parameters and other relevant indicators, such as the physical size and visual impact of infrastructure developments and crop growth, power generation costs, local economic benefits and additional road traffic. These are presented as a representative set of LCA indicators; the choice of which was guided by work that quantified the response of a local community to a new bioenergy development.

3.2 Progress to date

To date the energy, carbon and materials balances have been completed for two bioenergy systems. The economic evaluation has been partly completed, but not fully validated. The environmental balance has been commenced, but will be subject to revision following experimental work in the Supergen programme. The social indicators have been mostly calculated for the two systems, but multi-criteria evaluation by stakeholders has not yet commenced.

This paper presents the energy balances for two bioenergy systems. The technical process analysis for these has been completed with the ECLIPSE process simulator; although other software is being used for other thermochemical conversion systems being studied.
4. Process technical descriptions
The two systems evaluated are:

**Case 1:** 250 kWe downdraft gasification with gas engine fuelled by SRC from a single farm (DG-GE)

**Case 2** – 25 MWe fluidised bed combustion with steam turbine plant, supplied by short rotation coppice (SRC) from regional growers (CFBC-ST)

4.1 Cultivation stage
In case 1 (DG-GE) an arable farmer switches 50% of their land to SRC production. The land is good quality, agricultural soil, with small field sizes. Eradication of the previous cereal crop and final return to arable use are included in the assessment. There is some existing infrastructure on the farm, including barns for drying and storage. Digested sewage sludge is used in place of commercial fertiliser after each harvest, but otherwise conventional farming procedures are employed. Little explicit monitoring of the crop is required as this occurs naturally alongside other farm activities.

In case 2 (CFBC-ST) a much larger supply of SRC is required and use is made of lower grade, non-farming or marginal land. Larger fields of poorer soil are cultivated, which require more intensive agronomy and digested sewage effluent is regularly applied to the soil by a local water company. There is no existing drying/storage capacity. SRC is grown on 15% of land in the region and specific monitoring of the crop is required because of the larger area involved. Restoration to previous use is not included, as SRC establishment facilitates positive land remediation.

4.2 Fuel processing and provision
In case 1, SRC is harvested once a year in winter and transported to a grain shed for forced air drying. It is then transferred to storage barns using mobile mechanical plant. Final transport to the on-farm power plant is by tractor.

In case 2, year-round harvesting is employed and chipped SRC is left standing in the field to dry, before being transported by 40t trucks to a centralised processing plant, where it is dried and automatically transferred to the FBC plant.

4.3 Power generation
Figure 2 shows the DG-GE power generation cycle. SRC is dried in rotary driers (utilizing waste heat from the stack gases), then gasified at 850°C in an atmospheric pressure, bubbling fluidised bed reactor, with air as the fluidising gas and oxidant. The fuel gas is cooled and cleaned of tars and particulates in a cyclone and filter, before being combined with air in the carburetor. The gas-air mixture is compressed and combusted in the cylinder, generating electricity. The combustion products dry the incoming wood before being exhausted to atmosphere. Hot water may also be produced in CHP mode.

Figure 2: Process flow diagram of 250 kWe Downdraft Gasifier/Gas Engine
reception hall for storage. It is then pneumatically conveyed with preheated primary air, to a balanced draught, circulating fluidised bed combustor. Secondary air is injected through a set of nozzles in the chamber walls. Cyclones separate the majority of the solids from the flue gas, which preheat fluidising air, before being returned to the combustor. Most of the ash is removed from the base of the combustor, with residual solids in the gas stream being removed by bag filters.

**Figure 3: Process flow diagram of 25 MWc CFBC with steam turbine**

Radiant heat from the furnace and heat from flue gas cooling raises steam in a heat recovery steam generator. Cooled flue gases are discharged to atmosphere via an induced draft fan and stack. The steam generates electricity in a simple steam cycle with superheat conditions of 485°C, 65 bar, a condensing steam turbine and an air cooled condenser.

**4.4 Scope of life cycle assessment**
The scope of the LCA includes all physical steps necessary to switch from the previous land use to SRC cultivation over a 28 year period that includes plant construction, operation and decommissioning. This includes e.g. initial site preparation prior to planting, all agricultural and processing activities and transport and disposal of waste products. For each step the direct fuel consumption, energy embodied in the materials used and weighted energy associated with the use of machinery is calculated. The latter includes the energy used in construction and manufacture of any new process plant or buildings. Full life cycle energy costs of all fuel inputs are accounted for, including material extraction, processing and delivery. The embodied energy associated with the willow cuttings planted is included and has been calculated by a separate LCA of nursery production of the cuttings.

**5. Results**
Results for the system energy balances are presented below. It should be noted that the scope of the LCA is larger than for many other bioenergy LCA studies. This is consistent with the study objectives, but care should be taken if comparing to other published data. For wood production useful comparison may be made to Matthews, 2001.

**5.1 System Energy Balances**
Process technical modelling shows that CFBC-ST has a higher efficiency (25.22%) than DG-GE (21.98 %), although this ignores heat from potential CHP operation. However, when considering the overall bioenergy system CFBC-ST has a less favourable overall energy balance, as shown in table 1.

Figures for SRC yield have been taken directly from the experience of UK growers operating similar regimes to those described for each case and obviously yield can vary significantly in different circumstances. However, a sensitivity analysis shows the overall energy balance to be reasonably robust.
Table 1: System energy consumption per unit of electrical energy produced

<table>
<thead>
<tr>
<th></th>
<th>CFBC-ST</th>
<th>DG-GE</th>
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<tbody>
<tr>
<td>Wood production</td>
<td>0.17</td>
<td>0.11</td>
</tr>
<tr>
<td>Wood preparation and provision</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Electricity generation</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>0.41</td>
<td>0.18</td>
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Wood production - all steps up to and including field drying of chipped SRC
Wood preparation and provision - subsequent steps up to delivery of fuel at power station gate
Electricity generation - subsequent steps up to dispatch of electricity produced.

Table 1 shows that the relative energy consumed in wood preparation and provision for CFBC-ST is more than twice that for DG-GE, but figures 6 and 7 show that, in both cases, this is dominated, not by wood transport, but by drying. Use of the wood itself or another renewable fuel for drying could


to yield variations; with a 10% increase in yield resulting in the totals in table 1 decreasing to only 0.40 for the CFBC-ST and 0.17 for the DG-GE engine.

5.1.1 Wood production
A comparison of the energy inputs into the wood production stage for each case is shown in figure 4.

Agricultural fuel requirements are a significant source of energy consumption for wood production in both cases. This is dominated by the energy consumption in harvesting and chipping, which constitutes 40% of energy consumed in wood production for CFBC-ST and 63% for DG-GE. However the CFBC-ST case has a much higher level of energy invested in materials for wood production than DG-GE. This is because the SRC is planted on marginal land, requiring greater material inputs to maintain yield. Interestingly, it is the application of sewage effluent, rather than commercial products that dominates this additional energy input, as illustrated in figure 5.

Figure 5: Energy in materials used in wood production for CFBC-ST

These calculations are based on annual application of treated sewage effluent to established crops at an application rate routinely used in existing UK sites, transported an average 20 km round trip from the sewage plant. The increased SRC yield from this application cannot be justified energetically. However, there is a very significant environmental benefit arising from the effective treatment and disposal of the effluent.

Initial site protection with rabbit fencing also incurs a significant energy cost if larger proportions of the land requires fencing and smaller field sizes are used.

5.1.2 Wood preparation and provision
Table 1 shows that the relative energy consumed in wood preparation and provision for CFBC-ST is more than twice that for DG-GE, but figures 6 and 7 show that, in both cases, this is dominated, not by wood transport, but by drying. Use of the wood itself or another renewable fuel for drying could
therefore potentially improve the system energy balance.

5.1.3 Electricity generation

Energy inputs for electricity generation in table 1 are much higher for CFBC-ST than DG-GE. This is because of the much more significant start-up/support fuel requirement for FBC operation and the substantial energy cost of construction of the power plant, as shown in figure 8.

While the uncertainty attached to the figures for plant construction are greater than for other results presented here, the substantial difference in the two cases makes it clear that the efficiency advantages of larger, more complex plants must be considered alongside the more significant energy cost of construction and operation.

6. Conclusions

A comparison of life cycle energy balances for two bioenergy systems has demonstrated that more efficient process plants do not necessarily correspond to optimal life cycle energy balances. Due consideration must be given to the energy requirements for plant construction and operation. The energy cost of biomass transportation is shown to be less significant than the energy used in fuel drying, even for relatively large plants. The practice of spreading digested sewage effluent on SRC crops incurs a significant energy cost, but there are substantial environmental benefits of such disposal.

References

Matthews (2001), Modelling of energy and carbon budgets for wood fuel coppice systems, Biomass and Bioenergy, 21, pg 1-19

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