COST EFFECTIVE CARBON REDUCTIONS IN THE BIOENERGY SECTOR

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ABSTRACT: Bioenergy is a key element of UK and European strategies to reduce greenhouse gas emissions to address the global threat of climate change. This requires deployment of robust technologies that will actually provide real carbon emission savings. However, the actual reductions delivered by bioenergy systems can vary significantly and may be sensitive to a wide range of supply chain practices. This paper considers three very different bioenergy systems: production of first generation ethanol from wheat; utilisation of short rotation coppice in a district heating scheme and generation of electricity from imported wood chips. The greenhouse gas reduction efficiency of the schemes are compared and the options for maximizing the reductions are examined, including the likely impact of future technical developments. Techno-economic data is used to evaluate the actual cost of achieving greenhouse gas reductions with different bioenergy technologies. These figures are used to draw policy inferences relating to the cost of carbon reductions with different technology options and the strategies needed to support long term cost effectiveness.

INTRODUCTION

Bioenergy is a key element of UK and European strategies to reduce greenhouse gas emissions to address the global threat of climate change. This requires deployment of robust technologies that will actually provide real carbon emission savings. However, the actual reductions delivered by bioenergy systems can vary significantly and may be sensitive to a wide range of supply chain practices.

The work described in this paper was carried out as part of the Supergen Bioenergy consortium. This UK research consortium of academic and industrial partners is funded to undertake research into biomass thermal conversion routes to heat, electricity and transport fuels. The research scope covers the entire bioenergy system from establishment and cultivation of crops, through to harvesting, processing, conversion and delivery of final energy product. The work is structured around seven interlinking themes, one of which is systems analysis. This work was pursued within the systems analysis theme, which aims to take an integrated approach to assessing the technical, economic, social, political and developmental aspects of UK bioenergy implementation. Within this paper results are presented which integrate the techno-economic analysis and greenhouse gas balances of distinct bioenergy systems in order to evaluate the economic effectiveness of carbon reductions achieved by different . Four different systems have been evaluated and these are described below:

Fermentation of wheat to ethanol

Wheat is delivered to the plant, shredded and hot water is added to produce a mash, which is then cooled, before adding enzymes to facilitate breakdown of starches to simple sugars. Fermentation with yeast permits conversion to ethanol. Heat is then provided in a distillation process so that the ethanol evaporates and is cooled and condensed into a liquid, which is then
dehydrated to produce anhydrous ethanol suitable for blending with gasoline. Chemical by-products of acetic acid, furfural are dried distillers grains with solubles (DDGS) are produced.

**District heating using local short rotation coppice**

Short rotation willow coppice (SRC) is established on previously cultivated land and the agronomic regime broadly comprises ground preparation, establishment and direct chip harvesting on a 3 year-harvest cycle. Treated sewage sludge cake is applied every three years after harvest. Details of the agronomic regimes has been explored elsewhere [1]. Typical yields are 30 odt/ha per three year rotation, at 50% moisture content, equating to an average annual yield of 10 odt/ha, as received [2]. The chips are blown from the harvester into a trailer and transported 2 km to the storage area for drying. Natural drying at the storage area over a period of 30 days reduces the moisture content from 50% to 30% [3] from [4]. A lifetime of 7 harvest plus on establishment year is assumed. After cultivation of the energy crop, the land is returned to its original condition by applying further herbicide, and subsoiling and mulching of the roots to prevent further growth.

The SRC willow is transported 30 km by 120 m$^3$ dedicated haulage vehicle to the district heating site. At the district heating plant, at least one week’s supply of biomass is stored and automatically fed into a 300 kW boiler. The high-temperature flue-gas is passed through a heat exchanger and a cyclone separator ensures low dust emissions in the flue gas. The heat generated is used for space heating and hot water supply for small-medium sized buildings, homes, offices etc. The boiler is assumed to operate for 2200 hours per year (based on providing the base load requirements for typical UK heat profiles) and for 20 years.

The end product (or functional unit) is 1 MJ heat. The comparison natural gas and light fuel oil reference cases include the extraction of the fossil fuel, its clean-up and transportation to the end user and finally, its combustion in a similar sized boiler.

**Medium scale electricity plant using UK grown short rotation coppice**

The SRC is grown as described above and transported as above to a 25 MWe grate combustion plant. At the plant it is combusted in air and the flue gases passed through a steam boiler. Steam raised generates electricity in a steam turbine which is exported to the national grid.

**Imported forest residues combusted to produce electricity in a 350 MWe circulating fluidised bed unit**

Forest residues from a coniferous forest in north America are aggregated, chipped and dried before transporting to the UK for use in a large 350 MWe CFB electricity generating plant. At the plant it is combusted in air and the flue gases passed through a steam boiler. Steam raised generates electricity in a steam turbine which is exported to the national grid.

**METHODOLOGY**

**General framework**

For each of these systems process modelling has previously been carried out in the Supergen bioenergy consortium to produce mass-energy balances, which have been used to evaluate the techno-economic aspects of power, heat and transport fuel production using biomass. These results have previously been reported elsewhere [5-8].
Life cycle assessment of the systems has been undertaken using commercially or publicly available software to calculate the overall greenhouse gas balance for each system (with the exception of wheat to ethanol for which published results have been used).

The results of the LCA work and the techno-economic work have been combined to evaluate the cost effectiveness of the carbon savings achieved. In order to do this it has been assumed that each bioenergy system is effectively delivering two products: the energy product and the associated carbon savings. A benchmark figure for delivery of the same energy product from a fossil fuel based system has been established in each case. The additional cost of a bioenergy system above this has been ascribed to the carbon savings achieved. These have been calculated on a life cycle basis, using discounted cash flow techniques, so that the price arrived at is the effective discounted price of the carbon savings per unit of carbon reduction achieved. This allows the relative cost effectiveness of different bioenergy technologies to be compared. Detail of how this basic method has been applied in each of the cases is outlined below.

**Wheat to ethanol**

A detailed mass-energy balance and techno-economic evaluation have been carried out within the consortium for this system, based on a 200 tpd unit. This was used to calculate the ethanol selling price at which the net present value of the wheat to ethanol facility was zero. This effectively amounts to the break even selling price for ethanol, although it is recognized that this is sensitive to the price of wheat and other coproducts and this is discussed in the results section. This price for ethanol was compared to a long term average wholesale price for petrol [9]. The additional cost of the ethanol fuel compared to the fossil fuel was attributed to the cost of the carbon savings.

There are a large number of existing LCA studies in this area and so published data was used for the greenhouse gas balance for the overall system. This was taken from a UKERC review of sources of variability in greenhouse gas and energy balances for biofuel production [10]. The mean figure for greenhouse gas savings was combined with the figure for the net greenhouse gas savings per unit of delivered fuel to arrive at an effective cost attributed to the greenhouse gas savings.

**UK Grown SRC for District heating**

A detailed LCA study of SRC production, processing and conversion to electricity in a 300 kW boiler was carried out using Sima Pro. It was assumed that the boiler would provide hot water for the base load element of a typical residential heating profile in the UK. Sima Pro was used to calculate the total greenhouse gas savings of the system compared to liquid fuel oil heating and natural gas heating over an assumed 20 year lifetime.

In tandem with this a techno-economic evaluation of the same system was carried out using discounted cash flow techniques in a spreadsheet-based model. The discounted cost of a unit of delivered heat over the plant lifetime was calculated. This was compared to the equivalent costs with a gas-fired boiler providing the same heating load over the same lifetime. The additional cost of the wood-fired boiler was attributed to the carbon savings achieved and this was used to calculate the effective cost (discounted over plant lifetime) of the greenhouse gas savings in £/t of CO2 equivalent.

However, it is recognized that there are few applications where a wood-fired boiler will be able to directly replace a gas-fired boiler, owing to the difficulties of following the heat load. Therefore it is more likely that a wood-fired boiler would only provide the base load of the residential heat demand and would still need to be supplemented with a gas-fired boiler which would operate for peak loads. The techno-economic calculations were repeated for this scenario.
to evaluate the impact this had on the cost of the carbon savings achieved. This is discussed in the sensitivity evaluations included in the results section.

**UK Grown SRC for medium scale electricity**

An SRC feedstock, as described above is utilized in a 25 MWe FBC boiler which generates electricity only at base load. The greenhouse gas savings associated with this system were calculated using a bespoke spreadsheet model utilizing the same agricultural and other assumptions that are input into the Sima Pro model described above. These results have previously been reported elsewhere [11].

A techno-economic evaluation of this system was also carried out using the ECLIPSE process simulator, which has previously been reported elsewhere [5]. This work also involved comparison of the cost of producing electricity in this system with the range of electricity selling prices likely to be achieved for a plant operating in the UK within the UK Renewables Obligation regime. This incorporates payment for the electricity as well as for the ROC element. The electricity only payment was isolated to represent the comparative price of UK electricity generated from non-renewable generation. This price was subtracted from the cost of electricity production in the wood-fired fluidized bed to represent the premium paid in recognition of the carbon savings.

These two analyses were combined to calculate the cost of the carbon savings by assuming that all of the additional cost of generating in the wood fired fluidized bed was attributed to carbon savings. The result is the cost (discounted over lifetime) of achieving the greenhouse gas reductions.

**Large scale imported forest residues to electricity**

Forestry residues are harvested in America and transported to the UK via a specialist freight ship to be used in a large 350 MWe fluidized bed combustion plant. The carbon savings associated with the system are calculated in the BEAT2 model.

A techno-economic evaluation of base load electricity generation from the large scale electricity facility was carried out by others in the Supergen consortium. [7].

These two evaluations were combined to calculate the effective cost of the carbon savings achieved, using the same reference electricity price as above. The result is the cost (discounted over lifetime) of achieving the greenhouse gas reductions.
RESULTS

Table 1 shows the results obtained for the cost of carbon savings for the base run for each of the systems:

<table>
<thead>
<tr>
<th>System</th>
<th>Cost per tonne of carbon dioxide saved (£/t CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat to ethanol</td>
<td>383</td>
</tr>
<tr>
<td>Wood chips for district heating</td>
<td>25</td>
</tr>
<tr>
<td>SRC to electricity</td>
<td>62</td>
</tr>
<tr>
<td>Forest residues to electricity</td>
<td>42</td>
</tr>
</tbody>
</table>

The results indicate that the first generation biofuel technology is a considerably more expensive method of achieving greenhouse gas reductions than any of the others. The most cost effective method is the district heating scheme, with the large scale electricity being almost twice that cost and the small scale electricity two and a half times that cost.

Obviously there will be sensitivity to the assumptions used and some of these may be more significant than others. These are explored in more detail for each system below:

Cost of carbon savings for wheat to ethanol system

The carbon savings for the wheat to ethanol system were not actually modelled within the Supergen consortium as there is a very substantial existing body of data in respect of this and there seems to be little that the consortium could uniquely add to this. Therefore a figure for carbon savings of 44 g CO2/MJ was taken. This was a median figure quoted by Whitaker [10], following an extensive review of published studies carried out on behalf of UKERC. The work actually found a wide range, with a substantial part of the variation being due to decisions about co-product use and reference data (such as carbon emissions associated with electricity production). The table below illustrates the sensitivity impact of changing this average figure to one of the best levels of CO2 emissions from a wheat to bioethanol system. There is also a substantial sensitivity to feedstock price, as this forms 82% of the lifetime operating cost (Ghayur, “Wheat Grain to Ethanol Biorefinery”, Supergen Bioenergy 2010). Therefore reductions in the wheat price from 200 $/t to 120 $/t were also considered.

| Wheat price of $200/t and CO2 emissions of 44 g CO2/MJ | 383 |
| Wheat price of $200/t and CO2 emissions of 23 g CO2/MJ | 160 |
| Wheat price of $120/t and CO2 emissions of 44 g CO2/MJ | 207 |
| Wheat price of $120/t and CO2 emissions of 23 g CO2/MJ | 87  |

It can be seen that the overall cost of CO2 savings is sensitive to both of these parameters, but that improvements in both are essential if the cost effectiveness of this method of carbon reduction is to become competitive with other bioenergy sectors.

Cost of carbon savings for wood chip district heating scheme

The performance and costs of the wood chip boiler were benchmarked against those of a natural gas fired boiler. This showed that the wood fired boiler had a higher lifetime cost per unit of energy delivered than the gas boiler. This additional cost was equivalent to £6.01/MWh, discounted over the lifetime of the appliance.
The global warming potential of the wood fired boiler was evaluated in Sima Pro and it was established that this was 0.004198 kg CO2 eq/MJ. This is substantially lower than the 0.070764 kg CO2 eq/MJ calculated for a natural gas heating boiler in Sima Pro, giving net carbon savings of 0.0666 kg CO2 eq/MJ or 240 kg CO2/MWh. When combined with the techno-economic analysis this results in a cost of £25/t of carbon saved.

However, it should be noted that one of the key drawbacks of replacing a natural gas fired boiler with a wood fired one is that wood fired boilers are not capable of rapid modulation and load following. Therefore they tend to be used to supply the base load for heating applications, with a supplementary gas-fired boiler being used for peak load duties. This makes a substantial difference to the economics and the cost effectiveness of the carbon savings. If we assume that heating demands could be provided by a 1.03 MW gas boiler or by a combination of a 0.55 MW wood boiler and 0.48 MW gas boiler, the results are very different. The capital cost of the new system increases due to economies of scale and the CO2 savings per unit of heat delivered also decrease, since not all heat is being provided by wood. The net effect is that the cost per unit of heat increases from £6.01 to £6.22/MWh and CO2 savings decline from 240 kg CO2/MWh to 157 kg CO2/MWh, resulting in the cost of carbon savings increasing from £25/t to £39/t.

**Cost of carbon savings for small SRC to electricity scheme**

For a 25 MWe grate operating with SRC produced in the UK modelling was carried out within the consortium of the techno-economic analysis [5]. This demonstrated a break even electricity selling price that was some £34.20/MWh higher than the market price for traded electricity in the UK. Analysis was also carried out of the greenhouse gas balance of this system, taking into account the establishment, cultivation, harvesting, processing and transport of the SRC willow crop. This indicated CO2 savings of over 90% compared to UK grid electricity, with 38.7 kg CO2/MWh emitted, compared to a UK grid average of 586 kg CO2/MWh [12]. The net result is a cost per tonne of carbon saved of £62.50.

**Cost of carbon savings for large imported wood to electricity scheme**

One of the key findings of the previous Supergen techno-economics work [5] was that the banded RO policy put in place by the UK government was incentivising large scale electricity only plants with low feedstock costs rather than small scale, CHP or energy crop schemes. The additional incentives focused on these variants by the banded RO offered insufficient reward above the development cost price for developers to bring these schemes forward. The result is that a large number of large bioelectricity plants with low cost imported wood streams are currently being planned in the UK. Therefore the cost effectiveness of the carbon savings offered by these plants was also considered in this work.

A large (350 MWe) bioelectricity plant operating with forestry residues from north America was considered and found to offer lower CO2 savings (490 kg CO2/MWh) per unit of electricity than the small plant considered above. At a wood price of £50/dry tonne, this equates to a cost of carbon savings of £42.25/MWh. This is a substantial improvement compared to the small plant, despite the small plants higher carbon savings per energy unit. The sensitivity of this result to the wood fuel price was examined. If the price falls to £40/dry tonne (equivalent to £28/green tonne at 30% moisture content) then the cost of carbon savings decreases to only £30.62.

**DISCUSSION**

It will be noted from table 1 that wheat to ethanol is by far the least cost effective method of obtaining carbon savings from bioenergy of the 4 systems examined here. Small scale electricity from SRC offers very substantial improvements, but large scale electricity and heating are both superior in terms of cost effective carbon reductions.

However, if the highest carbon savings can be obtained from the wheat to ethanol plant and feedstock prices maintained at a more modest $120/t then the cost effectiveness of carbon
savings begins to approach that of the other technologies (although it appears unlikely to improve to the point of exceeding them).

Small scale electricity is attractive but out performed by the benefits of large scale production. The additional carbon cost in shipping large quantities of material to the UK is more than offset by the lower feedstock cost and economies of scale in terms of power plant economics.

Large scale electricity production initially appears not to reach the level of cost effectiveness of biomass heating schemes. However, this only applies if a biomass heating system can directly replace a gas boiler in providing a steady base load. If, as is the case for most heating applications, there is a need to load follow and a gas boiler is required for this a significant part of the carbon cost effectiveness is offset. The net result is a cost effectiveness of only £39/t. This is actually worse than that achieved by the large scale electricity system if its fuel cost can be sourced as low as £40/dry tonne. It should be noted that the cost of wood for the district heating scheme is assumed to be higher at £65/t, but this is considered realistic given the higher quality requirements, transportation and handling, and lower volume of fuel required for the district heating plant.

It seems clear that first generation ethanol is a relatively expensive way to achieve carbon emission reductions with bioenergy, particularly when wheat costs are high. Both the heat and electricity systems evaluated offer more cost effective emissions reductions. However, this is sensitive to a number of parameters and depending on the exact replacement scenario and cost of fuel large scale electricity or district heating may offer the better performance.

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