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The environmental and economic sustainability of potential bioethanol from willow in the UK

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ABSTRACT

Life cycle assessment has been used to investigate the environmental and economic sustainability of a potential operation in the UK in which bioethanol is produced from the hydrolysis and subsequent fermentation of coppice willow. If the willow were grown on idle arable land in the UK, or, indeed, in Eastern Europe and imported as wood chips into the UK, it was found that savings of greenhouse gas emissions of 70–90%, when compared to fossil-derived gasoline on an energy basis, would be possible. The process would be energetically self-sufficient, as the co-products, e.g. lignin and unfermented sugars, could be used to produce the process heat and electricity, with surplus electricity being exported to the National Grid. Despite the environmental benefits, the economic viability is doubtful at present. However, the cost of production could be reduced significantly if the willow were altered by breeding to improve its suitability for hydrolysis and fermentation.

1. Introduction

As concern about global warming grows, there is increased interest in producing biofuels as alternatives to fossil-derived gasoline and diesel. This interest also stems from the fact that reducing the usage of gasoline and diesel would relieve, to some extent, the reliance on imported oil and the associated political vagaries governing its supply and price. One such biofuel is second-generation bioethanol, which can be produced by the hydrolysis and fermentation of cell-wall polysaccharides in lignocellulosic feedstocks. Lignocellulosic biomass is the most abundant reproducible resource on the Earth, and so there are many potential feedstocks for the production of second-generation bioethanol, including fast-growing perennial crops (e.g. willow, poplar, switchgrass, and miscanthus) and wastes (e.g. agricultural, forestry, municipal, pulp and paper).

In the UK, significant attention has been paid to the perennial energy crop, willow, which can produce high annual yields of 7–12 dry te/ha (DEFRA, 2007) and is suitable for cultivation on low-quality land. The land used to grow perennial crops does not require ploughing during the lifetime of the crop (up to 30 years for willow) and therefore can act as a sink for carbon during this time, increasing the content of soil organic matter and improving the quality of the soil (Grogan and Matthews, 2001). At present, little arable land is dedicated to growing willow as an energy crop in the EU; however, whilst the demand for food is projected to stay roughly constant in Europe over the coming decades, improved agricultural practices are resulting in increased yields of crops, so that more land is being made available for other uses, such as the cultivation of energy crops. It has been estimated that by 2030, there will be between 44 and 53 million hectares of idle arable land in Europe (defined as the EU and Ukraine) suitable for the cultivation of bioenergy crops, with ~43% of this land being in the Ukraine and ~13% in Poland, whilst only ~1% is predicted to be in the UK (Fischer et al., 2009). It is therefore likely that a large proportion of willow used for the production of bioethanol in the UK would be imported from Eastern Europe in future. However, in many developing countries outside Europe, yields of food crops are predicted to fall in the coming decades owing to climate change. Access to food in these regions, which already have high levels of chronic undernourishment, will therefore be severely affected. As a result, it would be highly beneficial if marginal land, such as restored landfill sites which could not be used to grow food crops, were used to grow lignocellulosic energy crops. However, the yield achieved when cultivating these crops on marginal land is likely to be adversely affected by poor soil, such as shallow depth, compaction, low capacity for holding water and insufficient levels of plant nutrients.

Abbreviations: GHG, greenhouse gas; LCA, life cycle assessment; NPV, net present value; WIS, water-insoluble solids; WWT, waste-water treatment.

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If biofuels, such as bioethanol from lignocellulosic feedstocks, are to provide a sustainable alternative to fossil-derived transport fuels, they must be environmentally, economically and socially acceptable. These fuels have the potential to have significant environmental benefits by being carbon neutral, because growth of the feedstock uses photosynthesis to fix atmospheric CO_2, which is then released on combustion. However, the cultivation of biomass and its conversion to a liquid fuel requires inputs, e.g. electrical power and fertiliser, with each of these inputs having an associated environmental burden. It is therefore important to quantify the possible greenhouse gas savings associated with using such biofuels, as well as determining whether their production is economically and socially viable. Life cycle assessment (LCA) can be used to quantify the total environmental and economic performance of a process or service, from the production of raw materials to the disposal of waste and products at the 'end of life'. Environmental impacts, such as total greenhouse gas (GHG) emissions, acidification potential and eutrophication potential can be quantified by relating the emissions released by the process to a reference chemical, e.g. GHG emissions are quantified in terms of the equivalent mass of carbon dioxide emitted. As a result, much research using LCA to assess the environmental performance of biofuels has been undertaken, especially with regard to first-generation biofuels, which are already being produced in considerable quantity and are generally made from feedstocks that could also be used for food (e.g. bioethanol from corn or wheat, biodiesel from oilseed rape or soya beans). The life cycle GHG emissions associated with first-generation biofuels has been shown to vary substantially with the feedstock (DfT, 2008), agricultural procedures employed (Kim and Dale, 2008; Stephenson et al., 2008; Wicke et al., 2008) and the country where the crop is grown (DfT, 2008; Stephenson et al., 2010). It also depends on how the environmental burdens are allocated to the co-products, such as glycerol or meal.

Several studies have concerned the LCA of bioethanol from lignocellulosic feedstocks. Levelton (2000) and Spatari et al. (2005) demonstrated that the use of bioethanol from corn stover and switchgrass in Canada would release considerably fewer GHG emissions than fossil-derived gasoline (corn stover 82–84% lower; switchgrass 75–96% lower), whilst Levelton (2000) also concluded than ethanol from wheat straw would also save a considerable amount of GHG. Bioethanol from wood in the EU has also been studied (CONCAWE and EUCAR, 2006) and was found to have a life cycle GHG burden ~71% lower than fossil-derived gasoline. So far, no LCA studies have investigated the environmental performance of bioethanol from willow.

The economics of bioethanol produced from lignocellulosic feedstocks have been investigated, including from corn stover (Aden et al., 2002; Sassner et al., 2008b), spruce (Sassner et al., 2008b; Wingren et al., 2008), willow (Sassner et al., 2008b) and pine (von Sivers and Zacchi, 1995). However, most studies on willow are specific to Sweden and therefore an economic analysis assessing production in the UK is timely.

This paper uses life cycle assessment to investigate the environmental sustainability of the production of bioethanol from willow for a hypothetical second-generation ethanol plant built between 2009 and 2011 in the UK. The process economics have also been studied. In reality, second-generation bioethanol plants are not likely to be built in the UK for several years; however, this analysis was used to identify the key sensitivities likely to affect the economics and environmental performance of the process. The options of (i) importing willow from Europe, (ii) growing the crop on marginal land, and (iii) using willow modified by breeding to improve its suitability for hydrolysis and fermentation, have all been investigated. The cultivation of willow in both the UK and Poland has been considered, with the latter being an example of an eastern European country likely to have arable land available for the growth of energy crops in future.

2. Methods

2.1. Life cycle assessment (LCA)

Life cycle assessment was undertaken *via* the sequential stages of (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation and reporting (International Organization for Standardization, 2006a, 2006b) described below. The analysis was aided by the use of Gabi 4 software.

2.1.1. Goal and scope definition

The basis for comparison, or the *functional unit*, was defined as one tonne of bioethanol (99.5 wt% ethanol), which has been blended to a given fractional volume with conventional, fossil-derived gasoline, delivered to a filling station in the UK and combusted in a typical, compact-sized car engine. The results are based on information gathered during 2009.

The 'control volume' in this study encompasses all the stages directly used to produce the bioethanol (i.e. the foreground system, including the cultivation of willow and its conversion to bioethanol) and also the background system which comprises the homogeneous markets providing the materials and energy used by the foreground system.

2.1.2. Inventory analysis

Quantitative mass and energy balances were performed over each control volume, an activity requiring substantial data collection. Information regarding common practices employed when cultivating willow was gathered from the literature, in particular, a report published by DEFRA (2007). The chemical composition of willow, on a dry basis, was assumed to be 42.5 wt% cellulose, 3.0 wt% mannan, 15 wt% xylan, 2.5 wt% galactan, 1.5 wt% arabinan, 26 wt% lignin, 3 wt% acetate, 2 wt% ash and 4.5 wt% other, consisting mainly of extractives which are not part of the cell-wall (Sassner et al., 2008b). Currently, no second-generation bioethanol plant is in commercial operation in the UK, therefore the process information was gathered from the literature. Aden et al. (2002) provided a detailed design of a process plant to treat 2000 te/day of corn stover and to produce $\sim 2 \times 10^5$ te of 99.5 wt% bioethanol per annum. This design has been extensively reviewed and used in a number of subsequent studies (Gonzalez-Garcia et al., 2009; Gnansounou and Dauriat, 2010) and therefore was used as the basis for the design of the process plant in this study. However, rather than using the separate steps of hydrolysis and fermentation employed by Aden et al. (2002), this study assumed that these steps would be performed together in simultaneous saccharification and fermentation (SSF). This method has been shown to have several advantages over hydrolysis and fermentation undertaken separately, including alleviating end-product inhibition of the enzymes (Sassner et al., 2006). The results of Sassner et al. (2006, 2008b) on the SSF treatment of willow were used in our study to model the SSF process. In the present study, each unit operation in the process was modelled using a spreadsheet, apart from the distillation operations, where the flowsheeting software, Aspen HYSYS, was used. The Gabi 4 Professional LCI database was then employed to generate an inventory table, showing the resource usage associated with the production of one tonne of bioethanol.

2.1.3. Impact assessment and interpretation

Using the LCA software, it was possible to formulate the inventory table into a set of environmental themes, based on the EDIP (Environmental Development of Industrial Products) 2003 meth-