Sustainability considerations for integrated biorefineries

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Integrated biorefineries have the potential to contribute towards sustainable production of transportation fuels, energy, and chemicals. However, because there are currently no commercial biorefining plants in operation, it is not clear how sustainable they really are. This paper sets out to examine key issues associated with biorefining that should be considered carefully along the whole supply chain to ensure sustainable development of the sector.

Sustainability

Sustainable development is an approach that strives to satisfy human needs in an economically viable, environmentally benign, and socially beneficial way. There are many sustainable development issues, or, for short, sustainability issues that must be considered when evaluating whether a product or human activity is sustainable. These include, for example, environmental impacts such as global warming, acidification, and loss of biodiversity, economic aspects such as costs and profits, and social concerns such as employment, health, and human rights. The sustainability of a product or activity can be measured quantitatively and/or qualitatively by estimating or assessing the economic, environmental, and social impacts.

Integrated biorefineries

Integrated biorefineries use various biofeedstocks to produce biofuels, energy (electricity and heat), and chemicals (Figure 1). Typically, all of the heat and some of the electricity generated by the refinery are used for its operation, and the rest of electricity is sold to the grid. Owing to issues such as climate change, security of energy supply, and increasing costs of fossil fuels, the main driver for developing integrated biorefineries is the production of biofuels for transportation, with the co-products (electricity and chemicals) helping to maximize value derived from feedstocks.

Biorefineries, their feedstocks, and products can be classified as first, second, or third generation [1]. First-generation feedstocks are food crops such as corn (maize), wheat, and sugar cane. Currently, most of the global biofuel production consists of first-generation ethanol, which represents over 80% of liquid biofuels by energy content [2]. This has led to competition with food production, both in terms of

land use and reduced supply of food crops, pushing up food prices in some countries. The focus is now shifting from first-generation feedstocks to second- and third-generation feedstocks for use in integrated biorefineries. Second-generation feedstocks are lignocellulosic materials and include energy crops (e.g., poplar and miscanthus) and wastes (e.g., agricultural, forestry, and municipal waste). Third-generation feedstocks consist mainly of microalgae. Waste CO₂ from power plants or elsewhere could also be used as feedstocks in the future.

An integrated biorefinery can use a biochemical or thermochemical route, or a combination of both, to process the feedstocks into useful products (Figure 1). The biochemical route uses microorganisms (e.g., yeast) and enzymes in biological processes such as fermentation to process the biomass, whereas the thermochemical route relies on heating the feedstock to temperatures between 300 °C and 1000 °C with little or no oxygen. Each route will have to overcome a range of technological issues before it can become a commercial reality, including the flexibility to use different types of feedstocks, the efficient use of feedstocks, and the successful scaling-up from pilot- to large-scale plants [3]. In addition to technological issues, integrated biorefineries face a number of sustainability challenges – environmental, economic, and social – that must be considered on a life-cycle basis. This means that the whole life cycle of a biorefinery system must be considered (Figure 1), from the cultivation and harvesting of biomass (if applicable), to its collection and transportation to the plant, its conversion to fuels, energy, and chemicals, and their consumption by end users. This is necessary to avoid shifting sustainability impacts from one part of the supply chain to another – for example, reducing greenhouse gas (GHG) emissions from the refinery only to increase them through transportation of feedstocks to the refinery. Evaluation on a life-cycle basis is also required by various legislative acts related to biofuels, including the EU Renewable Energy Directive [4] and the US Energy Independence and Security Act [5].

The first commercial second-generation biorefining facility is expected to come online in late 2013 in the United States [6]. Therefore, I will focus on second-generation biorefineries for the following discussion of key sustainability issues in the supply chain.

Environmental considerations

Greenhouse gas emissions

One of the main drivers for biofuels and integrated biorefineries is their potential to save GHG emissions

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Figure 1. A simplified concept of integrated biorefinery on a life-cycle basis. Different types of biomass can be used to produce fuels, chemicals, and energy using biochemical or thermochemical conversion routes, or a combination of both.

compared to fossil fuels. This is illustrated in [Figure 2](#), which compares the life-cycle GHG emissions of ethanol from different biofeedstocks to petrol. As indicated, the GHG emissions from ethanol produced in an integrated biochemical refinery from second-generation feedstocks are negative, indicating a saving in GHG emissions ranging from -7 g CO₂ eq./MJ of fuel for wheat straw to -19 g CO₂ eq./MJ for poplar (T. Falano, PhD thesis, University of Manchester, 2012). This is due to the ‘credits’ for the co-products – in this case, electricity, lactic acid, and acetic acid – whereby their GHG emissions, which would have been generated by their production in conventional plants from fossil resources, are subtracted from the biorefinery emissions. In some cases, as in this example, the credits are greater than the actual emissions from the plant, hence the negative value, indicating that these emissions have been avoided or saved. This means that, compared to petrol, a saving of up to 104 g CO₂ eq./MJ of fuel could be achieved from ethanol produced by this integrated biorefinery. By comparison, the lowest GHG emissions from first-generation ethanol are from Brazilian sugar-cane ethanol, which saves up to 65 g CO₂ eq./MJ on petrol – this is 1.6 times lower than the saving from ethanol from the integrated biorefinery. In the worst case – ethanol from US corn – there are no GHG savings; in fact, its emissions are 1.5 times higher than from petrol [7]. This is due to the emissions of N₂O from the application of fertilizers during corn cultivation, which outweigh the global-warming potential of CO₂ emissions from petrol combustion.

Land-use change

Additional GHG emissions are generated if land is converted from its present use for the cultivation of biofuel feedstocks. This is relevant to energy crops and potentially microalgae, and might lead to both direct and indirect land-use change (LUC). The former involves conversion of land from its current use to cultivate biofuel feedstocks, and the latter is related to the displacement of existing agricultural activity (e.g., food crops) due to the cultivation of biofeedstocks. As a result, LUC is often associated with a change in land cover that leads to a change in carbon stocks,

which in turn generates GHG emissions. In some cases, LUC will result in GHG emissions that are large enough to outweigh the GHG savings gained from producing biofuels instead of fossil fuels. For example, when deriving ethanol from miscanthus ([Figure 2](#)), conversion of forest land in the United Kingdom to the cultivation of miscanthus releases 20 t CO₂ eq./ha/year [8], which increases the GHG emissions of ethanol from -11 to 310 g CO₂ eq./MJ. This is 3.6 times higher than the emissions from petrol. Therefore, LUC is a crucial factor that must be taken into account when estimating GHG emissions from biofuels.

Biodiversity

Loss of biological diversity can occur when forests and grasslands are converted to cultivate biofuel crops. For example, large mono-crop areas attract only a limited number of species. However, if degraded lands are restored for biofuel crop production, biodiversity can improve.

Forest and agricultural residues are expected to have lower negative impacts on biodiversity than energy crops [9]. However, the removal of agricultural residue from fields might increase weed growth, which could necessitate the increased use of herbicides, thus affecting local biodiversity as well as environmental pollution. Replacement of native forests with mono-crop plants, particularly more invasive species, could also result in a significant reduction in biodiversity. For example, eucalyptus, some miscanthus species, and switchgrass all exhibit some features of invasiveness [10].

Biodiversity loss can also occur owing to LUC. For example, if set-aside land in Europe is used to grow biofuel crops, impacts on biodiversity will need to be evaluated carefully because some of these set-aside areas can be more biodiverse than farmlands [1].

Water use

Water use varies widely with feedstock type. For example, feedstocks from waste require little or no water, whereas energy crops such as jatropha, eucalyptus, switchgrass, and miscanthus generally have higher water demand than arable crops owing to longer seasonal growth and

Figure 2. On a life-cycle basis, ethanol produced in an integrated biochemical refinery saves up to 104 g CO₂ eq./MJ compared to petrol (85 g CO₂ eq./MJ for petrol compared to -19 g CO₂ eq./MJ for ethanol from UK poplar) owing to the credits for the co-products, in this case electricity, lactic acid, and acetic acid. Ethanol from sugar cane in Brazil saves 65 g CO₂ eq./MJ, whereas ethanol from corn has much higher greenhouse gas (GHG) emissions than petrol. Land-use change (LUC) can increase GHG emissions significantly — in the case of biofuel from miscanthus to 310 g CO₂ eq./MJ or 3.6 times higher than petrol. GHG emissions for all fuel options are from 'cradle to grave', encompassing production of the feedstocks and fuels as well as fuel combustion during use of vehicles.

transpiration rates [9]. This can be an issue in water-stressed regions owing to the need for irrigation. For example, cultivation of jatropha in Bangalore requires 1311 mm/year of irrigation water, leading to the total water footprint of 58 700 l/diesel [11]. Conversely, water use by biorefineries is relatively modest: for example, producing biodiesel requires 1–3 l/l of fuel [9].

Other environmental impacts

Further environmental impacts associated with integrated biorefineries and their products include acidification, eutrophication, human toxicity, and eco-toxicity. The agricultural stage is the major contributor to these impacts owing to air emissions of ammonia and leaching of nutrients from fertilizers, as well as air emissions from the use of fuel in agricultural machinery. The biorefinery also contributes to these impacts owing to emissions of SO₂, NO, and NO₂, as well as other air and water emissions.

Economic considerations

Feedstock costs

Feedstock costs vary depending on their type and origin but, generally, agricultural residues have lower costs compared to energy crops. In Europe, for example, they range from €21 to €180 per tonne (US\$30–250) of dry matter [12]. Wood chips are at the upper end of the price range, whereas waste wood and agricultural residues are at the lower end; the average feedstock costs are below €60 per tonne of dry matter. These costs do not include the transport costs to the biorefinery, which can be significant, depending on the moisture content and the distance travelled [13].

Capital costs

Because there are currently no commercial biorefinery installations, the capital costs of integrated biorefineries are uncertain, and most estimates are based on design data. For example, the capital costs of a biochemical

refinery using corn stover as a feedstock are estimated at \$232 million, and for the thermo-chemical at around \$300 million [14]. Integration into an existing refinery or chemical plant seems to be the most cost-effective option across the different processing routes; the integration can also accelerate the planning process and lower investment costs by around 25% [12].

Biofuel costs

Feedstock and capital costs affect the costs of biofuels and, to a certain extent, the costs of the co-products. Although costs of biofuels from integrated biorefineries are currently uncertain, it is clear that higher oil prices and energy security drivers are beginning to make them commercially more attractive and, as the 'economies of scale' increase (a saving in costs gained from higher production scales), it is expected that the costs of lignocellulosic fuels will be in the same range as biofuels from food crops. For example, in 2006 the costs of second-generation ethanol were estimated at \$0.8–1.1 per litre, and these prices are expected to come down to \$0.25–0.65 per litre by 2030 [10]. This compares to a cost of \$0.6–0.8 per litre in 2006 for ethanol from corn, rising to an estimated \$0.35–0.55 per litre in 2030 [10]. However, these costs do not take into account changes in land prices that may arise from competing demands from agriculture. The costs of other input materials in addition to feedstocks are not considered either, but they could also affect the biofuel prices. For example, the cost of enzymes is expected to reach \$0.12–0.20 per litre of ethanol by 2015 [15], representing 15–18% of current biofuel prices.

Social considerations

Jobs and regional development

Cultivation of energy crops has the potential to create jobs in the agricultural sector. Although this potential is more limited for waste feedstocks, their use can provide an additional income to farmers and local communities, stimulating

rural development. However, this could adversely affect farmers or a rural population that is dependent on residues for animal feed or domestic fuel [1]. Further job opportunities exist during the construction and operation of biorefineries.

Health issues

Human health can be affected in many different ways along the supply chain. For example, health hazards include emissions of particulates as a result of biomass handling and the toxicity of fertilizers and pesticides. The application of pesticides is estimated to cause 2 million cancer cases and 10 000 deaths each year [1].

Human and labour rights

The issues of human and labour rights as well as gender discrimination are also relevant in this sector, especially in developing countries. Women are particularly vulnerable – they receive lower wages and are subjected to longer working hours than men [1]. In some countries, child labour might also be an issue.

Land availability and food prices

Energy crops could potentially compete with food crops for land, which could in turn affect food prices. For example, to meet the biofuel targets in Organisation for Economic Co-operation and Development (OECD) countries and some developing countries, accelerated production of lignocellulosic fuels could increase prices of cereal crops by around 15% by 2020. Using first-generation fuels would lead to a 30% price increase [9].

Intergenerational issues

Integrated biorefineries and their products have the potential to avoid or reduce the magnitude of some intergenerational issues associated with the use of fossil fuels. These include GHG emissions and related climate change impacts that would affect future generations. Similarly, avoiding the use of fossil fuels by using biofuels, biochemicals, and bioenergy helps save the fossil resources for future generations.

Concluding remarks

The sustainability of integrated biorefineries and their products will depend on many technological, economic, environmental, and social factors. These will have to be evaluated carefully to ensure sustainable development of the sector.

Arguably, however, the ‘right’ policies will have to be in place, promoting sustainable practices along the whole

supply chain. For a more sustainable sector globally, concerted action is needed worldwide to ensure that the ‘sustainability burden’ is not shifted from developed to developing countries and that there is a fair sharing of costs and benefits along supply chains.

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<http://dx.doi.org/10.1016/j.tibtech.2013.10.009> Trends in Biotechnology, January 2014, Vol. 32, No. 1