Global prospects for the biofuels industry

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The rapidly rising cost of oil and growing concern about global warming have dramatically increased the prospects for significant commercial biofuel production. Optimistically, biofuels could replace petroleum as the major transportation fuel within the next 2 decades. However, technical advances must be made to make bioethanol and biodiesel economically viable and sustainable replacements for petroleum. As a consequence, large investments are being made in research and development of bioethanol and biodiesel as alternative fuels by governments and the major oil companies.

Several major oil companies initiated major research initiatives in 2007 to develop biofuels. British Petroleum believes that, while worldwide demand for biofuels likely will grow at a rate of 15-20% per year, the technology for advanced biofuels is 5-10 years away. The company is developing woody crops to produce bioethanol and oily crops such as *Jatropha* species for biodiesel production [1]. BP have also set up a dedicated biofuels business in 2006 and announced plans to invest $500 million over 10 years in a new Energy Biosciences Institute; BP is partnering with the University of California Berkeley and the University of Illinois, Urbana-Champaign in this effort. BP also established a *Jatropha* demonstration project in India. In Australia, BP is working towards producing renewable diesel fuel from tallow.

Chevron and the US Department of Energy's (DOE) National Renewable Energy Laboratory have entered into a collaborative research and development agreement to study the potential use of algae to produce liquid transportation fuels, e.g. jet fuel [2]. Chevron believes that non-food feedstock sources such as algae and cellulose hold the greatest promise to grow the biofuels industry to large scale. Algae are considered a promising potential feedstock for next-generation biofuels because certain species contain high amounts of oil, which could be extracted, processed and refined into transportation fuels using currently available technology. Key technical challenges include identifying the strains with the highest oil content and growth rates and developing cost-effective production methods.

The European Union has expressed great interest in replacing petroleum-based fuels with biofuels as part of a strategy to mitigate greenhouse gas emissions and support regional economic development [3]. Life cycle analyses have shown that mixtures of biofuels with petroleum derived fuels can significantly reduce NOx emissions and can be energetically favourable and economic. Based upon a life cycle analysis, Hill *et al.* [4] concluded that bioethanol from corn grain yields 25% more energy than the energy invested in its production and biodiesel from soybeans yields 93% more; also they reported that greenhouse gas emissions are reduced 12% by the production and combustion of ethanol and 41% by biodiesel. Using an energy renewability efficiency (ERenEf) indicator, Malca and Fausto [5] found that a maximum ERenEf value of 48% currently can be obtained for wheat-based or sugar beet ethanol production which could result in a 0.70MJ energy savings if bioethanol replaced petroleum-based fuels. Faaij [6] postulates that the current contribution of bioenergy of 40-55EJ per year may increase to 200-300EJ by the end of the 21st century which could make biofuels a more important source of energy than petroleum.

The European Union has set a target for 2010 of 9.3 million tons of ethanol from the fermentation of 3.7 million hectares of wheat or sugar beets. Studies by the US DOE indicate that 1.3 billion tons of biomass can be produced for biofuel production; bioethanol production in the United States could reach 60 billion gallons per year by 2030 which would replace 30% of US petroleum usage [7]. Currently the United States consumes 7 billion barrels of oil each year, while only 100 million barrels of bioethanol are currently being produced from corn grain. However, many new small companies in the US are beginning to produce bioethanol, in part because of tax subsidies that help make such ventures economically feasible.

A major jump in biofuel production, nevertheless, is likely to depend upon being able to utilise cellulose-based biomass sources. Being able to utilise less expensive cellulosic wastes is important since the use of corn and other staple grains for bioethanol production results in rising food and feed prices. Extensive research is being carried out in Russia on the production of bioethanol from cellulose using cellulolytic enzymes [8], as well as in the United States, Australia, Canada and many other countries. The 4 billion plus gallons of ethanol produced each year in the United States from corn could be greatly increased by using plant lignocellulose. However, while glucose can be fermented to ethanol by a number of microorganisms, hydrolysis of cellulose and hemicellulose produces a wide range of both C_5 and C_6 sugars that are not efficiently fermented to produce ethanol. Ongoing research aims at engineering genetically modified microorganisms and enzymes that can enhance the efficiency of cellulose hydrolysis and ethanol production from all of the sugars produced in that way. The US DOE National Renewable Energy Laboratory [9] is promoting the development of organisms capable of producing bioethanol from a wide range of sugars and polymeric carbohydrates. The programme has supported work at the universities of Wisconsin and Toronto to increase the efficiency of bioethanol production using a yeast strain and a recombinant form of *Zymomonas*. According to the US DOE, bioethanol production costs of $1.07/gallon (in 2002 dollars) could be competitive with petroleum-based fuels and thus it is possible to make bioethanol truly competitive with gasoline by 2012 [10].

New plant species or biologically based production methods are being sought that could greatly enhance the efficiency of bioethanol production, particularly those that would increase the cellulose content of plants and allow for more efficient enzymatic hydrolysis at the time of harvest [11]. *Panicum virgatum* (switchgrass) is one such candidate to provide the biomass for biofuel production [12]. Because plants like switchgrass and *Miscanthus* grow rapidly in dense formations and have few pests and diseases they are ideal for biofuels; however, these same potentially beneficial traits raise concerns that they could become deleterious weeds if not properly contained.

Genencor has been carrying out research aimed at reducing the cost of cellulose-based bioethanol fuel production from agricultural and forestry byproducts, such as corn stover and corn fibre, wood chips, wheat straw, switch grass and paper pulp [13]. In 2007 Genencor announced it had successfully formulated a commercial complex of enzymes that hydrolyses lignocellulosic biomass into fermentable sugars for bioethanol production. The effort was partially supported by contracts with the US DOE National Renewable Energy Laboratory.

Lignocellulosic biowastes also can be utilised to produce biodiesel. The acid hydrolysate of *Populus euramevicana* can be converted by the yeast *Rhodotorula glutinis* to biodiesel, and this process may be further improved by developing an enzymatic hydrolysis process using cellulases and hemicellulases [14]. Algae that have high lipid contents are also potential sources of biomass for biodiesel production. Archer Daniels Midland established a partnership with Volkswagen to develop new biodiesel fuels. Currently, cotton oil, rapeseed oil and sunflower oil are used to produce biodiesel [15]. In the United States, biodiesel usually is made from soybean oil or recycled restaurant grease. In 2002, 15 million gallons of biodiesel was consumed in the United States.

Canada is estimated to have over 22 million tons of waste biomass that could be used to produce over 2 billion gallons of bioethanol. If hybrid poplars and other sources of cellulose could be used, at least 15 billion gallons of bioethanol could be produced. To realise such bioethanol production, the resistance of plant cell walls to enzymatic hydrolysis, known as 'biomass recalcitrance', would have to be overcome so as to reduce the current high costs of cellulose hydrolysis [16].

Iogen in Canada has a demonstration plant for producing commercial bioethanol from wheat straw and corn stover (leaves and stalks of corn) by using steam explosion to free cellulose from hemicellulose and lignin and digesting the cellulose with cellulase to produce fermentable sugars [17]. One ton of wheat straw yields 85 gallons of ethanol and 200kg of lignin which is burned as an energy source. The demonstration plant had a capacity of 3 million gallons per year. Iogen estimates the market for bioethanol from cellulose may grow to $10 billion by 2012, and hopes to make full scale bioethanol production a reality. Given the progress of research in this area, the full potential of biofuel production from cellulosic biomass may be obtainable in the next 10-15 years [18].

In conclusion, whereas in the 1980s the cost for bioethanol production was about $90 a barrel, making it economically unfavourable considering that the cost of a barrel of oil was under $50 at that time, currently the cost of a barrel of crude oil continues to rise (now costing almost $100 per barrel) while the cost of biofuels continues to decline. Thus, based upon economic considerations alone, there is likely to be a major shift from petroleum to biofuels over the next few decades, with cellulosic sources of biomass becoming the major starting materials for bioethanol production. Coupled with the urgent need to reduce emissions of greenhouse gases, bioethanol and biodiesel look like major fuels of the future.

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