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Perspective

The promise of cellulosic ethanol production in China

Bin Yang* and Yanpin Lu

Bourns College of Engineering, Center for Environmental Research and Technology, University of California, 1084 Columbia Avenue, Riverside, CA 92507, USA

As a signature piece of evidence for global warming, a US national panel of scientific specialists recently reported that the late 20th century was the warmest period in 1000 years as a result of human influence. The generation of greenhouse gases from use of fossil resources which modern society relies on for energy, mostly as oil, natural gas, and coal, contributes significantly to global warming. Currently, the USA is the largest single emitter of greenhouse gases and, with petroleum its largest energy source, it uses about 28% of the world oil supply. China uses about 6% of world petroleum production as the second largest petroleum consumer, and although per capita oil consumption in China is only 1/14 of that in the USA, demand is anticipated to grow, with a rapidly increasing GDP that jumped 3.8% in the final quarter of 2004 and 9.2% in the first quarter of 2005.[1] For example, the International Energy Agency (IEA) projects that Chinese petroleum demand will grow to about 14 million barrels per day (bpd) in 2030, only about one-third less than the current demand in the USA.[1] Use of vehicles is projected to expand from roughly 24 million vehicles now to 90–140 million by 2020 due to a nationwide promotion of the automobile industry, increasing the demand for transportation energy from 33% of total Chinese petroleum use to about 57% (from 1.6 million bpd in 2004 to roughly 5.0 million bpd in 2020).[1] Consequently, carbon dioxide emissions from fossil energy will grow to 7.14 $\mathrm{Gt\,y^{-1}}$ in 2030.[2]

Growing dependence on petroleum also makes China more dependent on imported oil. In 2005, China produced about 12.9 billion barrels of petroleum, which ranked the country fifth in the world for the 13th straight year. Oil production is not expected to increase significantly. China became a net importer of oil from other countries in 1993, including Saudi Arabia, Oman, Angloa, Iran, and Russia,[2] and petroleum imports increased to about 865 million barrels in 2005, accounting for about 42.9% of total oil consumption in China. China's dependence on imported oil is projected to continue to grow, reaching 75% of its petroleum use in 2030 and a quantity equal to that for the USA in 2004.[2] Thus, China is faced with mounting challenges of meeting energy demand, national energy security and addressing environmental pollution. In addressing its rapidly expanding demand for fuel, China, as the world's leading developing economy, has the opportunity to become a global leader in promoting and applying sustainable energy technologies and strategies, including the production and use of cellulosic ethanol.

Energy challenges and dependence on fossil fuel are global problems. Alternative fuels from renewable resources, such as fuel ethanol from cellulosic biomass, provide numerous benefits in terms of environmental protection, economic development, and national energy security. Ethanol made by biological processing of cellulosic biomass generates little if any net greenhouse gas emissions and offers a powerful route to sustaining both the environment and resource supply.[3,4–7] Cellulosic ethanol has received increasing attention in the USA, which is the biggest oil importer and consumer, with over two-thirds of petroleum being consumed by the transportation sector. President Bush has called for a significant increase in ethanol production for transportation fuel and has urged commercialization of cellulosic ethanol within a few years. The Secretary of Energy recently proposed 30% replacement of transportation fuel by ethanol, requiring 60 billion gallons of ethanol to meet the current usage of 140 billion gallons of gasoline per year in the USA. The current annual production of ethanol from corn and grain in the USA is around 4.5 billion gallons, and the annual production is projected to be at least 7.5 billion gallons by 2012, much less than the Secretary's proposal. It can be estimated that the USA could sustainably produce about 130 billion gallons of fuel ethanol from cellulosic biomass. Thus, replacement of a major fraction of oil for transportation would not be realized without the involvement of cellulosic ethanol.[8]

Like the US government, the Chinese government foresees energy challenges. A Renewable Energy Law was passed on February 28, 2005 to accelerate the

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* Correspondence to: Bin Yang, Bourns College of Engineering, CE-CERT, University of California, 1084 Columbia Avenue, Riverside CA 92507, USA
E-mail: binyang@cert.ucr.edu

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development of renewable energy, including wind, solar, hydro, and biomass, and China began research on the supplementation of gasoline with ethanol in 1999. In February 2004, exclusive use of gasoline containing 10% ethanol was initiated in all areas of Heilongjiang, Jiling, Henan, and Anhui provinces and in selected areas of Hebei, Shandong, Jiangsu, and Hubei provinces. Furthermore, it was made illegal to sell or purchase gasoline not containing 10% ethanol in these areas.

To serve the market created by these mandates, the government invested in factories in several provinces to produce fuel ethanol from grain, with corn as the primary feedstock. Xinglong Energy Inc. in Jiling, with an annual capacity of 250 million gallons of ethanol, is now the biggest fuel ethanol producer, and China expects to achieve a total annual fuel ethanol production capacity of about 534 million gallons in the near future.[9] Initially, these processes targeted the use of grain that was stored so long as a war supply that it was no longer suitable as food or animal feed. In addition, fresh corn was also targeted to compensate for its overproduction in certain areas. To better prepare the grain ethanol industry for the future challenges of entering the World Trade Organization, the government introduced policies to promote production of grain-based ethanol, such as eliminating sales tax and providing subsidies to compensate for any revenue loss during processing and sale. Meanwhile, the government set the selling price of ethanol at about $1.65 per gallon as 91.1% of the selling price of gasoline. However, production of ethanol from corn at $147 per dry ton costs about $1.84 per gallon, resulting in large subsidy payments by the government. The planned phase-down of these subsidies means that ethanol producers will need to significantly reduce production costs within a couple of years, a challenge that will be exacerbated as spoiled grain runs out and more expensive fresh corn must be used. Furthermore, China has a population of 1.3 billion to feed, potentially driving up corn prices and begging the question of whether there is enough corn to meet the demand for food and fuels. In fact, a grain shortage of about 30 million tons was reported in China in 2005, with a shortage of 35 million tons projected by 2010 due to urbanization of agricultural land (Ministry of China Nature Resource, 2004).

China is an agricultural country and almost all the land mass suitable for planting for conventional crops has been used. On the other hand, lignocellulosic biomass can be grown on land not suitable for regular crops and can also be cultivated in combination with such materials. In addition, lignocellulosic biomass is low in cost and potentially perpetually available in abundant quantities to realize meaningful energy security, balance of trade, and rural employment benefits in China. For example, cellulosic biomass costs about $22 per dry ton, including transportation costs, in Henan province (Junshe Sun, personal communication), and equivalent to about $7 per barrel of petroleum based on energy content. Thus, cellulosic biomass is much less expensive than corn at regulated prices of about $147 per dry ton in China in 2004.

Cellulosic biomass, such as agricultural and forestry residues, major portions of municipal solid waste, and dedicated herbaceous and woody crops, provides a meaningful alternative feedstock for ethanol production.[3] Recoverable crop residues in China are estimated to be 5.53 EJ per year by 2030,[10] and annual production of forest industry residues is predicted to reach 0.9 EJ at that time, assuming that three-quarters of milling and manufacturing wood wastes and one-quarter of the forest residues are recoverable.[11] In addition, about 0.6 EJ of animal dung could be available, assuming one-eighth of the generated dung could be used as feedstock.[11] Biomass energy plantations could have an average yield of 15 dry tons per hectare per year and could be established on 10% of the total land now employed for forest/woodlands, croplands, and permanent pastures.[11] Thus, total biomass production could reach about 23 EJ per year by 2030, roughly equivalent to 4 billion barrels of petroleum. This amount of ethanol would be sufficient to meet the future demand for 12.4 EJ of liquid fuel for transportation in 2030 in China as predicted by IEA.[2] The challenge for large-scale commercialization is to overcome the perceived risk of employing the technology for the first time. In addition, attention should be given to reducing processing costs through applying the continually evolving tools of biotechnology to enhance performance and to make valuable coproducts that improve profitability.[12]

A few systematic studies have evaluated processing of cellulosic biomass to ethanol in China because of its environmental, security, and economic advantages since the early 1970s. However, because cellulosic ethanol was eventually ignored in Chinese energy policy for years and the Chinese fuel ethanol industry is in its infancy, many barriers must be overcome before low-cost cellulosic biomass sources can make a significant impact on the future of Chinese energy.

In 2005, China promoted the National Key R&D Program (863) for cellulosic ethanol as a step to promote technology development. The carbohydrate conversion yields in the China 863 plan were targeted to 0.77 of cellulose and 0.68 of xylan to ethanol. This goal is similar to the US National Renewable Energy Laboratory 2002 model parameters, representing technology available within several years, whose targets are 0.855 of cellulose and 0.765 of xylan to ethanol.[13] The US mature technology model, which is based on technology projected to be available within 25 years, predicted that the yields of cellulose and xylan to ethanol would both be 0.9. Both US models include utilization of other subdominant carbohydrates (e.g., mannan, arbinan, galacton), with conversion yields ranging from 0.765 to 0.9, but China's 863 plan did not take these carbohydrates into account. Yet high yields of dominant carbohydrates and utilization of subdominant carbohydrates are vital to long-term successful competitiveness of cellulosic ethanol.

China lacks important domestic intellectual property in relevant biological technology, such as microorganisms able to ferment all five sugars from biomass and competitive hydrolysis enzymes. For pretreatment technology, China needs to conduct more systematic research comparing existing methods and exploring new methods, although a few reports have been published. China needs to make a major effort to carry on basic and applied work on domestic technology development to convert lignocellulosic biomass to ethanol. In addition, China needs to carry out an economic evaluation of a whole bioconversion process on a commercial scale and a comprehensive analysis of the national availability of biomass.

To estimate the feasibility of bioconversion of cellulosic biomass to ethanol, we did a case study in Henan Province. With 6.825 Mha of arable land, Henan is a well-known major agricultural province in central China and an important producer of agricultural and sideline products. Henan is also one of the provinces that enforce addition of 10% ethanol to gasoline. Currently, over 23 million gallons of gasoline are consumed annually in Henan, and consumption is expected to increase with the rapid growth in automobile use. If an ethanol yield of 100 gallons of ethanol per ton of corn stover were realized, only 1.1 million tons of corn stover, corresponding to about 5% of the 20 million dry tons generated each year, would be needed to produce 134 million gallons of ethanol to fill the current 10% ethanol blending market for Henan. In this situation, about 5000 dry tons per day of corn stover from a land area of about 5000 km^2 would be sufficient to meet this production level. When all costs for residue gathering, storage, and transport are included for an average residue transport distance of about 100 km, the delivered residue cost would be about \$22 per dry ton – a cost that is likely to be a conservative estimate for China, because of the lower labor cost.[14]

To estimate the cost of producing cellulosic ethanol in China, two cellulosic ethanol techno-economic assessments were adapted to reflect the situation in China. The first was reported by the US National Renewable Energy Laboratory (NREL) in 2002 to represent near-term technology available within a few years. The mature model was based on an estimate of what mature, advanced technology would look like within 25 years. A feedstock rate of 2000 tons of corn stover per day with annual production of 69.3 million gallons of ethanol and 157 MkW electricity was applied in the NREL model, and 5000 tons of corn stover per day with annual production of 184 million gallons of ethanol and 1057 MkW electricity was used in the mature model. The cost of feedstock was determined as \$30 per ton and \$40 per ton in the NREL and mature models, respectively.

The NREL and mature models both employ pretreatment, biological hydrolysis and fermentation, ethanol recovery, waste treatment, and steam and electricity generation from residues. For pretreatment, the NREL model applied dilute acid,[13] and the mature model used ammonia fiber explosion (AFEX),[15] which promises some benefits for sequential enzymatic hydrolysis and fermentation of cellulose. For the biological steps, the NREL model used simultaneous saccharification and fermentation (SSF) technology, in which cellulases are added to the solid substrate and the resulting sugars are fermented to ethanol by microorganisms in the same vessel. In the mature model, the biological step is based on consolidated bioprocessing (CBP), which features cellulase production, cellulose hydrolysis, and sugar fermentation in one operation. CBP has the potential of offering significantly lower costs than other configurations.[16] Nearly 100% ethanol is recovered from the fermented beer by distillation and dehydration, and the residues are burned to provide all the electricity and heat for the process, with excess power exported to the grid.

When adapting US technology to China, it would be ideal to estimate equipment costs based on Chinese conditions, as some equipment could likely be made in China at some fraction of what it would cost in the USA. However, estimation of equipment costs in China is complicated, and in the light of the time available for this study, we assumed that equipment costs would be the same as for the USA. On this basis, total capital cost estimates for the NREL and mature models are \$197.4 million and \$396.9 million, respectively. Fortunately, variable and fixed operating costs could be more readily estimated for Chinese circumstances. Of the variable operating costs, the feedstock cost in China is estimated as \$22 per ton, about half of the \$40 per ton price applied in the US mature model and a bit lower than the \$30 per ton price in the US NREL model. Because the average electricity price in China (\$0.623 per kW h) is close to the average electricity price in the USA (\$0.666 per kW h), the selling price of excess generated electricity was not changed. The annual variable operating cost in China, which is the cost of materials and waste treatment minus the by-product electricity credit, decreased from \$31.5 million to \$24.54 million for the NREL model and from \$37.44 million to \$2.44 million for the mature model due to the low cost of corn stover and high generation of electricity. For the fixed operating cost, we used average salary rates in foreign invested plants in big cities of eastern China, which are usually relatively high. We assumed that the general manager is paid about \$100 000 per year, a similar salary as those in US models. The annual salaries for middle-level employees, such as plant manager, engineer, maintenance supervisor, and lab manager, range from \$17 756 to \$36 991. The lower-level salary, such as for shift supervisor, lab technician, and maintenance technician, is about \$7398 per year. The shift operators, yard employees, clerks and secretaries are assumed to be paid \$2219–4439 a year. The number of below middle-level employees is doubled on the basis of the parameters in the US models because more employees are generally hired in China in actual operations than that in the USA. Other parameters to estimate maintenance remained the same as those in the US models (Yanjun Lu, Personal communication). Overall, these assumptions resulted in estimated annual savings of \$1.5 million and \$2.69 million on the fixed operating cost when applying the NREL and the mature technology to China, respectively.

Based on these capital and operating cost assumptions, we estimated a minimum ethanol selling price for an internal rate of return (IRR) on capital of 10% or 12% using a discounted cash flow to a net present value of zero after 20 years. When adapted to Chinese conditions, the minimum ethanol selling price decreased by 11.5% and 33.9% from the US NREL and mature models to \$0.95 per gallon and \$0.43 per gallon, respectively. By comparison, the current fuel ethanol price in China, which is set as 0.911 of the price of gasoline by the Chinese government, is on average about \$1.65 per gallon. Even for an increase in the cost of corn stover to \$30 per ton as for the US NREL model, the mature model projects that the minimum ethanol selling price for China is still quite low at \$0.484 per gal. Thus, these initial estimates of the costs for new cellulosic ethanol commercial plants suggest that application of US cellulosic ethanol technology in China is economically feasible. Because starch ethanol processes generally share some common equipment with cellulosic ethanol processes, the economic feasibility would likely be even more desirable if the commercial cellulosic ethanol plant could be integrated with an existing starch ethanol facility.

In summary, a petroleum substitute is needed to fuel the transportation sector in China, and ethanol could have major economic, environmental, and strategic benefits in this context. Although China is promoting fuel ethanol use by requiring ethanol sales in several provinces and through subsidies for fuel ethanol plants, grain ethanol is faced with a number of important challenges that will no doubt limit its growth. Fortunately, more abundant and cheaper cellulosic biomass could be an alternative feedstock to produce fuel ethanol, and data for Henan Province suggest that enough cellulosic biomass is potentially available to meet the ethanol blending market. Furthermore, operating costs are projected to be sufficiently low that ethanol could be made at costs competitive with current ethanol prices in China even if capital costs are assumed to match those in the USA. Thus, building the world's first commercial cellulosic ethanol plant in China is economically possible. In addition, such an operation could provide valuable experience and technical information for the development of a cellulosic fuel ethanol industry in other areas of the world. The recent announcement of the Chinese central government to spend \$5 billion in capital investment over the next 10 years on ethanol capacity expansion with a focus on cellulosic ethanol is to be commended and should attract foreign technology and capital to the Chinese fuel ethanol market. However, they should also consider supporting more fundamental research, systematic analyses of national biomass availability, detailed economic feasibility assessments, and international cooperation, and develop a legal and policy framework to accelerate the development of a major cellulosic fuel ethanol industry in China. Furthermore, development of renewable cellulosic ethanol in China will not only better meet China's growing energy demands but also will benefit the world's economic growth and environmental protection.

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