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A Preliminary Assessment of Biomass Conversion to Fischer-Tropsch Cooking Fuels for Rural China

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ABSTRACT

A variety of liquid hydrocarbons can be produced via Fischer-Tropsch synthesis from biomass. We present energy balance results for two configurations for co-producing domestic cooking fuels (synthetic LPG or kerosene) and electricity from gasified biomass. We make a preliminary estimate of the costs of co-producing electricity and LPG from corn stalks in the context of rural Jilin Province, China. Direct combustion of corn stalks for cooking is extensively practiced in rural Jilin today, contributing to health problems due to indoor air pollution.

1. INTRODUCTION

Cooking by direct combustion of biomass is practiced by over 2 billion people worldwide (WHO, 1997), primarily in rural areas of developing countries. The resulting indoor air pollution accounts for nearly 60% of all human exposure to particulate air pollution (Smith, 1993), contributing to health damages, especially to women and children. Cooking with fluid fuels is far cleaner than cooking with solid biomass. It is also far more efficient (Fig. 1), even considering biomass-to-fuels conversion losses. Thus, converting biomass to fluid fuels has the potential to reduce negative health impacts of biomass use today, while also meeting the energy demands of greater numbers of people.

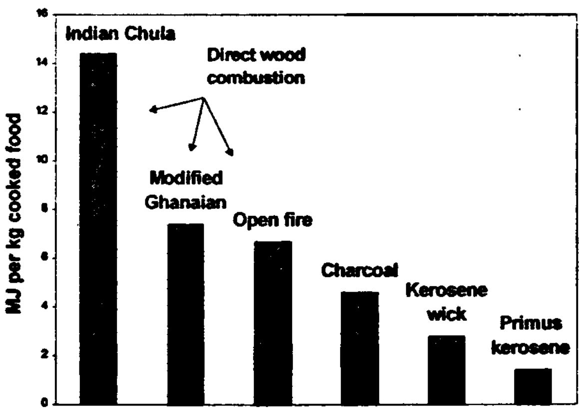

Figure 1. Energy requirements for cooking with different fuels (Dutt and Ravindranath, 1993).

In this paper, we consider the idea of producing liquid hydrocarbons from biomass via Fischer-Tropsch (F-T) synthesis for use in cooking. F-T synthesis involves the production of hydrocarbons from CO and H_2. The latter molecules can be generated from carbon-containing feedstocks, including biomass. Until recently, commercial application of F-T synthesis had been restricted to production of vehicle fuels from coal in Germany in the 1930s and 1940s and in South Africa from 1950 to the present. A recent resurgent interest in F-T technology in the oil and gas industry is being driven by the goal of converting remote natural gas resources into marketable liquid products, especially high-cetane number, low-aromatic, no-sulfur diesel blending stock for reducing diesel-engine-vehicle tailpipe emissions. Larson and Jin (1999) review some fundamentals of F-T synthesis and recent developments in synthesis technology, and present comparative energy balances for F-T liquids production from natural gas, coal, and biomass. Using the approach described by Larson and Jin (1999) for calculating energy balances, we examine the production of synthetic liquefied petroleum gas (LPG--a mixture of propane and butane) or kerosene from biomass for use in cooking. We present a preliminary assessment of the cost for producing these fuels from corn stalks in the context of rural Jilin Province, in Northeast China, where direct combustion of stalks is widely used today to meet household cooking needs.

2. ENERGY BALANCES FOR F-T COOKING FUELS FROM BIOMASS

Two clean cooking fuels that can be produced from biomass via F-T synthesis are synthetic LPG (C_3-C_4 hydrocarbons) and kerosene (C_{10}-C_{12} hydrocarbons). LPG can be burned very cleanly and efficiently. Kerosene is less clean, but F-T kerosenes burn more cleanly than petroleum-derived kerosenes because of the largely paraffinic nature of F-T liquids. For example, F-T kerosenes produced at the Shell "gas-to-liquids" F-T facility in Malaysia are characterized by a "smoke point" (the height to which a flame can be adjusted in a standard burning apparatus before smoking starts) greater than 50mm and zero sulfur content (Tijm *et al.*, 1995). For comparison, British standards specify a minimum smoke point of 35mm and a maximum sulfur content of 0.04% by mass for kerosene used in domestic free-standing burners (without a flue). For burners connected to a flue the corresponding figures are 20 mm and 0.2% sulfur (Francis and Peters, 1980).

Figure 1 is a simplified process flow diagram for "once-through" co-production of F-T liquids and electricity. In this configuration, gasified biomass is passed once through the F-T synthesis reactor. Any gas that is not converted to liquids in the reactor is sent to a gas turbine combined cycle to generate electricity. The "once-through" configuration eliminates additional reaction steps and recycle loops that would be needed to maximize the production of liquids. Larson and Jin (1999) show that the effective efficiency of "once-through" production of F-T liquids from biomass[1] is about the same as the efficiency of producing liquids in a facility designed to maximize liquids production. They argue that the much simpler process configuration in the "once-through" design should provide for better economics of liquids production.

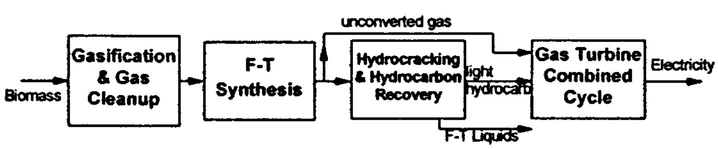

Figure 1. Simplified diagram of "once-through" co-production of electricity and F-T liquids from biomass.

For the analysis here, we consider two "once-through" design configurations. For the gasification step in both cases we have adopted the gasifier performance indicated by Menville

[1] The effective efficiency is the energy contained in the F-T liquids divided by the difference in energy content of the biomass feed to the "once-through" facility and the biomass that would be needed in a stand-alone gasifier/combined cycle power plant to generate the same amount of electricity as in the "once-through" facility.

Table 1. Calculated energy balances for producing F-T cooking fuels from biomass, assuming "once-through" design with indirectly-heated gasifier.

Case[a]	A	B
Gasifier performance		
mass % H_2	3.38	
CO	35.8	
CH_4	10.2	
CO_2	39.3	
C_2H_2	1.33	
H_2O	5.52	
N_2	4.29	
kg_{gas}/kg_{feed}	0.932	
GJ_{gas}/GJ_{feed}	0.727	
Process electricity demand		
GJ_e/GJ_{feed}	0.025	0.029
Products (GJ/GJ_{feed})		
Electr. (GJ_e/GJ_{feed})	0.197	0.184
LPG (C_3-C_4)	0	0.287
Naphtha (C_5-C_9)	0.067	0
Kerosene (C_{10}-C_{12})	0.132	0
Diesel (C_{13}-C_{18})	0.066	0
Waxes (C_{19+})	0	0
Fraction of Feedstock HHV		
Net electricity	0.172	0.155
Net hydrocarbons	0.265	0.287
Overall HHV eff.	**0.437**	**0.442**
Incremental eff.[b]	**0.521**	**0.515**

a. The process designs vary in the operation of the hydrocracker. In case A, the output of the hydrocracker is as reported by Tijm, *et al.* (1995). In case B, the hydrocracker maximizes C_3 and C_4 hydrocarbon output. The higher hydrogen requirement of the hydrocracker in case B is taken into account in our energy balance.

b. Incremental efficiency equals higher heating value of net hydrocarbons divided by HHV of biomass charged to hydrocarbon production. The latter is the total biomass input less the biomass that would be required for a stand-alone BIG/GTCC to generate the same amount of net electricity as generated at the F-T facility. Assuming a stand-alone generating efficiency of 35% (HHV), Incremental efficiency = NH/[1 - (NE/0.35)], where NH = net hydrocarbon fraction and NE = net electricity fraction.

(1998) for the indirectly-heated biomass gasifier design of the Brightstar Synfuels Company (BSC). The BSC design is based on steam reforming of biomass. A 16 t/day capacity commercial demonstration BSC gasifier has been operating near Baton Rouge, Louisiana since 1996. For the synthesis step, we assume $\alpha = 0.95$ [see Larson and Jin (1999) for discussion of α characterization of the synthesis reactor]. With this assumption, the predominant hydrocarbon products of the synthesis step are high molecular weight waxes. The waxes are hydrocracked to form the final liquid products.

The two cases (Table 1) differ in the operation of the hydrocracker. In Case "A," the hydrocracker output is similar to that at Shell's gas-to-liquids facility in Malaysia when operating in its "kerosene mode" (Tijm *et al.*, 1995): about half of the hydrocracker output is kerosene, and one-quarter each are naphtha-like and diesel-like hydrocarbons. For this case, the fractions of input biomass converted to cooking fuel (kerosene) and to electricity are 13% and 17%, respectively (Table 1). A substantial amount of naphtha-like and diesel-like hydrocarbons are also produced. In Case "B," hydrocracking is assumed to be carried to a further extent such that all of the input wax is converted to C_3 and C_4 hydrocarbons (synthetic LPG). This configuration converts aabout 29% of the input biomass into cooking fuel (LPG) and 16% to electricity.[2]

3. PRELIMINARY COST ASSESSMENT FOR F-T COOKING FUELS

3.1. Context

To illustrate the potential economics of producing cooking fuels from biomass via F-T synthesis, we present a preliminary cost estimate for co-producing synthetic LPG and electricity from corn stalks in the context of the province of Jilin in Northeastern China. Jilin, with only 2% of China's population, grows 14% of China's corn. Some 35 million tonnes of corn stalks (~460 PJ) are generated annually with the corn harvest, about half of which are used for soil conditioning and fertilization, for livestock fodder, and for industrial feedstock (Cao, 1998). In addition, a large number of rural households also burn stalks for domestic cooking and heating,

[2] In reality the ratio of LPG to electricity would be somewhat less than we calculate because hydrocracking would produce some C_1 and C_2 hydrocarbons that would be converted to electricity. In the absence of empirical data for a hydrocracker operating to maximize LPG output, we have assumed that all of the wax feed is cracked to LPG.

contributing to poor indoor air quality in many homes. With rising farmer incomes, there is an ongoing shift away from stalks and toward coal briquettes. The use of coal briquettes is not especially less polluting than stalks, but wealthier farmers are preferring the greater convenience of purchasing briquettes as needed from merchants rather than collecting and storing stalks. The shift to coal is creating a new and serious air pollution problem from the open burning of excess crop residues in the field. (In many areas the residues dry out quickly and thus decompose slowly. To prevent buildup of undecomposed residues that can harbor insect infestations, residues are burned in the field.)

Converting stalks to a clean cooking fuel such as LPG would help alleviate both indoor and outdoor air pollution problems. LPG is already a familiar cooking fuel in many Chinese households. Conventional LPG is widely used in urban areas, and it is estimated that (as of 1994) some 30 million rural households (16% of all rural households) also use LPG for at least some of their cooking needs (Wang, 1997).

3.2. Cost estimate

Although intensive corn production is practiced in Jilin province, the quantity of corn stalks that can be concentrated at a conversion facility is limited by transportation logistics and costs. Thus, a facility for producing LPG from corn stalks could not be large by the standards of today's gas-to-liquids industry. Based on the energy balance for Case "B" in Table 1, a corn-stalk conversion facility having LPG and electricity co-production capacities of 1500 GJ/day [or 250 barrels per day crude oil equivalent (bpdcoe)] and 9.4 MW_e, respectively, would require some 400 tonnes/day (5219 GJ/d) of corn stalks. Cao (1998) indicates that this amount of stalks are available within a radius of about 11 km in the corn-belt of Jilin Province.

Assuming that process technology is commercially mature, we estimate the total installed capital cost for such a facility would be about $33 million,[3] or $132,000 per bpdcoe of F-T liquids (Table 2). For comparison, the cost for a 10,000 bpd gas-to-liquids conversion facility based on technology like that of the Shell Malaysia plant (not once-through) might reach $30,000/bpd if widely implemented commercially (Tijm *et al.*, 1995). Companies like Syntroleum, who are focussing on smaller-scale gas-to-liquid plants, are projecting 2500 bpd facilities costing under $30,000/bpd (Knott, 1997). In a recent study, Bechtel and Amoco estimated the capital cost for a once-through 8815 bpd GTL plant if built today to be about $48,000/bpd (Choi *et al.*, 1997). As part of the same study, a 50,556 bpdcoe plant using coal as the feedstock and maximizing F-T liquids production (not once-through) was estimated to have a capital cost of about $64,000/bpd (Bechtel, 1998).

Other than capital, key factors in our cost analysis are labor rates, feedstock costs, and electricity sales price. Details of the cost assumptions are provided in the notes to Table 2. The average cost for operating labor for the facility is based on an assumed compensation to employees that is an estimated two times the compensation provided to young advanced-degree engineers employed in Beijing today. The cost of delivered corn stalks ($0.54/GJ) is based on a detailed cost-supply curve for the Jilin Province corn belt presented by Cao (1998). An electricity sale price of 5 ¢/kWh is shown in Table 2. For comparison, the retail price for grid-

[3] All costs in this paper are expressed in 1998 US$. The GNP deflator has been used to convert to 1998$ costs originally given in other-year dollars.

Table 2. Cost estimate (1998$) for biomass conversion facility co-producing synthetic LPG (250 bpd crude oil equivalent capacity) and electricity.

Plant Performance and Cost Assumptions[a]		Levelized LPG cost from corn stalks in rural Jilin Province context	
LPG capacity, GJ/d	1500	Assumptions	
Electric capacity, MW_e	9.4	Biomass cost, $/GJ[f]	0.54
Biomass input capacity, GJ/d	5219	Electricity sales, ¢/kWh[g]	5.0
Capacity factor	90%	Labor rate ($/yr)[h]	4200
Annual quantities		Yearly capital charge rate	15%
LPG production (TJ/yr)	493	Levelized cost of LPG, $/GJ	
Electricity output (GWh/yr)	73.8	Capital	10.0
Biomass consumed (TJ/yr)	1715	Biomass feedstock	1.9
Installed capital cost (10^6 $)[b]		Operation & maintenance	1.3
Syngas production	12.5	Electricity revenue	-7.5
Syngas conversion/refining	12.7	Net cost of LPG production,	5.7
Gas turb. combined cycle	7.70		
TOTAL	32.9		
Maintenance & ins. (10^3 $/yr)[c]	330		
Catalysts & chem. (10^3 $/yr)[d]	127	Retail price for LPG in rural China today: $7.7/GJ[i]	
Operating labor (no. of	45		

a. The energy performance of this facility is based on the last column of Table 4.
b. Capital cost is estimated for a biomass integrated-gasifier/gas turbine combined cycle plant with an oversized syngas production area plus a syngas conversion/refining area. Installed BIG/GTCC cost is \$1645/kW$_e$ (based on scaling Elliott and Booth (1993) estimate of \$1500/kW$_e$ by US GNP deflator). Half the cost of a stand-alone BIG/GT power plant is assumed to be for syngas production and half for the combined cycle. Thus, the combined cycle in the table (9.363 MW$_e$ capacity) costs 9363 kW$_e$ x 1645/2 = \$7.7 million. The syngas production area costs 9363 x $(5219/2311)^{0.6}$ x 1645/2 = \$12.55 million, where 5219 GJ/day is the rated biomass consumption of the facility shown in this table and 2311 GJ/d is biomass consumption of a 9.4 MW$_e$ stand-alone BIG/GT power plant with assumed efficiency of 35% (HHV). The cost of syngas conversion/refining is scaled using 0.6 exponent from a detailed cost estimate by Choi *et al.* (1997) for this area of a natural gas-based once-through F-T synthesis process.
c. Annual maintenance and insurance cost is assumed to be 1% of initial capital cost, as indicated by Bechtel (1994) for a coal-based F-T synthesis process.
d. Catalysts and chemicals are assumed to cost \$0.26/GJ, based on Bechtel (1994).
e. Number of operating employees estimated based on detailed study by Bechtel (1994) that estimated 1088 employees would be needed to operate a large (300,000 GJ/day) coal-based F-T synthesis plant. Scaling from the Bechtel estimate by production capacity gives number of employees = 1088 x $(1500/300000)^{0.6}$ = 45.
f. The cost of air-dried corn stalks delivered to a conversion facility in the corn-growing region of Jilin is: Yuan RMB/tonne = 43.02 + (1.163 x r), where r is the radius (km) of delivery Cao (1998). Assuming exchange rate of 8 Yuan RMB/\$, the cost of delivered stalks in US\$/tonne = 5.4 + (0.145 x r). Assuming 13 GJ/t delivered stalks, stalk cost in \$/GJ = 0.415 + (0.011 x r). Supplying a facility with capacity indicated in this table would require a delivery radius of about 11 km in the corn belt of Jilin (Cao, 1998).
g. Typical price for grid electricity in rural Jilin villages is 10 ¢/kWh (Qiang, 1998).
h. Assumed annual salary of \$3000, plus 40% benefits. This is over twice the compensation level found today in Beijing for young engineers holding advanced university degrees.
i. Wang (1997) gives LPG price in rural China in 1996 of 3000 YuanRMB/tonne, a higher heating value of 48 GJ/tLPG, and exchange rate of 8.3 YuanRMB/US\$. Converting to US\$/GJ and correcting to 1998\$ using the US GNP deflator gives a price of \$7.7/GJ.

supplied electricity paid by rural consumers in Jilin province is typically about 10 ¢/kWh today (Qiang, 1998).

The calculated net cost of producing F-T LPG (including revenue from electricity sales) is \$5.7/GJ, which is about 25% lower than the retail price typically paid in rural China today for conventional LPG (Table 2). Figure 2 shows the sensitivity of the LPG cost to the assumed biomass feedstock price and the assumed electricity sales price.[4]

4. POTENTIAL IMPACT IN RURAL CHINA

Some order-of-magnitude calculations help to put in perspective the potential impact of producing F-T cooking fuels from biomass in Jilin Province and in China as a whole.

In rural Jilin Province, the current cooking fuel demand (if gas fuel were to be used) is estimated to be about 10 GJ/year per four-

[4] Our cost calculations take no account of any inherently higher value of F-T LPG over conventional LPG, as is the case with some other F-T fractions. For example, Marano *et al.* (1994) and Tijm *et al.* (1995) estimate that F-T middle distillates, because of their high cetane number and zero sulfur content, can command a premium of ~\$1.2/GJ over conventional diesel.

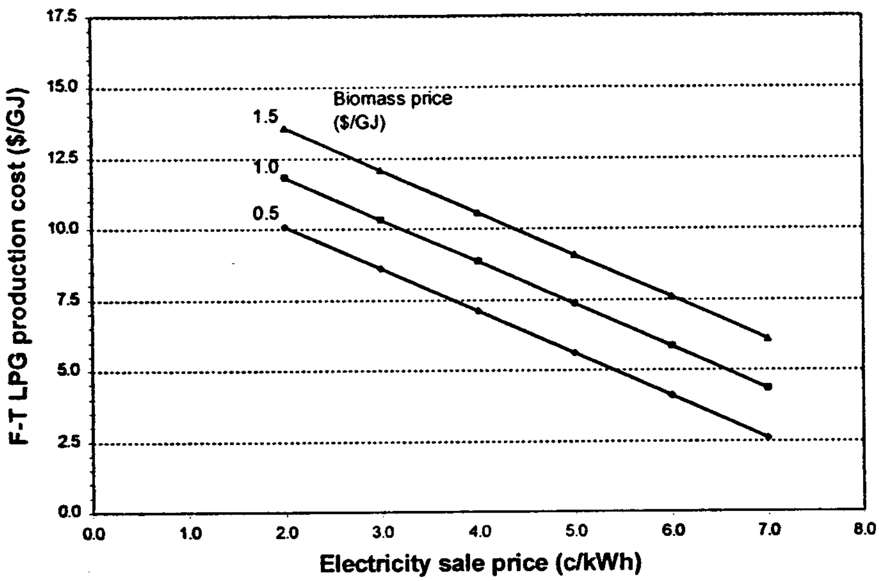

Figure 2. Estimated production cost of Fischer-Tropsch LPG from biomass in a "once-through" facility as a function of sale price for co-produced electricity. See Table 2 for details.

person household, or a total of some 36 PJ/yr for all 3.56 million rural Jilin households (Qiang, 1998). Rural electricity demand is presently some 1.2 kWh/day per household, or a total of some 1,560 GWh/yr for all rural households (Qiang, 1998). Assuming 230 PJ/year of stalks (half of the total generated) are converted to F-T LPG and electricity with efficiencies shown in Table 1 (Case B), the total production of LPG and electricity would be 66 PJ/yr and 9,900 GWh/year, or nearly twice the current rural demand for cooking fuel and six times the demand for electricity. Meeting all of current cooking fuel demand would require 73 facilities with production capacity as in Table 2.

For China as a whole, Li, *et al.* (1998) project, based on detailed assessments, that some 376 million tonnes of agricultural residues (about 4900 PJ/yr) will be available for energy production in 2010 (from a total residue generation of 726 million tonnes). The available residues would be sufficient to produce some 1400 PJ/year of cooking fuels via once-through F-T synthesis, or enough to meet the cooking fuel demand (at current Jilin rates of use) of some 560 million people (about 40% of China's projected 2010 population). Electricity would be co-produced at an average rate of 24 GW_e (about 2.5 times the production rate projected for the Three Gorges hydroelectric facility).

5. CONCLUSIONS

A resurgence of interest in Fischer-Tropsch conversion technology is being driven by the goal of converting remote natural gas resources into marketable liquid products such as high-cetane number, low-aromatic, no-sulfur diesel blending stock for reducing diesel-engine vehicle tailpipe emissions. We have presented a preliminary analysis of the novel concept of converting biomass to F-T hydrocarbons suitable for use in cooking. We have examined in particular the idea of producing LPG from corn stalks in rural Jilin Province, China as a cooking fuel for rural villages. Based on our energy balances, the supply of corn stalks in Jilin is sufficient to meet all of current rural cooking fuel demand twice over, with the co-produced electricity equivalent to six times the current rural electricity demand. Our preliminary cost analysis for small-scale co-production of synthetic LPG and electricity in Jilin is encouraging, and more detailed analysis is warranted.

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7. ACKNOWLEDGEMENTS

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