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Techno-economic evaluations of biofuel technologies

Mark Mba Wright
Iowa State University

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Techno-economic evaluations of biofuel technologies

by

Mark Mba Wright

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MASTER OF SCIENCE

Co-majors: Mechanical Engineering; Biorenewable Resources and Technologies

Program of Study Committee:
Robert Brown, Major Professor
Robert Anex
Dermot Hayes

Iowa State University

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Table of Contents

List of Figures

List of Tables

Abstract

This thesis consists of three related techno-economic studies of biofuels production. The major purpose of these studies is to establish meaningful comparisons between different technologies for producing biofuels and explore scenarios leading to optimal biofuel costs.

Three journal papers have been published in Biofuels, Bioprocessing, and Biorefining from the results of this study: “Comparative economics of biorefineries based on the biochemical and thermochemical platforms”, “Establishing the optimal size of different kinds of biorefineries”, and “Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids”.

Several major conclusions were drawn from this study. Advanced biorefineries will require capital investments that are 4 to 5 times larger than current grain ethanol plants. Nevertheless, optimally sized thermochemical plants (240 to 486 million gge output) can produce lower cost fuel than biochemical ethanol plants. A 550 million gallon Fischer-Tropsch liquids can reduce fuel costs ($1.56/gallon) by preprocessing of biomass before delivery to the central upgrading facility.

General Introduction

Introduction

Conclusions from a 1981 technoeconomic paper published by Palsson et. al.[1] helped shape long standing perceptions of the relative merits of biochemical and thermochemical biomass conversion technologies. The biochemical approach has long been considered more economical than thermochemical pathways. Biochemical plants based on sugar conversion to ethanol have flourished in the United States and contributed to the current interest in alternative fuels. The success of the ethanol industry has shifted much of the attention on advanced fuels towards enzymatic hydrolysis of cellulose for the production of ethanol. Nevertheless, the production of biofuels via thermochemical conversion of biomass has remained an intriguing option[2].

Various advanced biorenewable technologies are in active development for the production of transportation fuel. These technologies focus on the conversion of lignocellulosic material into biofuels. Biorefineries based on cellulose should allow for a larger displacement of fossil fuels than the current sugar platform. The cost of these advanced technologies continues to be debated particularly when compared to the established biochemical industry. Differences in key assumptions among published studies have made it difficult to compare the cost of biofuels based on the thermochemical pathway to the biochemical platform.

The main purpose of this paper is to address some of the questions affecting advanced biofuel technologies. The establishment of a common comparison in the first paper of this study allows for further analyses of advanced biorefinery scenarios. One such analysis consists of establishing the biorefinery plant capacity at which biofuel costs are minimized. A different analysis explores the impact of biomass preprocessing to reduce transportation costs. These analyses are conducted over three separate but related papers.

Background

Various biomass biochemical and thermochemical conversion technologies are considered in this study. The sugar platform is represented by the corn grain process[3] and dilute acid hydrolysis[4, 5, 6] of cellulose to produce ethanol. All thermochemical technologies employ gasification to produce a synthetic gas that is further upgraded to yield a liquid product[7, 8]. Liquid fuels considered in this study include hydrogen, methanol, and Fischer-Tropsch Liquids from which green diesel can be derived.[9,10]A special case is that of biomass fast pyrolysis[11], which yields a primarily liquid product known as bio-oil. Bio-oil is not suitable as a transportation fuel and most scenarios assume it is mostly employed as an intermediate to other fuels. Table 1 summarizes the various technologies and products considered throughout this study.

Table 1 Biofuel Technologies for Production of Transportation Fuels

Platform	**Primary Feedstock**	**Liquid Product**
Biochemical	Starch	Ethanol
	Cellulose	Ethanol
Thermochemical	Cellulose	Hydrogen
		Methanol
		Fischer-Tropsch Liquids

The biochemical platform is well established commercially in the United States and Brazil employing corn grain and sugar cane as the main feedstock respectively. Ethanol is the transportation biofuel with the highest production (15–29tons) worldwide[12,13]. The low cost of feedstock (average of $2.57 per bushel of corn historically)[14] coupled with low capital cost requirements and favorable policies encouraged the growth of ethanol production. Concerns over the availability of grain as demand for ethanol increases has prompted interest in advanced biochemical technologies employing primarily lignocellulosic material[15].

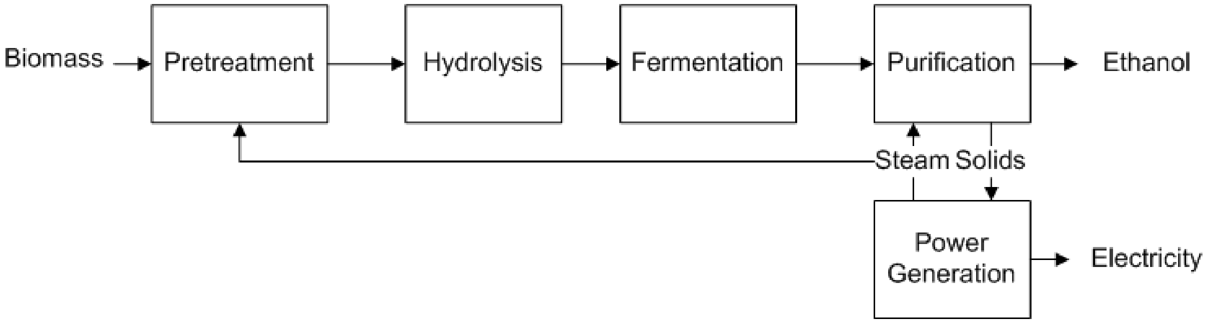

Figure 1 Cellulosic Biomass to Ethanol

Advanced biochemical platforms employ a pre-fermentation process to breakdown the cellulosic material in efforts to make the simple sugars more accessible to microorganisms. Various pretreatment approaches have been envisioned; short –term cellulosic ethanol will probably employ enzymatic hydrolysis[16] which provides for higher yields, lower maintenance costs, and higher compatibility with downstream processes than other pretreatment processes[17,18, 6]. A shift towards cellulosic material will allow for higher production of ethanol but various key obstacles remain[19]. Challenges for advanced biochemical technologies include level of development as well as higher capital and operating costs. Various technoeconomic studies on the production of ethanol via the starch[20, 3] or cellulosic[21, 22, 23, 24] process have been published.

Table 2 Pretreatment processes for production of cellulosic ethanol

Pretreatment Methods	Reference
Dilute acid	25
Flowthrough	26
Partial flow pretreatment	26
Controlled pH	27
AFEX	28
ARP	29
Lime	30

The thermochemical platform employs well-known technology that is commonly found in the coal and gas industries. Theuse of non-petroleum feedstock for transportation and chemical markets has been very limited with few exceptions such as SASOL[31, 32, 33] in South Africa where an embargo forced the development of alternatives to petroleum. Thermochemical technologies for production of liquid fuelsare typically based on the partial combustion of biomass in the absence of oxygen (pyrolysis) or with limited availability (gasification). Biomass pyrolysis produces gaseous, solid, and liquid products of which the liquid yield can be catalytically upgraded to transportation fuel[34]. The gasification process employs numerous types of feedstock to produce a Carbon Monoxide and Hydrogen rich gas known as producer gas or synthetic gas (syngas). Figure 2 shows some of the most common chemicals and liquid fuels that can be produced from syngas.

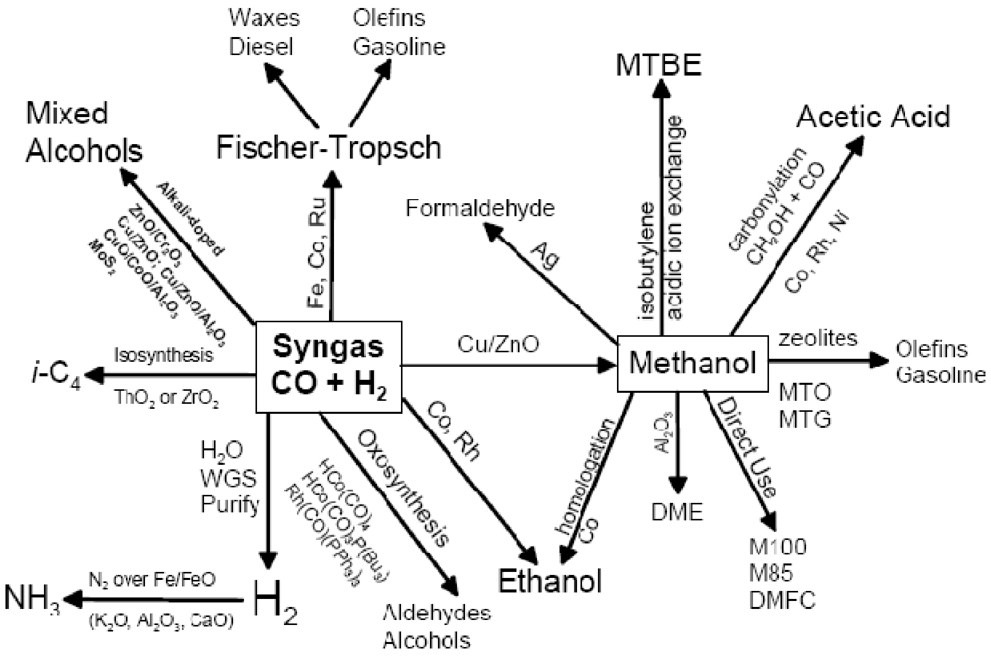

Figure 2 Common Synthetic Gas Derived Chemicals[35]

The general schematic of thermochemical process based on gasification is shown in Figure 3. Operating conditions and process requirements vary for different products and some fuels can be produced through various scenarios. Biomass pretreatment is generally a function of the gasification specifications. Particle reduction may be required for some designs and moisture in the biomass negatively affects the thermal performance of the reactor. Common reactor designs are variations on four main designs[36, 37]: updraft, downdraft, bubbling bed, and circulating bed. Downdraft and updraft gasifiers entrain biomass particles in a hot gas stream that flows co-current or counter-current to the solids respectively. For large scale operations, fluid bed designs (bubbling and circulating) are commonly used[38, 39]. Gas cleaning is employed to remove particulates that can reduce catalytic activity or pose harm to the environment. Some compounds are particularly damaging to catalyst with Sulfur being a notable example that can cause fouling at concentrations of 0.2 ppm[40]. Gas processing can consist of various operations based on the catalytic reactor specifications and syngas components. Methane reforming and water-gas-shift are two process that increase the hydrogen and carbon monoxide content in the syngas; removal of inert compounds also falls under this category. Finally, catalytic synthesis allows for the conversion of syngas to various products as shown in Figure 2. Numerous catalysts have been employed for the production of transportation fuels from syngas and this area is in active development[41].

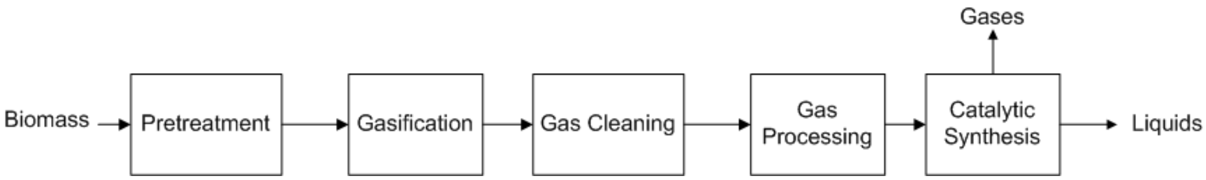

Figure 3 Thermochemical Conversion To Transportation Fuels

Biomass-to-liquids (BTL) via the thermochemical pathway would create a biorenewable resource for transportation fuels beyond ethanol[42]. As shown in Figure 2, various fuels may be produced from syngas including ethanol. Specific process requirements limit the number of chemicals that may be produced by a single facility, but with further development and investment, a plant can be envisioned where multiple chemicals are produced based on demand[43]. This approach would be very similar to that employed by petroleum refineries where yield of various distillation columns is carefully controlled and fine tuned to the state of the market[44]. Technoeconomic studies for different thermochemical biomass to fuel technologies can be found in the literature[4,10, 45, 46, 47, 48].

Biomass pyrolysis is the thermal heating of biomass in the absence of oxygen[49]. Pyrolysis actually takes place during the gasification process as the biomass is heated prior to coming in contact with the oxidizing agent. Biomass pyrolysis yields solid (char), liquid (bio-oil) and gaseous products. The solid fraction can be combusted to provide process heat or employed as a soil amendment. Bio-char benefits include increased soil water availability and organic matter and enhanced nutrient cycling[50]. Gas and liquid yields can be used for power generation,[51] while bio-oil can be upgraded to transportation fuel[52]. Small-scale pyrolysis reactors can be built for biomass densification purposes[53] which would alleviate biomass delivery concerns for large facilities. This scheme has been explored in this study as well as others[54,55, 56,] .

A concept that has gained interest recently is the so called hybrid platform[57]. This platform combines the biochemical and thermochemical approaches to take advantage of their strengths and reduce the impact of weaknesses. With this concept, feedstock is first thermochemically converted to synthetic gas which is then fed into a biochemical reactor where bugs convert the CO and H_2 to ethanol or other chemicals[58]. This approach eliminates a strict H_2 to CO ratio requirement of various catalysts[35]. It also allows for a larger variety of feedstock to be employed than the typical biochemical route. Recent high profile investment in this concept has raised awareness of this approach[59].

The USDA has conducted various technoeconomic studies related to grain ethanol[3, 60, 61, 62, 63]and cellulosic ethanol in collaboration with NREL[5,6]. Other researchers have also published studies on ethanol production with an emphasis on the economic aspects[4,64, 65]. There are also numerous reviews on ethanol production[66, 67,68, 6923].

Technoeconomics studies of thermochemical ethanol and mixed alcohols have been conducted by NREL[70, 71]. Hydrogen and methanol[9] production as well as Fischer-Tropsch liquids[10] were explored in detail by the Netherland group.Bridgwater has published extensively on fast pyrolysis[72, 73, 74] and NREL published a recent technoeconomic study on large scale biomass pyrolysis11. There are numerous other technoeconomic studies on syngas based fuels some of which are included inTable 3.

Table 3 Summary of select technoeconomic studies for thermochemical technologies

Fuel	References
Hydrogen/Methanol	75,76,77
Ethanol/Mixed Alcohols	70,71
Fischer-Tropsch Liquids	10, 78, 79
Pyrolysis Oil	11, 72, 73, 74, 80

Thesis Organization

This thesis is a compilation of three journal articles: “Comparative economics of biorefineries based on the biochemical and thermochemical platforms”[81], “Establishing the optimal size of different kinds of biorefineries”[82], and “Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids”[83].

“Comparative economics of biorefineries based on the biochemical and thermochemical platforms” establishes a common basis of comparison between biochemical pathways represented by starch and cellulosic based ethanol, and thermochemical fuels represented by hydrogen, methanol, and Fischer-Tropsch liquids. Key assumptions converted to a common basis in this study include plant capacity, fuel energy content, feedstock cost, method of calculating capital charges, and year in which the analysis is assumed. The primary researcher and author of this paper is Mark M. Wright; the corresponding author is Robert Brown. Both authors are affiliated with the Iowa State University department of Mechanical Engineering

“Establishing the optimal size of different kinds of biorefineries” employs economies of scale and biomass transportation costs to determine the plant capacity at which fuel costs are minimized. Economies of scale dictate that unit costs decrease with increasing capacities. Biomass transportation costs produce diseconomies of scale due to increasing costs at larger capacities. A minimum is established at which increases in plant size result in higher fuel costs due to increasing transportation costs and reduced economies of scale.The primary researcher and author of this paper is Mark M. Wright; the corresponding author is Robert Brown.

"Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids" explores the concept of biomass preprocessing to reduce transportation costs. This concept employs fast pyrolysis to convert biomass into bio-oil, which has a higher energy density, prior to delivery to a centralized facility. At the central facility, bio-oil can be upgraded to produce Fischer-Tropsch liquids. A reduction in transportation costs allows for further fuel costs reduction at larger output capacities. The primary author for this paper is Mark M. Wright; the corresponding author is Robert Brown. Akwasi A. Boating is a contributing author from the ERRC/ARS/USDA.

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Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms

A paper published in *Biofuels, Bioproducts & Biorefining*

Mark M. Wright and Robert C. Brown

Abstract

A variety of biochemical and thermochemical technologies have been proposed for the production of biofuels. Meaningful economic comparisons requires that they be evaluated on the same bases in terms of plant capacity, the energy content of the fuel, feedstock costs, method of calculating capital charges, and year in which the analysis is assumed. Such an analysis reveals that capital costs will be comparable for advanced biochemical and thermochemical biorefineries, costing 4 to 5 times as much as comparably sized grain ethanol plants. The cost of advanced biofuels, however, will be similar to that of grain ethanol as corn prices exceed $3.00/bushel.

Introduction

The commercial success of the grain ethanol industry has increased interest in processes that convert fibrous biomass (lignocellulose) into biofuels. Much of this attention has been directed toward enzymatic hydrolysis of cellulose to simple sugars and its subsequent fermentation to ethanol, the so-called biochemical platform. However, the recent announcement by the Department of Energy that three of the six biorefinery projects selected for federal funding include gasification technologies has increased interest in the thermochemical platform [1]. This approach thermolytically transforms biomass into gaseous or liquid intermediate chemicals that can be upgraded to transportation fuels or commodity chemicals. The thermochemical platform is closely related to the commercially successful processes used by the petroleum and petrochemical industries to transform fossil fuels into fuels and chemicals. Opinions vary widely on which of these platforms is most likely to prevail in the emergence of cellulosic biofuels. Although a number of techno-economic studies for various manifestations of these two platforms have appeared in the literature, a direct comparison of them on the same bases are difficult to find.

This paper compares the capital costs and operating costs of the current generation of starch-based ethanol plants to advanced platforms for producing biofuels. These advanced platforms include enzymatic hydrolysis of cellulose to ethanol (the biochemical platform) and three manifestations of the thermochemical platform in which biomass is gasified and upgraded to hydrogen, methanol, or Fischer Tropsch diesel.

Background

Current ethanol production is based on either sugar or starch crops, with the former dominating in Brazil and the latter in the United States, the two largest commercial ethanol producers in the world. The present study focuses on dry milling of corn (a starch crop) because of its relevance to U.S. markets. Although wet milling has some efficiency and production cost advantages, dry milling has dominated the recent grain ethanol industry because of its lower requirements for capital and labor.

Dry milling consists of four major operations: grinding to make the starch accessible to enzymes; cooking with enzymes to hydrolyze the starch to sugars; fermentation of sugars by yeast to produce ethanol, and distillation to produce neat ethanol. The byproduct of this process is distillers dried grains, a fiber and protein-rich material that is used as livestock feed.

Techno-economic analyses of dry grind ethanol in the United States and Europe estimate production costs to be between $0.80 and $1.36 per gallon of ethanol depending upon assumptions, especially feedstock costs[2,3, 4]. The present study employs for the grain ethanol base case the often cited 2000 report by McAloon and colleagues at the National Renewable Energy Laboratory[5]. This report estimates that a dry grind corn processing plant producing 25 million gallons of ethanol per year would cost $27.9 million (1999

US). The operating cost of this plant was estimated to be \$0.88 per gallon of ethanol based on feedstock cost of \$1.94 per bushel of corn grain.

The advanced biochemical platform employs cellulose (and hemicellulose) from plant fibers instead of starch in the production of ethanol. The process of biologically converting structural carbohydrate into ethanol consists of four major operations: pretreatment of plant fibers to make cellulose accessible to enzymes (which often chemically hydrolyzes hemicellulose to simple sugars); treatment with enzymes to hydrolyze cellulose to glucose; fermentation of the simple sugars to produce ethanol, and distillation to produce neat ethanol. Lignin is a byproduct of this process, which can be used as boiler fuel.

Based on the current state of technology, capital costs for biochemical ethanol from cellulose are estimated to be between \$4.03 and \$5.60 per gallon of ethanol annual capacity. Operating costs are estimated to be between \$1.34 and \$1.69 depending upon the assumptions made about feedstock costs, enzyme costs, and the kind of pretreatment to be employed[6,7, 8, 9]. Projected capital cost for future plants employing anticipated improvements in conversion technologies are estimated to be \$3.33 - \$4.44 per gallon ethanol annual capacity with operating costs dropping to \$0.40 and \$0.89 per gallon of ethanol[10]. The present study uses the recent analysis of Hamelinck et. al., which builds upon earlier studies and employs more recent information on the unit operations employed for this technology. The process is based on dilute acid pre-treatment and enzymatic hydrolysis. The total capital investment was calculated to be \$294 million, while the operating costs were an estimated \$1.51 per gallon of ethanol.

Unlike the biochemical platform, for which the fuel product is defined (ethanol) and there is reasonable consensus as to the unit operations to be employed, there is greater diversity of opinion on how the thermochemical platform should be configured. Thermolytic processing of biomass can generally be categorized as either gasification (to produce a gaseous product) or fast pyrolysis (to produce primarily liquid product). A variety of catalytic[11] or even biocatalytic schemes[12]have been proposed to upgrade the thermolytic products into alcohols, ethers, esters, or hydrocarbons. The present analysis focuses on gasification followed by catalytic synthesis to three fuels: hydrogen, methanol, and Fischer-Trospch liquids.

Hydrogen can be manufactured from syngas via the water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

This reaction requires the mixing of steam with syngas since biomass gasification rarely releases sufficient water vapor for this purpose. Although hydrogen might be one of the most cost-effective clean-burning biofuels to produce, the physical characteristics of hydrogen present challenges in its use as transportation fuel[13].

Methanol is commercially manufactured from syngas using a copper based catalyst via the reaction[14]:

$$CO + 2H_2 \rightarrow CH_3OH$$

As a transportation fuel, it has many of the same advantages and disadvantages as ethanol[15]. However, methanol is considerably more toxic than ethanol. Recent rulings by the U.S. Environmental Protection Agency (EPA) are likely to ban the closely related and similarly toxic methyl tertiary butyl ether (MTBE) as a fuel additive because of concerns about ground water contamination[16].

Fischer-Tropsch liquids are synthetic hydrocarbon fuels produced from syngas by the action of metal catalysts at elevated pressures. The primary products of Fischer-Tropsch synthesis are a mixture of light hydrocarbon gases, paraffin waxes, and alcohols according to the generalized reaction[17]:

$$CO + 2H_2 \rightarrow \text{—}CH_2\text{—} + H_2O$$

The optimal H_2/CO ratio of 2:1 is achieved through the water-gas shift reaction ahead of the synthesis reactor. Depending on the types and quantities of F-T products desired, either low (200–240°C) or high temperature (300–350°C) synthesis is used with either an iron (Fe) or cobalt catalyst (Co). Additional processing of the F-T products yields diesel fuel or gasoline.

The five major unit operations of the thermochemical platform based on gasification include fuel preparation, gasification, gas clean-up, catalytic processing to the desired fuels, and separations. Fuel preparation is typically size reduction and drying to levels consistent with the gasification technology employed. Although a large variety of biomass gasification technology can be envisioned[18], the thermochemical base cases included in this analysis assume oxygen-blown, high temperature gasification with the F-T process also employing pressurized gasification. Gas clean-up includes removal of particulate matter and trace contaminants including sulfur, chlorine, and ammonia. Separations are designed to yield pure fuel. Catalytic processing may require multiple catalysts operating at different conditions of temperature and pressure. The water-gas shift reaction is common to production of most synfuels, including hydrogen, methanol, and Fischer-Tropsch liquids. Methanol synthesis is optimal at a syngas H_2:CO ratio of 3:1 while Fischer Tropsch synthesis favors a H_2:CO ratio of 2.15[19]. Of course, hydrogen production involves the complete reaction of CO and steam to form hydrogen fuel. Separations are an integral part of thermochemical processing but, unlike the aqueous phase processes of the biochemical platform, thermochemical processes employ vapor-phase reactions that do not require energy intensive distillations to remove water from the fuel product.

The literature includes several studies on the cost of hydrogen from biomass. Capital costs range from \$0.65 to \$1.33 per gallon of liquid hydrogen capacity[20, 21] depending upon the type and size of gasifier plant. Operating costs range from \$0.31 to \$0.44 per gallon of liquid hydrogen produced[22] depending upon the cost of biomass and the kinds of processes employed[23]. The study by Hamelinck and Faaij[24] represents one of the most recent studies (2002) on biomass-to-hydrogen and include data in sufficient detail to serve as the base case for the present study. For a gasification plant producing 220 million gallons of liquid hydrogen fuel per year, the estimated capital cost is $206 million with operating costs of $0.24 per gallon of liquid hydrogen produced.

Early techno-economic studies of methanol plants report that production costs range from $0.91 to $1.11 per gallon of methanol[25, 26].The techno-economic analysis of Hamelinck and Faaij was chosen for this study because it analyzes both hydrogen and methanol plants. Based on averages from their analysis, a gasification plant producing 87 million gallons of methanol per year would require a capital investment of $276 million. The production cost of methanol was $0.62 per gallon of methanol.

Previous studies of gasification plants producing Fischer-Tropsch diesel suggest that costs range from $1.1 to $4.1 per gallon of F-T diesel[27,28]. Among the most recent and complete techno-economic analyses of a Fischer Tropsch diesel plant is that by Tijmensen et. al.[29]. This analysis employs the oxygen-blown, pressurized gasifier of the Institute of Gas Technology configured to achieve the preferred H_2 to CO ratio. A reformer and water shift reactor are not necessary for this configuration. The product selectivity for hydrocarbon chains of five carbons or longer is 73.7 to 91.9 percent. Capital cost for a plant producing about 35 million gallons of F-T diesel per year is estimated to be about $341 million with operating costs of about $2.37 per gallon of F-T diesel.

Table 4 summarizes the data on plant capacity, capital cost, fuel efficiency, and heating value of the fuel produced for each of the five biofuel plants analyzed in this study. Fuel efficiency is defined as the fraction of energy inputs that appear as chemical enthalpy in the product transportation fuel. Other energy or material outputs (such as process heat, electricity, and distillers' dried grains) do not appear in efficiency calculations but count towards credits in calculating net operating costs. Table 5 breaks down the operating costs for each plant. Clearly, direct comparisons among these five plants are difficult without placing them on a common basis, as described in the methodology section.

Table 4 Capital Costs of Reference Plants

Plant Type	Plant capacity (MMGPY)*	Capital Cost (million)	Fuel Efficiency	Basis Year	Fuel Heating Value (MJ/L)	Source
Grain Ethanol	25	$27.9	35%	1999	21	[5]
Cellulosic Ethanol	50	$294	35%	2005	21	[10]
Methanol	87	$254	45%	2002	16	[24]
Hydrogen	182	$244	50%	2002	8	[24]
Fischer Tropsch	35	$341	46%	2002	36	[29]

* Millions of gallons per year; all fuels assumed to be liquefied.

Table 5 Operating Cost Components of Reference Plants

Plant Type	Biomass Feedstock (million)	Operation and Management (million)	Credits (million)	Capital Charges (million)	Total (million)
Grain Ethanol	$17.0	$10.5	$7.1	$2.8	$22.0
Cellulosic Ethanol	$35.4	$11.1	*	$29.4	$76.0
Methanol	$24.8	$10.2	$8.68	$30.2	$56.5
Hydrogen	$24.7	$9.76	$9.88	$29.0	$53.6
Fischer-Tropsch	$29.2	$14.6	*	$43.8	$87.5

* Byproducts or waste energy are used for process heat within the plant

Methodology

The approach to this study was to modify existing techno-economic analyses found in the published literature to place them on the same bases. These adjustments include: plant capacity, the gasoline equivalency of the fuel, feedstock costs, method of calculating capital charges, and the year for which costs are estimated to allow meaningful comparisons.

Since economies of scale strongly influence the cost of production, capital costs in the original studies were adjusted to a common plant size of 570 million liters per year (150 million gallons per year) gasoline equivalent. This size was selected as representative of expected early generation cellulosic biofuel plants, but no attempt was made to optimize plant size (which will be different for each of the technologies employed). Capital costs were scaled to plant size using a simple power law commonly employed to account for economies-of-scale[30]. A scaling exponent of 0.63 was assumed for the grain ethanol and cellulosic ethanol (biochemical) platforms while a scaling exponent of 0.7 was assumed for the thermochemical platforms. Following usage in the petroleum industry, capital costs are expressed as dollars "per barrel per day" (pbpd) of production capacity. The capacity factor of the plant is assumed to be 0.9.

Plant capacity is customarily reported as the volume of fuel produced although the volumetric energy density (MJ/L) can vary considerably among different kinds of fuels. For example, ethanol, the most prominent biofuel manufactured today, has only 2/3 the enthalpy of an equal volume of gasoline. Thus, production capacity and production cost are reported in this paper on the basis of the gasoline equivalence of the fuel produced.

Operating costs are broken down into categories of biomass feedstock, operation and management, byproduct credits, and capital charges. Biomass costs are proportional to plant capacity and process efficiency in converting biomass into fuels. Cellulosic feedstock costs are assumed to be \$50 per Mg. Corn is priced at \$2.12 per bushel, the price prevailing in the basis year (2005). Operation and management costs include plant and management labor, materials and supplies to operate the plant, and utilities. Credits are given in some instances for by-products. For example, grain ethanol produces distillers dried grains, which can be sold as cattle feed. Gasification generates high temperature heat that can be used for electric power generation. A realistic analysis of operating costs must include the cost of capital although this calculation can be complicated by the fact that actual projects are usually financed by a combination of debt and investor capital. To simplify the evaluation, this study assumes 100% debt financing over 20 years at an annual interest rate of 8%. Inflation can make it difficult to compare studies performed in different years. Accordingly, all costs were adjusted to 2005 dollars.

Results

The capital costs and operating costs for the various biochemical and thermochemical biofuels plants on a common basis are compared in Table 6 . It is clear that advanced biofuels will come at very high capital cost – more than five times that of comparably sized starch ethanol plants – based on the current state of technology. In terms of least capital cost, the order of preference for cellulosic biofuels is thermochemical hydrogen, methanol, lignocellulosic ethanol, and Fischer-Tropsch diesel. The difference in capital costs among the cellulosic biofuel options is significant: Fischer-Tropsch diesel requires almost 50% greater investment than thermochemical hydrogen. This difference reflects the additional unit operations required to convert syngas into Fischer-Tropsch diesel.

The two most fungible fuels among the advanced biofuels, lignocellulosic ethanol and Fischer-Trospsch diesel, are the most capital intensive processes. At $76,000 pbpd and $86,000 pbpd, respectively, their capital costs are essentially the same within the uncertainty of the analysis (+/- 30%). In comparison, the capital cost for a grain to ethanol plant is only $13,000 pbpd.

The rank ordering in terms of operating costs is the same as for capital costs, with thermochemical hydrogen being the least expensive followed by methanol, lignocellulosic ethanol, and Fischer-Trospsch diesel. Operating costs range from a low of $1.05/gal of gasoline equivalent for hydrogen to $1.80/gal of gasoline equivalent for Fischer-Tropsch diesel. In comparison, grain ethanol for this size of plant could be produced for $1.22/gal of gasoline equivalent. This is cheaper than all the cellulosic biofuels except hydrogen.

Figure 4helps understand the differences in operating costs for the various biofuels plants. Much of the advantage of thermochemical hydrogen comes from its relatively low biomass costs, which arises from its high fuel efficiency. As shown inTable 4, thermochemical hydrogen has a fuel efficiency of 50% compared to about 45% for the other two thermochemical technologies. Whereas hydrogen production from syngas requires only water-gas shift reaction and gas separation, methanol production requires an additional catalytic step, and Fischer-Tropsch diesel requires at least two additional catalytic steps, each with attendant loses in efficiency. At 35%, lignocellulosic ethanol is even less efficient, which arises from its inability to convert the non-carbohydrate fraction of lignocellulose into biofuel.

Grain ethanol has the highest biomass costs among the five technologies evaluated. This reflects a combination of relatively low fuel efficiency (about one-third of the corn grain ends up as the byproduct distillers dried grains) and high fuel cost (corn grain at $2.12 per bushel is almost 75% more than lignocellulosic biomass on a dry weight basis). However, as Figure 4 illustrates, the byproduct from a dry mill corn ethanol plant (distillers dried grains) yields a production credit almost three times greater than achieved by any of the other processes. If the expanding grain ethanol industry produces an oversupply of distillers dried grains (assumed to be worth $99/Mg in the present study, the attractive production cost for corn ethanol could evaporate.

Another scenario that could diminish the attractive production cost of grain ethanol is already developing. The present analysis was based on the 2005 price for corn grain, which was only $2.12 per bushel. Substituting $3.00 per bushel, which is more typical of the selling price in late 2006, increases production cost of grain ethanol to $1.74/gal of gasoline equivalent, which is comparable to the price for cellulosic ethanol and Fischer-Tropsch diesel.

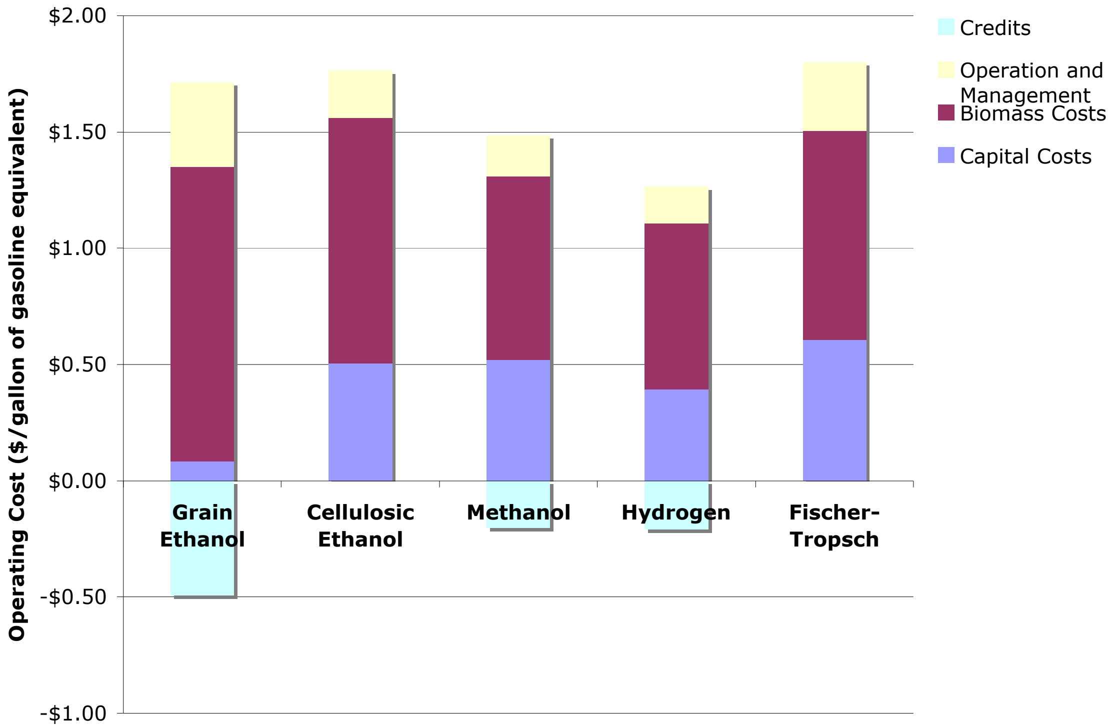
Table 6 Capital cost and operating costs for 150 MMGPY gasoline equivalent plants (2005 dollars)

Fuel	Total Capital Cost (millions)	Capital Cost Per Unit Production (pbpd)*	Operating Cost $/gal*
Grain Ethanol	$111	$13,000	$1.22
Cellulosic ethanol	$756	$76,000	$1.76
Methanol	$606	$66,000	$1.28
Hydrogen	$543	$59,000	$1.05
Fischer Tropsch	$854	$86,000	$1.80

*** per barrel per day gasoline equivalent**

**** gallons gasoline equivalent)**

Figure 4 Operating Costs for 150 MMGPY of Gasoline Equivalent



Conclusions

The rapidly expanding renewable fuels industry will soon have to turn to technologies that convert lignocellulosic biomass into biofuels. Although much of the attention on advanced biofuels has focused on lignocellulosic ethanol, thermolytic processes have also been proposed for production of renewable fuels. Meaningful comparison of advanced fuels technologies to the current grain ethanol process requires that techno-economic analysis be placed on the same basis.

Such an adjustment to techno-economic analyses has been done for lignocellulosic ethanol, thermochemical hydrogen, methanol, and Fischer-Tropsch diesel production plants of 150 million gallons of gasoline equivalent per year. This analysis reveals that advanced biofuels will come at very high capital cost – more than five times that of comparably sized starch ethanol plants. Thus, raising the $0.5 billion to almost $1 billion in capital for a cellulosic biofuels plant will be much more difficult than has proved to be the case for grain ethanol plants. The smaller number of unit operations associated with thermochemical hydrogen makes it the least capital intensive of the four advanced biofuels options evaluated, including lignocellulosic ethanol. However, the larger problems of hydrogen storage and distribution infrastructure compared to other fuels makes it less likely to be adopted within the 10 year time frame envisioned for significant expansion of biofuels in the United States. The capital costs for lignocellulosic ethanol and Fischer-Tropsch diesel, probably the most fungible fuels among the four advanced biofuel options considered, are essentially the same within the uncertainty of the analysis, costing about $80,000 pbpd.

Thermochemical hydrogen also has the lowest production cost, at about $1.05/gal of gasoline equivalent, of the four advanced biofuels options for a plants of 150 million gallons gasoline equivalent annual capacity. It even bests grain ethanol, which would cost $1.27/gal of gasoline equivalent. Lignocellulosic ethanol and Fischer-Tropsch diesel have almost the same production costs, at about $1.78/gal of gasoline equivalent. If corn prices increase from $2.20 per bushel that prevailed in the basis year of this analysis (2005) to $3.00 per bushel found in late 2006 and expected in future years because of increased corn demand, then biofuels from lignocellulosic biomass will have comparable costs of production.

From these comparisons it can be concluded that neither the biochemical nor thermochemical platforms have clear advantages in capital costs or operating costs for production of advanced biofuels. Both technologies have opportunities to compete against grain ethanol as corn prices continue to rise, especially if the high capital costs of advanced biofuels plants can be dramatically reduced.

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Establishing the Optimal Sizes of Different Kinds of Biorefineries

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Mark M. Wright and Robert C. Brown

Abstract

This paper explores the factors that influence the optimal size of biorefineries and the resulting unit cost of biofuels produced by them. Technologies examined include dry grind corn to ethanol, lignocellulosic ethanol via enzymatic hydrolysis, gasification and upgrading to hydrogen, methanol, and Fischer Tropsch liquids, gasification of lignocellulosic biomass to mixed alcohols, and fast pyrolysis of lignocellulosic biomass to bio-oil. On the basis of gallons of gasoline equivalent (gge) capacity, optimally sized gasification-to-biofuels plants were found to be 50 – 100% larger than biochemical cellulosic ethanol plants. Biorefineries converting lignocellulosic biomass into transportation fuels were found to be optimally sized in the range of 236 to 488 million gge per year compared to 74 million gge per year for a grain ethanol plant. Among the biofuel options, ethanol, whether produced biochemically or thermochemically, are the most expensive to produce. These lignocellulosic biorefineries will require 4.4 – 7.8 million tons of biomass annually compared to 1.1 million tons of corn grain for a grain ethanol plant. Factors that could reduce the optimal size of lignocellulosic biorefineries are discussed.

Introduction

The petroleum-based motor fuels industry is characterized by giant refineries, processing petroleum at rates equivalent to ten gigawatts of power or more (140,000 barrels of petroleum per day). This situation exists because operating costs are driven by economies of scale, which causes operating costs to increase more slowly as plant size gets larger. Thus, unit costs for transportation fuels and commodity chemicals derived from fossil fuels are expected to decrease monotonically with increasing plant size.

The situation is dramatically different for biorefineries where biomass feedstocks are obtained from a multiplicity of “farm gates” as opposed to a single “mine mouth” or “well head” of a refinery based on fossil fuels. These farm gates are widely distributed geographically, resulting in transportation costs to the plant that strongly depends upon the size of the processing plant. Furthermore, transport of solid, low density biomass is more labor intensive and expensive than the movement of gaseous and liquid fuels, like natural gas or petroleum. As a result, it has been argued that biomass processing will occur at relatively small scales, drawing biomass from a distance as little as 15 miles around the plant. The corresponding rate of processing of biomass is equivalent to several hundred megawatts of power – at least an order of magnitude smaller than petroleum refineries.

In fact, there is an optimal size for biorefineries since unit costs for processing go down while feedstock transportation costs go up as the plant size gets bigger.[1, 2, 3] The optimal size for different kinds of biomass processing plants are not established but they are expected to depend upon the nature of biomass processed and the kind of processes employed.

This paper expands upon a previous study by the authors which compared the economics of advanced biorefineries based on the biochemical and thermochemical platforms.[4] While the previous paper compared capital and operating costs of comparably sized plants, the present paper explores the factors that influence the optimal size of biorefineries and calculates the optimal size of several kinds of biofuels plants and the resulting unit costs for biofuels produced in them. Technologies examined include dry grind corn to ethanol,[5] lignocellusic ethanol via enzymatic hydrolysis,[6] gasification and upgrading to hydrogen, methanol, and Fischer Tropsch liquids,[7, 8] conversion of lignocellulosic biomass to mixed alcohols,[9] and fast pyrolysis of lignocellulosic biomass to bio-oil.[10]

Background

Biochemical conversion of sugar cane or grain crops (particularly corn) to ethanol is commercially available and widely practiced in Brazil and the United States, respectively. Grain ethanol plants are generally classified as wet or dry milling based on the grain pretreatment. Wet milling plants have the advantage of lower production costs and higher efficiencies, but the grain ethanol industry is currently dominated by dry milling plants due to the lower capital and labor costs of the latter[11] and is thus the focus of this study.

Figure 5 illustrates the five major steps of dry milling of corn to ethanol: grinding to expose the starch to enzymes; liquefaction by the action of heat and enzymes; saccharification by enzymatic activity; fermentation of sugars by yeast to produce ethanol; and distillation to neat ethanol. A by-product of this process is distillers dried grains (DDGS), a fiber and protein-rich that is used for livestock feed.

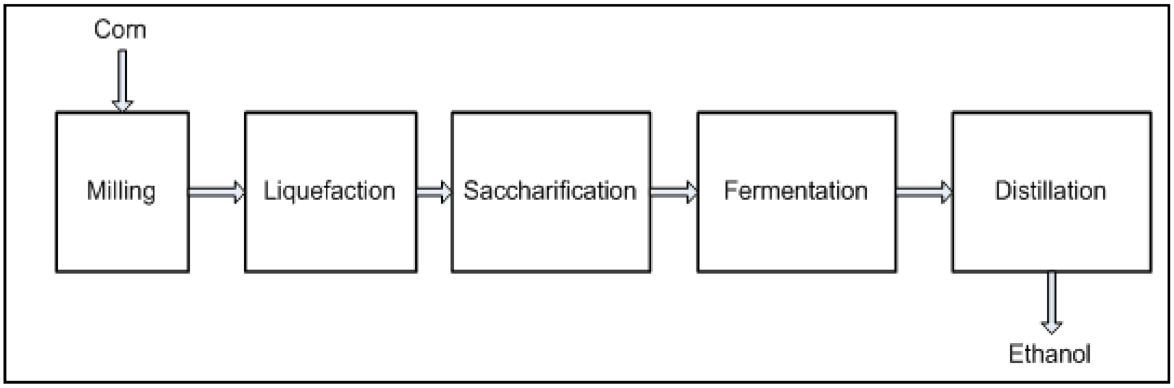

Figure 5 Process flow diagram for dry grind of corn to ethanol

Technical and economic data for the dry grind ethanol process comes from McAloon et. al.[5]They determined that a plant of 25 million gallons annual ethanol capacity had a production cost of $0.88 per gallon of ethanol (2000 basis year).

As shown in Figure 6, biochemical conversion of cellulosic biomass into ethanol consists of four major steps: chemical and mechanical pre-treatments to release sugars from hemicellulose and to make cellulose accessible to enzymes; acid or enzymatic hydrolysis of cellulose into glucose; fermentation of the resulting hexose and pentose to ethanol, and distillation to yield neat ethanol. A by-product of this process is lignin, which can be employed as boiler fuel.

Technical and economic data for biochemical conversion of biomass to ethanol comes from the analysis by Hamelinck et. al.,[6] which assumes dilute acid pretreatment and enzymatic hydrolysis. The analysis found that a plant of 69.3 million gallon per year capacity would produce ethanol at a cost of $1.51 per gallon of ethanol (2005 basis year).

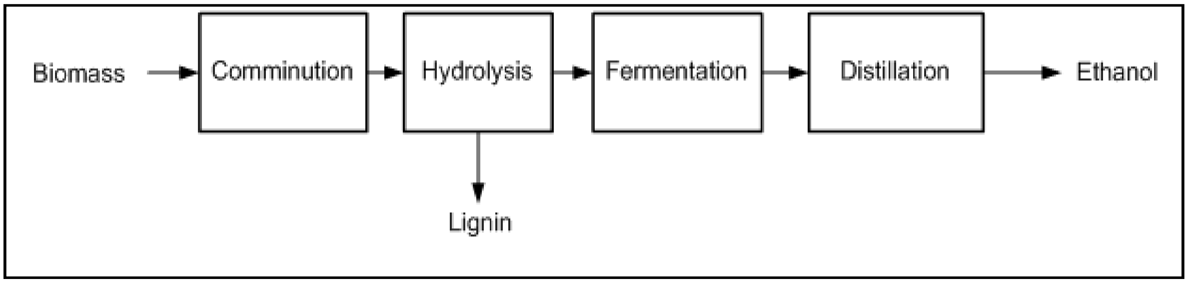

Figure 6 Process flow diagram for biochemical conversion of lignocellulosic biomass to ethanol

Thermochemical conversion of biomass offers a diversity of pathways to a number of biofuels. In general, these pathways are based on either gasification of biomass to gaseous products or fast pyrolysis to liquid products. In both cases these products represent intermediates in the manufacture of transportation fuels.

Gasification of lignocellulosic biomass yields syngas which consists mostly of hydrogen (H_2) and carbon monoxide (CO).[12] A variety of catalytic and even biocatalytic schemes have been developed to upgrade syngas into alcohols, ethers, esters, and hydrocarbons. In this study, four fuels from syngas are considered: hydrogen, methanol, mixed alcohols (with the purpose of maximizing ethanol synthesis), and Fischer Tropsch liquids. The optimal H_2:CO molar ratio differs for each synthesis route. Methanol synthesis favors a hydrogen-to-carbon monoxide molar ratio of 3:1 while Fischer Tropsch diesel is optimized at a ratio of 2.15:1.[13] Mixed alcohols optimized for ethanol production employs a syngas ratio of 0.6:1[9].

As illustrated in Figure 7, gasification routes to biofuels have four major operations in common: comminution of the feedstock; gasification; gas cleaning to remove tar, particulate matter, and inorganic contaminants; and water-gas shift reaction to enrich hydrogen with respect to carbon monoxide.[14] If pure hydrogen is the desired product, at least two stages of water-gas shift are employed followed by gas purification to remove carbon dioxide. Conversion of biomass to methanol, mixed alcohols, or Fischer Tropsch liquids adds catalytic synthesis steps after the water-gas shift unit operation. Production of mixed alcohols further adds a distillation step to separate fuel ethanol from the other alcohols. In all cases, unit operations are highly integrated to achieve heat recovery and utilize waste heat in electricity production.

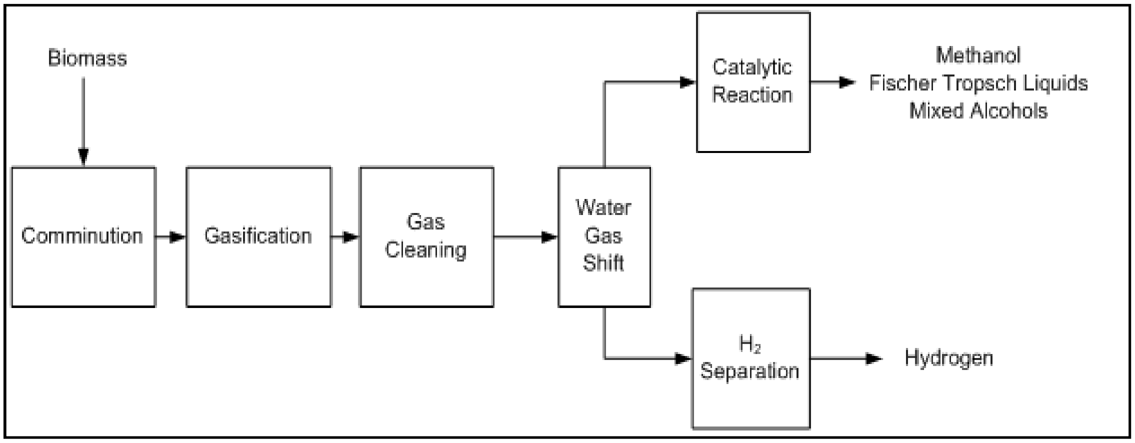

Figure 7 Process flow diagram for gasification of lignocellulosic biomass to hydrogen, methanol, mixed alcohols, or Fischer Tropsch liquids

Technical and economic data for hydrogen and methanol production come from Hamelinck and Faaij,[7] which assumed biomass throughput equivalent to 400 MW thermal and pressurized, oxygen-blown gasification. This represents a hydrogen plant yielding 182 million gallon per year at a cost of $0.24 per gallon of hydrogen or a methanol plant yielding 96 million gallons per year at a cost of $0.64 per gallon (2002 basis year). Technical and economic data for production of Fischer Tropsch liquids comes from a study by Tijmensen et al., [8] which assumes pressurized, oxygen-blown gasification. This analysis found that a plant of 35 million gallon per year capacity would produce Fischer Tropsch liquids at a cost of $2.37 per gallon (2002 basis year).

Technical and economic data for production of mixed alcohols comes from a study Phillips et. al.,[9], which assumed atmospheric, indirectly heated gasification. This analysis found that a plant of 61.8 million gallons of ethanol per year capacity would have a production cost of $1.01 per gallon (2005 basis year).

Fast pyrolysis is another thermochemical route to liquid fuels. Rapid heating of biomass at moderate temperatures (450 – 500 C) in the absence of oxygen directly yields a liquid product. As illustrated in Figure 8, bio-oil production involves four major operations: comminution of the feedstock; fast pyrolysis; gas cleaning to remove particulate matter; and recovery of bio-oil. Although bio-oil can be directly used as boiler fuel or even fired in certain kinds of engines, it is not suitable as transportation fuel without further upgrading. However, the optimal size of a plant to produce bio-oil is included in this study because it illustrates the opportunities to explore distributed processing of biomass. Technical and economic data comes from Ringer et. al.[10] Their analysis found that a plant of 28 million gallons per year capacity (assumed 90% capacity factor) would have a production cost of $0.59 per gallon of bio-oil (2003 basis year).

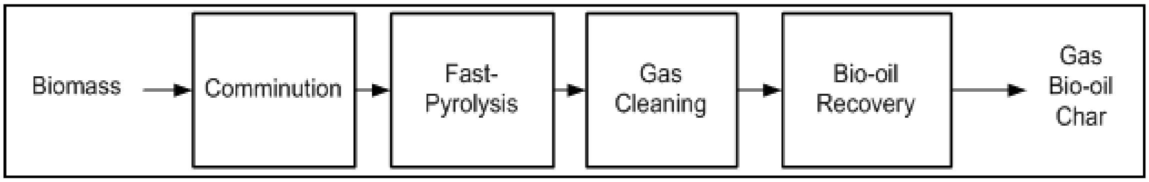

Figure 8 Process flow diagram for production of bio-oil from fast pyrolysis

One option for upgrading bio-oil is hydrocracking it to diesel fuel and gasoline.[15] Another option for upgrading bio-oil is gasification followed by catalytic synthesis to Fischer Tropsch liquids. However, insufficient technical and economic data is currently available to include these biofuels options in the present study.

Methodology

The petroleum-based motor fuels industry is characterized by giant refineries, processing petroleum at a rate equivalent to gigawatts of power. This situation exists because plant operating costs are driven by economies of scale, which causes plant operating costs to increase more slowly as a plant gets bigger. Specifically, the operating cost (excluding fuel costs) of a plant, C_P, scales with plant capacity, M, according to the power law:

$$C_P = C_{Po} (M/M_o)^n \tag{1}$$

where C_{Po} is the plant operating cost for a plant of capacity M_o and n is a power law exponent less than unity, often assumed to be 0.6 (the "sixth-tenth" rule). Ngyuen and Prince[2]suggest that n is likely in the range of 0.6 to 0.8 while Jenkins[3], in analyzing the optimal size of electric power plants, argues that this range is only appropriate for biomass power plants of size less than 50 MW electrical. He cites a study by Fisher et al.[16] that supports values of n as large as 0.93-0.94 for coal-power plants in the size range of 100 – 1,400 MW.

The total cost, C_T, for producing a quantity M of motor fuel from fossil fuel is the sum of the cost of plant operations, C_P, the cost of feedstock at the mine mouth, C_F, and the cost of feedstock delivery (transportation), C_D:

$$C_T = C_P + C_D + C_F \tag{2}$$

$$= C_{Po} (M/M_o)^n + C_{Fo} (M/M_o) + C_{Do} (M/M_o) \tag{3}$$

where C_{Fo} is the feedstock cost and C_{Do} is the feedstock delivery cost for a plant of capacity M_o. The unit cost for the resulting motor fuel ($ per gallon) is determined by dividing through by the plant capacity M:

$$(C_T /M)= (C_{Po}/M_o^n)\, M^{n-1} + (C_{Fo}/M_o) + (C_{Do} /M_o) \tag{4}$$

Thus, for n less than unity, it is evident that unit cost of the motor fuel from fossil fuel feedstocks decreases as the plant gets bigger without limit.

The case is more complicated for biomass fuel since it does not come from a single mine mouth located a fixed distance from the plant but is dispersed over a large area surrounding the plant. Thus, delivery cost for a unit of biomass fuel increases as the capacity of the plant increases because the biomass must be delivered from increasingly greater distances. Such an analysis has been explored by several researchers [1, 2, 3].

The cost of biomass delivery is proportional to both transport distance and the quantity of biomass transported. Since the amount of biomass around a plant increases as the square of distance, D, from the plant, the cost of delivery is:

$$C_D = C_{Do}(D/D_o)(M/M_o) = C_{Do}(M/M_o)^{0.5}(M/M_o) = C_{Do}(M/M_o)^{1.5} = C_{Do}(M/M_o)^m \qquad (5)$$

where D_o is the delivery distance for a plant of capacity M_o and m has been substituted for 1.5 to allow for some variation in this power law. Nguyen and Prince[2] argue that the power law exponent m might be as large as 2 if available land for biomass becomes increasingly sparse with distance from a plant, although in most cases 1.5 is probably a realistic value for m.

The total cost for producing a quantity of biomass-derived motor fuel is the cost of plant operations, C_P, the cost of biomass fuel delivery, C_D, and the cost of biomass fuel at the farm gate, C_F:

$$C_T = C_P + C_D + C_F \qquad (6)$$

$$= C_{Po}(M/M_o)^n + C_{Do}(M/M_o)^m + C_{Fo}(M/M_o) \qquad (7)$$

This expression is divided by M to obtain the unit cost for motor fuel produced from biomass:

$$(C_T/M) = (C_{Po}/M_o^n)\, M^{n-1} + (C_{Do}/M_o^m)\, M^{m-1} + (C_{Fo}/M_o) \qquad (8)$$

Since n-1 is less than zero and m-1 is greater than zero, the first term on the right hand side of Eq. 8 decreases with plant capacity while the second term increases with plant capacity. Thus, there is an optimum plant size to achieve minimum unit cost of motor fuel derived from biomass, which is obtained by differentiating Eq. 8, setting it equal to zero, and solving for M_{opt}/M_o. The result obtained is:

$$(M_{opt}/M_o) = \{[(1-n)/(m-1)](C_{Po}/C_{Do})\}^{1/(m-n)} \quad (9)$$

It is evident from this expression that if operating costs C_{Po} for a baseline plant of size Mo are much greater than the transportation cost C_{Do} of biomass, then the optimum plant size M_{opt} will be much greater than the size of the baseline plant.

Further insight into plant size optimization can be found by rearranging Eq. 9 as follows:

$$C_{Do}(M_{opt}/M_o)^m \,/\, C_{Po}(M_{opt}/M_o)^n = (1-n)/(m-1) \quad (10)$$

The quantity on the left hand side of Eq. 10 is recognized as the ratio of cost of delivery of biomass to the cost of plant operations, R, under the conditions of optimization; thus:

$$R_{opt} = (C_D/C_P)_{opt} = (1-n)/(m-1) \quad (11)$$

This indicates that, for a plant sized to give the minimum unit cost of motor fuel, the ratio of delivery cost to operating cost depends only on the power law exponents m and n. For example, assuming n is 0.6 (the sixth-tenth rule of economies of scale) and m is 1.5, delivery costs will equal 80% of plant operating costs in an optimally sized plant for minimum unit cost of motor fuel.

Nguyen and Prince[2] present data on the unit cost of motor fuel for sugar cane ethanol plants of different sizes in an effort to identify the value R_{opt} that gives the minimum cost ethanol. Their data indicates that this minimum occurs when R_{opt} is about 0.46 (although they mistakenly report it to be 0.60 in their paper). This corresponds to n equal to 0.77, somewhat larger than the classical sixth-tenths value but not unexpectedly large.

Once values of n and m are selected, the unit cost of biofuel as a function of plant of size M can be calculated from Equation 8 and from knowledge of the cost of plant operations, the cost of feedstock, and the cost of feedstock delivery for a plant of arbitrary baseline size M_o. The cost of plant operations, C_{Po}, for baseline cases of the various kinds of biofuel plants was obtained from the literature cited in the background section of this paper. All plant operating costs were inflation adjusted to place them in the common basis year of 2005. The farm gate cost of feedstock was assumed to be \$75.71/ton (\$2.12/bushel) for corn (the price in the basis year 2005) and \$40/ton of lignocellulosic biomass.

The cost of delivering feedstock from the farm gate to the plant gate is calculated from:

$$C_{DL} = C_{DU} \cdot \bar{r} \cdot F \tag{12}$$

where C_{DU} is the unit cost for feedstock delivery (dollars per ton per mile), $\bar{r}$ is the average delivery distance of feedstock, and F is the tons of feedstock delivered annually to the plant. The unit cost of feedstock delivery for corn grain[17] is \$0.018/bu/mi and for lignocellulosic biomass[18] is \$0.71/ton/mi.

For biomass uniformly distributed around a processing plant, the maximum radius r_{max} around the plant from which feedstock must be delivered is given by:

$$r_{\max} = \sqrt{\frac{F}{\pi f Y}} \tag{13}$$

where f is the fraction of the acreage around a plant devoted to feedstock production (assumed to be 60% in this study) and Y is the annual yield of feedstock (assumed to 140 bushel per acre or 3.92 tons/acre for corn grain and 5 tons/acre for lignocellulosic biomass).

The average (land area-weighted) radius from which feedstock is obtained around the plant is two-thirds of r_{max}. The actual distance traveled by a truck delivering biomass is greater than the radial (straight-line) distance to the plant depending upon the nature of the road network. To account for this additional distance, a "tortuosity factor" τ is defined as the ratio of actual distance traveled to the straight-line distance from the plant. Tortuosity factors can be about 1.2 for developed agriculture regions where roads are laid out in rectangular grids or as great as 3.0 for less developed regions. The present analysis assumes the tortuosity factor is 1.5. Based on these adjustments, the average delivery distance is:

$$\bar{D} = \tfrac{2}{3}\tau\sqrt{\frac{F}{\pi f Y}} \tag{14}$$

Capital costs range from a low of $68 million for the 74 million gge grain ethanol plant to $1.52 billion for the 488 million gge Fischer-Tropsch diesel plant. All of the cellulose-to-biofuels plants exceed one-half billion dollars to build at their optimal size (which are larger than 236 million gge of biofuels). The unit cost of bio-oil is only $0.64 per gge for the optimally scaled plant although bio-oil is not suitable as motor fuel without additional upgrading. It is followed by hydrogen at $1.21, methanol at $1.35, grain ethanol at $1.47, Fischer Tropsch diesel at $1.53, biochemical cellulosic ethanol at $1.78, and ethanol from the mixed alcohols process at $1.82. Among the cellulosic biofuel options, ethanol, whether produced biochemically or thermochemically, is the most expensive to produce.

The total production costs for each of the plants (with the exception of the fast pyrolysis process) are plotted as functions of plant size in Figure 7. As expected, total costs at first decline rapidly as plant capacity increases. Eventually total costs reach a minimum value. These minima are remarkably shallow. With the exception of the grain ethanol plant, capacity can be varied by 100 million gge or more around the optimal capacity without substantially affecting unit cost of biofuel production. Below about 50 million gge, or 75 million gallons ethanol, the grain ethanol process yields the lowest unit cost of biofuel. At larger plant capacities, grain ethanol becomes

Table 7 tabulates the average delivery distances and annual cost of delivering biomass to the baseline plants calculated according to Equations 14 and 12, respectively. Average delivery distance ranges between 5.5 miles and 11.4 miles for these seven base cases. The table also includes the volumetric (lower) heating values of the biofuels produced for each process because comparisons among the different fuels are done on the basis of gallons gasoline equivalency (gge).

Table 8 is a compilation of plant size, capital cost (inflation adjusted to 2005), plant operating costs (inflation adjusted to 2005), unit cost of biofuels production, and R value of the various baseline biofuel plants to support the subsequent analysis of this study. The fact that none of the R values approaches the optimal value of 0.8 suggests that these baseline plants are far from the size that yields the minimum unit cost of biofuels production.

Results

Table 9summarizes the results of the plant size optimization for processing cost power law exponent, n, and delivery cost power law exponent, m, equal to 0.6 and 1.5 respectively (corresponding to R equal to 0.8). The biofuels plants are listed in order of increasing optimal plant capacity in terms of gallons of gasoline equivalent (gge): corn grain ethanol, fast pyrolysis of biomass to bio-oil, biochemical production of cellulosic ethanol, gasification of lignocellulosic biomass to methanol, hydrogen, mixed alcohols, and Fischer Tropsch diesel. The relatively low unit cost of plant operations relative to feedstock delivery for corn grain ethanol allows it to be built at an optimal scale of 74 million gge. In comparison, biochemical cellulosic ethanol requires a plant of 236 million gge capacity and the gasification-based biofuel plants range is size from 344 million gge to 488 million gge to produce biofuel at minimum unit cost. On the basis of gallons of gasoline equivalency, optimally sized plants based on gasification are 50 – 100% larger than biochemical cellulosic ethanol plants. With the exception of the pyrolysis to bio-oil plant, all optimally-sized biofuel plants using lignocellulosic biomass as feedstock consume 4.4 – 7.8 million tons of biomass annually compared to 1.1 million tons of corn for the optimally sized grain ethanol plant.

Capital costs range from a low of $68 million for the 74 million gge grain ethanol plant to $1.52 billion for the 488 million gge Fischer-Tropsch diesel plant. All of the cellulose-to-biofuels plants exceed one-half billion dollars to build at their optimal size (which are larger than 236 million gge of biofuels). The unit cost of bio-oil is only $0.64 per gge for the optimally scaled plant although bio-oil is not suitable as motor fuel without additional upgrading. It is followed by hydrogen at $1.21, methanol at $1.35, grain ethanol at $1.47, Fischer Tropsch diesel at $1.53, biochemical cellulosic ethanol at $1.78, and ethanol from the mixed alcohols process at $1.82. Among the cellulosic biofuel options, ethanol, whether produced biochemically or thermochemically, is the most expensive to produce.

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Table 7 Average delivery distances and delivery costs for baseline cellulosic biomass plants

Plant	Biofuel Heating Value (MJ/L)	Plant Size (million gge*)	Biomass Input (million tons)	Average Delivery Distance** (miles)	C_{Do}*** (millions)
Grain Ethanol	21	16.7	0.25	6.44	$1.16
Biochemical Cellulosic Ethanol	21	33.5	0.66	11.8	$5.51
Gasification to Hydrogen (Liquid)	6	47.9	0.67	10.5	$4.99
Gasification to Methanol	16	43.4	0.67	10.5	$4.95
Gasification to Mixed Alcohols	21	41.2	0.77	11.3	$6.15
Gasification to Fischer-Tropsch Diesel	36	40.4	0.64	10.3	$4.66
Fast Pyrolysis to Bio-oil	19.6	17.3	0.18	5.46	$0.695

* Gallons gasoline equivalency

** Assumes feedstock yield of 3.92 tons/acre for corn grain and 5 tons per acre for lignocellulosic biomass; land utilization factor of 60%; and tortuosity factor of 1.5.

*** Assumes feedstock delivery cost of $0.018/bu/mi for corn grain and $0.71/ton/mi for lignocellulosic biomass.

Table 8 Base Case Sizes and Annual Costs

Process	M_0 (million gge*)	Biomass Input (million tons)	Capital Costs** (millions)	Operating Costs (millions)				C_T/ M_o (per gge*)	R***
				C_{Po}**	C_{Do}	C_{Fo}	C_{To}		
Grain Ethanol	16.7	0.25	$27.9	$5.86	$1.16	$18.9	$25.9	$1.55	0.20
Biochemical Cellulosic Ethanol	33.5	0.66	$294	$40.5	$5.51	$26.4	$72.4	$2.16	0.14
Gasification to Hydrogen (Liquid)	47.9	0.67	$244	$38.8	$4.99	$26.8	$70.6	$1.47	0.13
Gasification to Methanol	43.4	0.67	$254	$40.4	$4.95	$26.8	$72.2	$1.66	0.12
Gasification to Mixed Alcohols	41.2	0.77	$137	$61.9	$6.15	$30.8	$98.9	$2.40	0.10
Gasification to Fischer-Tropsch Diesel	40.4	0.64	$341	$54.6	$4.66	$25.6	$84.8	$2.10	0.09
Fast Pyrolysis to Bio-oil	17.3	0.18	$30	$4.35	$0.695	$7.20	$12.2	$0.71	0.16

* Gallons gasoline equivalency

** Adjusted to 2005 basis year

*** R is the ratio of cost of delivery of biomass to the cost of plant operations

Table 9 Optimum Plant Annual Capacity and Operating Costs (R = 0.8)

Process	M (million gge)	Biomass Input (million tons)	Capital Cost (millions)	Operating Costs (millions)				C_T/M (per gge)	Volumetric Annual Plant Capacity (millions of gallons)	C_T/M (per gal)
				C_P	C_D	C_F	C_T			
Grain Ethanol	74	1.11	68.2	$14.3	$11	$84	$109	$1.47	111	$0.98
Fast Pyrolysis to Bio-oil	110	1.14	91.6	$13.2	$11.1	$45.8	$70.1	$0.64	178	$0.14
Biochemical Cellulosic Ethanol	236	4.65	949	$131	$103	$186	$420	$1.78	354	$1.19
Gasification to Methanol	344	5.31	881	$140	$111	$212	$463	$1.35	690	$0.67
Gasification to Hydrogen	362	5.06	822	$131	$104	$203	$437	$1.21	1376	$0.32
Gasification to Mixed Alcohols	416	4.42	549	$248	$197	$311	$756	$1.82	624	$0.71
Gasification to Fischer-Tropsch Diesel	488	7.73	1520	$243	$196	$309	$748	$1.53	425	$1.76

Relatively optimistic assumptions were made about lignocellulosic biomass yield (5 tons per acre) and the percentage of land around the plant that would be devoted to growing this biomass (60%). Reductions in either yield or the percentage of land use could significantly reduce the optimal size of biomass processing plants as calculated in this study. For example, substituting an agriculture residue such as corn stover for a dedicated energy crop might reduce the yield of lignocellulosic biomass to 2.5 tons per acre. Alternatively, the number of producers surrounding the plant willing to produce a dedicated energy crop like switchgrass might control only 30% of the land surrounding a processing plant. In either case, the optimal size of plants processing lignocellulosic biomass would be reduced by about 30%.

Another scenario that would result in smaller optimally sized processing plants is illustrated in **Figure 10**, which is a plot of optimum plant size as a function of the power law exponent n that describes the scaling of feedstock processing costs with plant size. For low values of n, the optimal plant capacity increases with increasing n. After a maximum optimum plant size is reached, optimal plant sizes decrease rapidly with increasing n indicating that small biofuels plants could be economically built if linear scaling (n approaching unity) prevailed. In principle, linear scaling could be approached by mass production of small-scale biofuels plants whereas today plants are custom designed and constructed. However, the authors are not aware of any such instances of mass production that demonstrate the practicality of this principle. Of course, any technology advances that reduce the capital cost and hence capital charges in the plant operating costs would also tend to reduce the optimal size of plants.

On the other hand, it is easy to envision changes to the grain ethanol plant that would increase its optimal size and reduce the cost of ethanol production. For example, many ethanol producers are considering the addition of front-end separation of corn oil to their dry-grind ethanol plants, which would increase plant processing costs. Transportation costs for these plants could be significantly reduced if grain was shipped by rail or barge instead of by truck. According to Eq. 9, these factors will increase the optimal size of a grain ethanol plant to something larger than the 74 million gge calculated in this study as well as lower the cost of grain ethanol.

Conclusions

Unlike fossil fuel processing plants for which unit cost of fuel product decreases as the plant gets larger, optimal biomass processing plant capacities are expected that achieve the lowest unit cost of biofuel production. The optimal capacity depends upon the value of power law exponents used in scaling relationships that describe the costs of feedstock processing and delivery, respectively, and upon the relative cost of feedstock processing compared to feedstock delivery.

Data from the published literature was used to evaluate the optimal size of several biorefinery concepts. In the order of their increasing optimal plant size these are: corn grain ethanol, fast pyrolysis to bio-oil, biochemical production of cellulosic ethanol, gasification to methanol, gasification to hydrogen, gasification to mixed alcohols, and gasification to Fischer Tropsch diesel. Optimally sized plants based on gasification are 50 – 100% larger (gge basis) than the biochemical cellulosic ethanol plant. Biorefineries converting lignocellulosic biomass into transportation fuels are optimally sized in the range of 236 to 488 million gge per year and require 4.4 – 7.8 million tons of biomass annually compared to 1.1 million tons of corn grain for an optimally sized grain ethanol plant. Capital costs for advanced biofuels plants are similarly much greater than for a grain ethanol plant, ranging from $549 million for a mixed alcohols plant to $1.52 billion for a Fischer-Tropsch diesel plant compared to $68.2 million for the grain ethanol plant. Among the cellulosic biofuel options, ethanol, whether produced biochemically or thermochemically, is the most expensive to produce.

The minima in the unit cost of cellulosic biofuel vs. plant capacity are so shallow that, with the exception of the fast pyrolysis plant, plant size can be varied by as much as 100 million gge around the optimal capacity without substantially affecting unit cost of biofuels production.

Although optimally sized biorefineries based on lignocellulosic biomass are predicted in this study to process four to seven times as much feedstock as grain ethanol plants, three factors could reduce the optimal size of these advanced biorefineries. First, reductions in either biomass yield or the percentage of land surrounding a plant dedicated to biomass crops would significantly increase the distance required to collect biomass, making it too expensive to build as large of plant as projected in this study. Second, making the power law for biomass processing nearly linear through mass production of small-scale biofuels plants might reduce the optimal size of these plants. Finally, technology advances that reduce capital costs of the plant would reduce the size of plant that produces biofuel at the lowest unit cost.

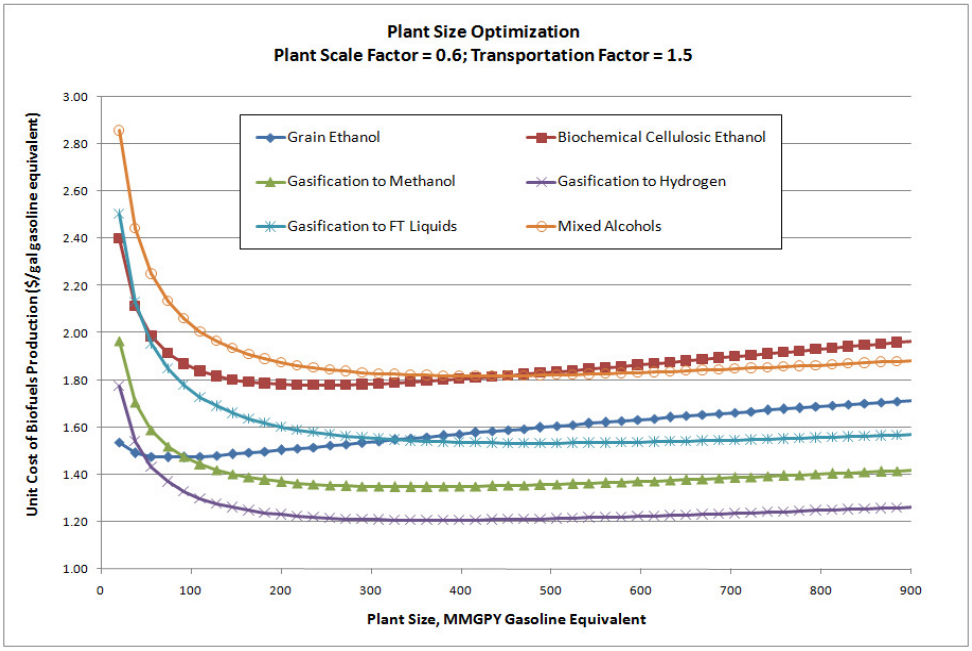

Figure 9 Unit Cost of Biofuels Production vs Plant Size

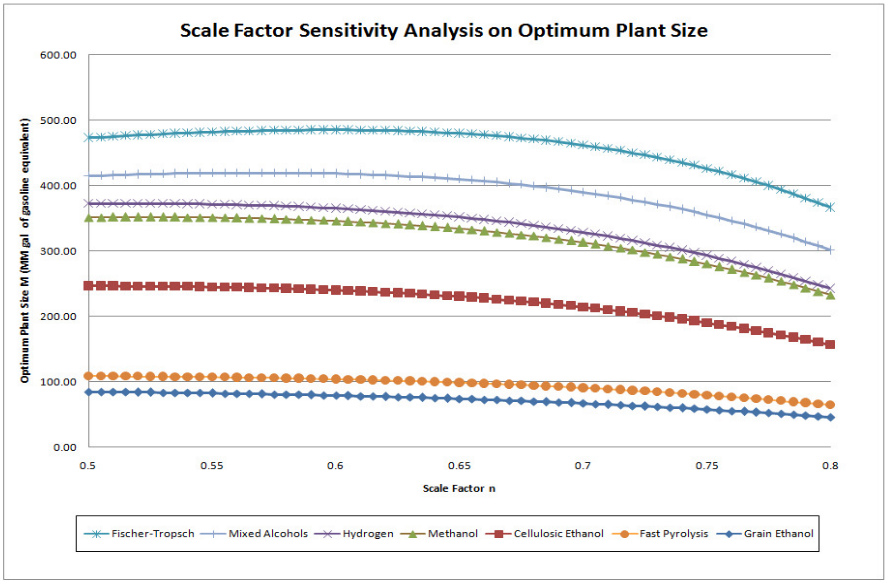

Figure 10 Effect of processing cost scale factor n on the optimal size of biofuels plants

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Distributed Processing of Biomass to Bio-Oil for Subsequent Production of Fischer-Tropsch Liquids

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Mark M. Wright, Robert C. Brown, Akwasi A. Boateng

Abstract

This study compares centralized processing to distributed processing of biomass for subsequent production of Fischer-Tropsch liquids (FTL) at a centralized catalytic synthesis facility. Distributed processing in this study is based on fast pyrolysis to bio-oils, which are more economically transported to a centralized F-T plant where bio-oil is gasified and the syngas catalytically converted to F-T liquids. The study indicates that a centralized gasification plant can produce Fischer-Tropsch liquids from biomass for \$1.56 per gallon of gasoline equivalent (gge) in an optimally sized plants of 550 million gge per year. Three distributed processing systems were investigated based on the scale of biomass processing capacity: "on-farm" pyrolyzers of 5.4 ton per day (tpd) capacity; "small cooperative" pyrolyzers of 55 tpd capacity, and "large cooperative" pyrolyzers of 550 tpd capacity. Distributed processing is combined with very large centralized bio-oil processing plants that accept bio-oil for catalytic upgrading to transportation fuels, achieving costs as low as \$1.43 for total fuel production capacities in excess of 2500 million gge. Total capital investment (distributed pyrolyzers and centralized bio-oil processing plant) for this optimally sized distributed processing system is projected to be \$4 billion compared to \$1.6 billion for the centralized biomass processing facility.

Introduction

The optimal size of advanced cellulosic biofuel plants are expected to be up to five times as large as existing grain to ethanol plants.[1] As much as 23,000 tons of biomass would have to be shipped daily to such a plant, which would have serious impacts on transportation infrastructure and communities near the plant. Distributed biomass processing has the potential to alleviate biomass delivery expenses by densifying biomass prior to shipping to a central facility for upgrading to renewable transportation fuels.

One method of densifying biomass is converting it to bio-oil via fast pyrolysis.[2] The specific gravity of bio-oil from switchgrass is 1.2-1.3 compared with 0.5 for pelletized switchgrass.[3] Biomass pyrolysis can reduce transportation costs by converting feedstock to a liquid product. Badger and Fransham argue that fast pyrolysis reactors can be built economically at small scales, allowing their use in distributed processing systems.[4] The high density of bio-oil is expected to result in lower transportation costs compared to chopped or baled biomass, allowing it to be transported longer distances at a reduced cost. Low transportation costs will result in larger optimally-sized fuel production facilities and lower unit costs for fuel.[1]

This paper considers fast pyrolysis as a means of densifying biomass for transportation with subsequent upgrading at a centralized refinery to transportation fuel. Two scenarios are considered for producing Fischer-Tropsch liquids (FTL): centralized gasification of biomass crops and centralized gasification of bio-oil produced from distributed processing of biomass crops. Distributed processing is considered at three scales: 5.4 tons per day (“on-farm”), 55 tons per day (“small co-op”), and 550 tons per day (“large co-op”).

Background

Thermochemical conversion of biomass via gasification is likely to occur in large-scale plants processing in excess of 2000 ton per day.[1] Large plants take advantage of economies of scale to reduce unit production costs. This is evident in the petroleum industries where petroleum refineries can achieve process rates equivalent to 140,000 barrels per day (about 2 billion gallons per year) due to relatively low crude oil transportation costs. While increasing capacity generally leads to lower production costs, biomass processing facilities are constrained by feedstock availability. Because of the diffuse nature of biomass, land availability and transportation costs limit biomass conversion plants to an optimum plant size. In a previous study, the optimum plant size for a biomass to Fischer-Tropsch liquids (FTL) plant was found to be 486 million gallons of gasoline (gge) equivalent per year and 104 million gge for fast pyrolysis to bio-oil requiring biomass inputs of 1.08 and 7.69 million tons per year, respectively.[1]

Biomass-to-liquids (BTL) is premised on the gasification of biomass followed by catalytic upgrading to FTL.[5] The primary products of Fischer-Tropsch synthesis are a mixture of light hydrocarbon gases, paraffin waxes, and alcohols according to the generalized reaction:[6]

$$CO + 2H_2 \rightarrow \text{—}CH_2\text{—} + H_2O$$

Depending on the types and quantities of Fischer-Tropsch products desired, either low (200–240 °C) or high temperature (300–350 °C) synthesis is used with either an iron (Fe) or cobalt catalyst (Co). Additional processing of the F-T products yields diesel fuel or gasoline.

The biomass gasification to Fischer-Tropsch liquids process can be conceptualized as a five step process. These processes, which are shown in Figure 11, include comminution, gasification, gas clean-up, water gas shift, and catalytic processing to the desired fuels. A large number of variations and additions to this biomass gasification technology can be envisioned.5

Comminution consists of mechanical treatment of the feedstock to reduce its particle size and moisture content based on process requirements. Selection of reactor type and operating conditions generally dictate the extent of the pre-treatment required for optimal conversion to synthetic gas. Gasification can occur at a variety of operating conditions but for Fischer-Tropsch catalysis oxygen-blown, high pressure (>10 bar) and high temperature (>1000 ^{o}C) gasifiers are preferred. The concept selected in this paper employs and oxygen-blown, pressurized gasifier from the Gas Technology Institute (GTI) operating at 20.3 bars and 980 ^{o}C.[7] Gas cleaning includes removal of particulate matter and trace contaminants including sulfur, chlorine, and ammonia. Some contaminants, particularly sulfur, are extremely active catalyst poisons that can limit the catalytic process and result in high expenses for catalyst replacement. Fouling of the catalyst can occur at very small concentrations measured in the parts per billion ranges.[8] Synthetic gas composition can vary widely from different gasifier technologies and operating conditions, and catalyst requirements depend on the major metal component employed; the water-gas shift reaction adjusts the H_2:CO ratio of the syngas when required by the catalyst. Finally, a Fischer-Tropsch reactor using a metal based catalyst is used to convert the syngas to a mixture of hydrocarbons.

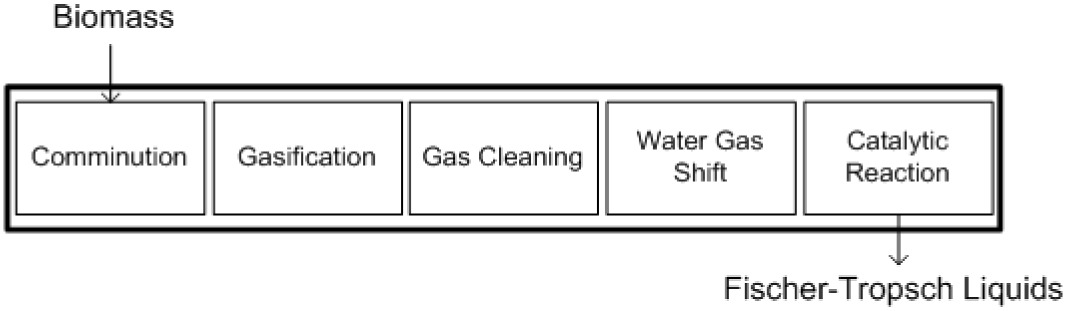

Figure 11 Flow diagram biomass to liquids production based on centralized biomass gasification

Studies of biomass gasification plants producing Fischer-Tropsch liquids have found fuel costs range from \$1.10 to \$4.10 per gallon. [9,10] We employ the frequently cited study of Tijmensen et al.[7] Their analysis of a 35 million gallon plant yielded a production cost of \$2.37 per gallon fuel.

Distributed processing is one potential solution to supplying feedstock to large biorefineries. In this concept, small processing equipment or facilities located in close proximity to the feedstock are employed to densify the biomass prior to shipping. While different approaches to densification can be considered, this paper examines fast pyrolysis for distributed processing. The resulting bio-oil is more easily shipped to a centralized processing facility for generation of electric power[11,12] or for upgrading to transportation fuel.[13]

Fast pyrolysis employs a rapid heating of biomass at moderate temperatures (450 – 500° C) in an anaerobic environment to yield liquid, solid (char), and gaseous products.[14] The liquid product is known as pyrolysis liquid or more commonly as bio-oil. Bio-oil is a mixture of various organic compounds resulting from fragmentation of cellulose, hemicellulose, and lignin polymers. [15, 16, 17] Up to 75 wt-% of the biomass weight can be converted to liquids with the balance consisting of non-condensable gas (NCG) and charcoal. [18]

The scheme for pyrolytic pretreatment of biomass and bio-oil upgrading is illustrated in Figure 12. Biomass is ground to 1-3 mm fiber lengths and dried to about 10% moisture to achieve the desired yields of bio-oil. [14] The biomass is pyrolyzed and the resulting vapors passed through a particulate matter separation device before being condensed to liquid product. Numerous reactor designs have been considered,[19] but fluid bed and circulating fluid bed reactors are most commonly employed due to ease of operation and scale-up.[20] Gas clean-up is used to separate solid particles, or aerosols, entrained in the gas stream. Condensation can take place over various heat exchangers to yield different bio-oil fractions.[3]Bio-oil can be pumped into a tanker truck for transportation to an upgrading facility.[4] Gasification of bio-oil followed by Fischer-Tropsch Synthesis is one method to convert bio-oil into a transportation fuel.[13]

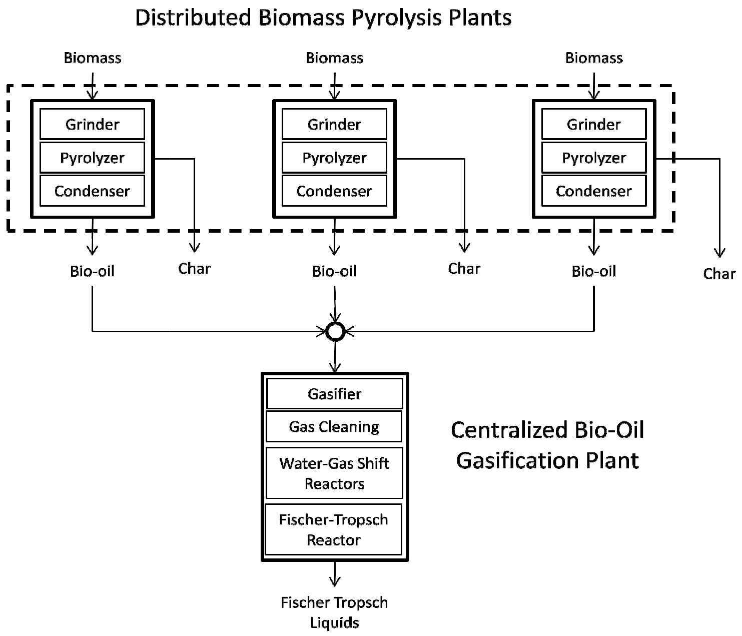

Figure 12 Distributed Biomass Processing Diagram

Charcoal can provide the energy for pyrolysis although the energy value is only about $25/ton based on coal selling for $1.10/GJ. However, charcoal is increasingly being recognized as a valuable co-product that can be used for soil enrichment and carbon sequestration. [21] When markets develop for sequestering carbon dioxide from the atmosphere, the value of charcoal as a carbon sequestration agent could be considerably higher than its fuel value.

Various techno-economic analyses of fast pyrolysis plants are available in the literature.[22, 23, 24, 25] Prior investigations estimated bio-oil production costs to range between $0.41[22] and $1.21[26] per gallon. Our analysis is based on the NREL report by Ringer et. al.[27] for a 550 dry tons per day plant producing 28 million gallons of bio-oil per year at a cost of $0.62 per gallon. This recent (2006) analysis includes the detailed technoeconomic study of pyrolysis technology that could be employed with minimum modifications in this research.

Methodology

The approach to this study consists of combining data from existing techno-economic analyses to compare the cost of producing Fischer-Tropsch liquids via centralized and distributed biomass processing systems. The present analysis incorporates analytical methods for scaling plant capital and production costs, calculating feedstock delivery costs, and determining the optimal size of plants that process biomass.

Two main process configurations are considered in this paper: centralized biomass gasification (CBG) and distributed biomass processing (DBP). Distributed processing is considered at three scales: 5.4 tons per day ("on-farm"), 55 tons per day ("small co-op"), and 550 tons per day ("large co-op"). These distributed pyrolyzer sizes were chosen as representative of potential fast pyrolysis applications as well technology availability. For example, processing 5.4 tons of biomass per day would consume the output of an average size Iowa farm (355 acres) [28] yielding 5 ton/acre of biomass crop.

Plant capital costs follow a power law commonly known as economies of scale that dictates decreasing costs with increasing plant capacity. This relationship is expressed as:

$$C_p = C_{po}\left(M \middle/ M_o \right)^n \tag{1}$$

where C_{po} is capital cost for a plant of annual fuel production capacity M_o and n is the scale factor, which is usually taken to be about 0.6 (the "sixth-tenth rule). Linear scaling (n = 1.0), which implies that capital costs per unit of production is invariant with the size of the plant, favors the construction of smaller plants to achieve the lowest fuel production costs.[1] Linear scaling might be achieved through mass production, which would require processing plants small enough to be factory assembled or field assembled from a few modular subsystems. Anecdotal evidence suggests a factory assembled or modular plant might be as large as a few tens of tons of biomass per day, setting the upper bound on the size of a plant that could be mass produced and achieve linear scaling. In this analysis, large plants (biomass gasification and large co-op) follow a 0.6

scale factor while the 5.4 tpd and 55 tpd distributed pyrolysis plants employ linear scaling.

Table 10 Biorefinery Capital Cost Components Based on Reference Plant Size*

Gasification + FT **(35 MMGPY FTL)**[7]	Cost (millions)	**Fast Pyrolysis** **(28 MMGPY Bio-oil)**[27]	Cost (millions)
Pre-treatment	$71.6	Handling and Drying	$5.57
Gasifier	$61.4	Pyrolysis Reactor	$3.92
Oxygen Plant	$51.1	Quench	$1.94
Cleaning Section	$61.4	Heat Recovery	$1.14
Shift	$3.41	Product Recovery and Storage	$0.80
FT Reactor	$20.5	Recycle	$1.38
Gas Turbine	$23.9	Steam and Power Production	$3.16
Heat Recovery Steam Generator	$37.5	Utilities	$3.13
Other	$10.2	Contingency	$7.37
Total	$341	**Total**	$28.4

*** Only total capital costs employed in scaling calculations**

Operating costs typically involve various components of which some are specific to certain processes. To determine the annual feedstock cost for a given fuel output, the first step is to calculate the amount of biomass required:

$$F = {}^{M\ E_G}\big/_{\eta_{BTF}\ E_B} \qquad (2)$$

where F is the total biomass input in units of tons per year, E_G and E_B represent the energy content of gasoline and biomass respectively, and η_{BTF} is the biomass to liquid fuel efficiency. The plant capacity *M* is given in units of gallons of gasoline equivalent (gge) per year and converted to energy units by a factor of 31.8 MJ per gallon of gasoline. The biomass energy value assumed here is 19.5 MJ/kg. The value of η_{BTF} is process dependent and has a value of 46% for biomass to Fischer Tropsch liquids and 40% for biomass to Fischer Tropsch liquids with fast pyrolysis processing. The farm-gate cost of feedstock is assumed to be $40 per ton for all concepts. Other plant operating cost components are process dependent and include items such as maintenance and labor charges. A full listing of all estimated process cost components and their calculation methods are included inTable 11 and Table 12.

Table 11 Biomass Gasification Annual Operating Cost Components Based on Reference Plant Sizea

Gasification + FT (35 MMGPY)	Cost (millions)	Explanation
Capital Charge	\$44.4	13% of TCI
Maintenance	\$10.2	3% of TCI
Personnel	\$2.22	Linear scaling
Dolomite	\$1.06	Linear scaling
Waste water	\$1.03	Linear scaling
ZnO consumption	\$0.03	\$33.3k/year
FT cat. Insurance	\$0.44	1% Ann Dep.
Key Parameter	Parameter Value	Explanation
Biomass to Fuel Efficiency	46%	MJ FTL per MJ Biomass
Bio-oil to Fuel Efficiency[b]	58%	MJ FTL per MJ Bio-oil
FTL Energy Value	36	MJ per Liter

[a]Farm gate feedstock cost of \$40 per ton for all concepts
[b]All data comes from Ref. [7] except for Bio-oil to Fuel Efficiency which comes from Ref [13]

The charcoal byproduct from fast pyrolysis has the potential of becoming an important revenue stream. Establishing a long-term carbon price is a speculative process at this time even though some markets have seen significant activity.[29] A \$50/ton credit is assigned to charcoal production, which assumes the charcoal (85% carbon) has value as a carbon sequestration agent equivalent to \$16/ton carbon dioxide. The charcoal, which contains various inorganic compounds, also has potential as fertilizer[30] and soil organic matter,21 but this has not been factored into the charcoal credit.

Table 12 Biomass Fast Pyrolysis Annual Operating Cost Components Based on Reference Plant Size[a]

Fast Pyrolysis (28 MMGPY)	Cost (millions)	Explanation
Water Treatment	\$1.00	Linear scaling
Electricity (credit)	\$0.21	Linear scaling
Labor	\$1.34	0.6 power law scaling
Overhead	\$0.80	60% Labor
Maintenance	\$0.57	2% Equip.
Insurance/ Taxes	\$0.72	1.5% TCI
Charcoal (credit)	\$1.92	\$50/ton
Key Parameter	Parameter Value	Explanation
Biomass to Bio-oil Efficiency	69%	MJ Bio-oil per MJ Biomass
Char yield	16.2%	Kg Char per Kg Biomass
Bio-oil Energy Value	19.7	MJ per Liter

aAll data adapted from Ref. [27] except for Charcoal (credit) which comes from Ref.[29]

For the centralized biomass processing case, the average delivery distance to the central plant from a circular area surrounding the central plant is given by:

$$\bar{r}_{circle} = \frac{2}{3}\tau\sqrt{\frac{F}{\pi Y f}} \qquad (3)$$

where τ is the tortuosity factor, which is a function of a region's road development and reflects the ratio of actual distance traveled to the straight line distance to a location.[31] A tortuosity factor of 1 corresponds therefore to a straight line trajectory between two given points. A value of 1.5 is assumed here, which is characteristic of a rectangular grid road layout. Y is the biomass yield in tons per acre. The factor *f* is the fraction of land surrounding the plant that is devoted to biomass crops. The exact value is site specific and depends upon land availability, environmental concerns, and other local considerations; here a value of 60% is assumed. Once the average delivery distance is calculated, it is multiplied by a unit cost for biomass transportation (\$0.71[32] per ton per mile).

For the distributed biomass processing case, a square grid is assumed around the centralized bio-oil processing plant with distributed pyrolysis plants located at the center of the squares making up the grid. The average biomass transportation distance to a pyrolysis plant is equal to the average distance from a random point in the square to the center of the square:[33]

$$\bar{r}_{square} = \frac{1}{6}\tau\sqrt{\frac{F}{Y\,f}}\left(\sqrt{2}+\ln(1+\sqrt{2})\right) \tag{4}$$

Also needed is the average distance that bio-oil must be shipped from distributed pyrolysis plants to the centralized bio-oil processing plant. This quantity depends upon the amount of biomass that must be converted to bio-oil and the size of the distributed pyrolysis plants, as shown in Figure 3. From this figure a power law for calculating bio-oil transportation distance was determined:

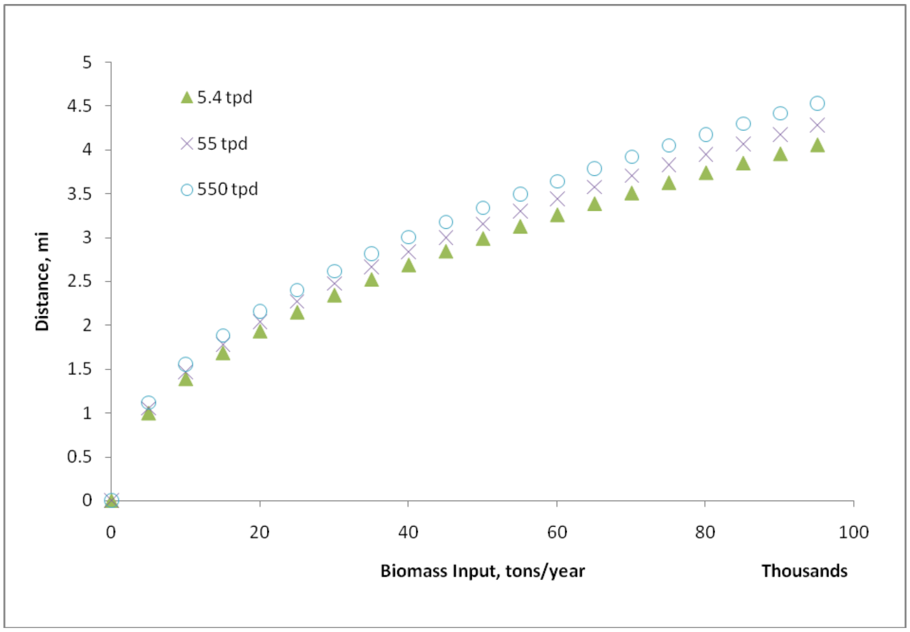

Figure 13 Average Bio-oil Delivery Distance to Central Plant

$$\bar{r}_{grid} = 0.423\tau\left(\frac{F}{F_{Plant}}\right)^{0.476}\sqrt{\frac{F_{Plant}}{Y\,f}} \tag{5}$$

A larger mass of bio-oil can be transported than biomass by a single truck by virtue of its higher volumetric density. This is reflected in a lower bio-oil unit transportation cost. The unit cost for bio-oil transportation is assumed to be $0.14 per ton per mile.[34]

Using the above information on processing costs and transportation costs, the unit cost of biofuel as a function of total fuel output was calculated for centralized biomass processing and distributed biomass processing with subsequent centralized upgrading to FTL. As described in a previous paper, an optimal size for minimum fuel production costs is expected[1].

Results

Figure 14 plots fuel cost as a function of fuel production capacity for centralized biomass gasification (CBG) and three scales of distributed biomass processing (DBP). CBG has a clearly discernable minimum cost of $1.56 for fuel production that occurs at a fuel production capacity of 550 million gge. From Figure 14, fuel cost for DBP appears to decrease monotonically with increasing fuel production capacity. In fact, DBP also has optimal plant sizes, but these occur at fuel production capacities well in excess of 2.5 billion gge. Fuel cost also decreases for DBP as the size of the distributed pyrolyzers gets smaller. For sufficiently large fuel production capacity, DBP is more cost-effective than CBG. This occurs at 450 million gge for 5.4 tpd pyrolyzers and 700 million gge for 550 tpd pyrolysis plants.

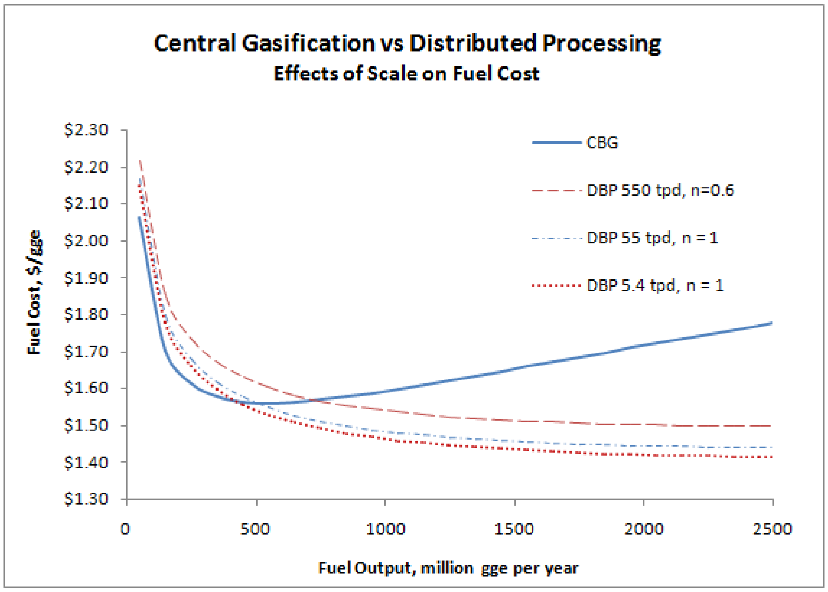

Figure 14 Fuel Production Cost at Different Plant Sizes for Central and Distributed Processing

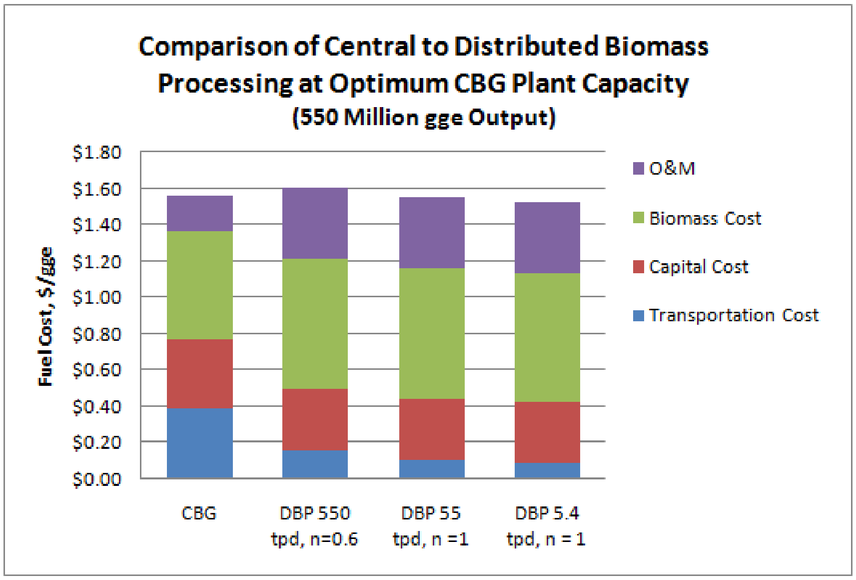

Figure 15 Operating Cost Components at Optimum Centralized Processing Output Size

Figure 15 shows the major cost components for the four biomass processing scenarios for total fuel production capacity of 550 million gge which is the optimum capacity for the centralized biomass processing concept. Differences in fuel costs are essentially indistinguishable for these four scenarios at this capacity (± 30% uncertainty), however, there are major differences in the distribution of major cost components for CBG and

DBP. O&M costs are lower for CBG because of favorable economies of scale. Biomass costs are also lower for CBG because a centralized plant has higher thermodynamic efficiencies. On the other hand, transportation costs for DBP are less than half that of CBG because of the short distances that biomass has to be hauled for a distributed system (0.56 miles compared to 37 miles). Keep in mind that as total fuel capacity increases beyond 550 million gge, biomass transportation costs for CBG balloons while it increases only modestly for DBP because transportation costs per mile for bio-oil is only 20% the cost of biomass transportation. This difference in transportation costs also explains why distributed processing employing the smallest pyrolyzers (5.4 tpd) yielded the lowest production costs shown in Figure 5.

Table 4 summarizes capital costs for the four biofuel production systems. Capital costs for the 550 million gge CBG plant totals $1.63 billion. Capital costs for the centralized bio-oil plant in the DBP system is only $1.6 billion because of the simpler feedstock handling system for bio-oil compared to biomass. Of course, the distributed pyrolyzers required for DBP add substantially to the capitals cost of this approach to biofuels. Large coop pyrolyzers (550 tpd) cost $47.8 million each which comes to a $2.63 billion investment for the pyrolyzers alone. Total capital cost of DBP employing large coop pyrolyzers would come to $4.1 billion. The small coop pyrolyzer and on-farm pyrolyzer systems have identical aggregate costs within a 5% uncertainty

Table 13 Capital Costs for Centralized and Distributed Plant Scenarios at 550 Million gge Capacity

	CBG	**DBP**	
	Central	Central	Distributed
Number of Plants	1	1	55
Capital Cost (billions)	$1.6	$1.4	$2.6
Total	$1.6	$4.1	

Capital costs for DBP based on 550, 55, and 5.4 tpd pyrolyzers are identical within ±5% uncertainty

A sensitivity analysis was conducted to study the effects of key variables. These are biomass yield, fuel conversion efficiency, transportation cost. Charcoal credit sensitivity was included in the pyrolysis technologies analysis. While there are numerous factors that could greatly affect the cost of BTL fuels, the impact of these selected variables can easily be studied in this model for both CBG and DBP. Figure 16 includes the results of this analysis.

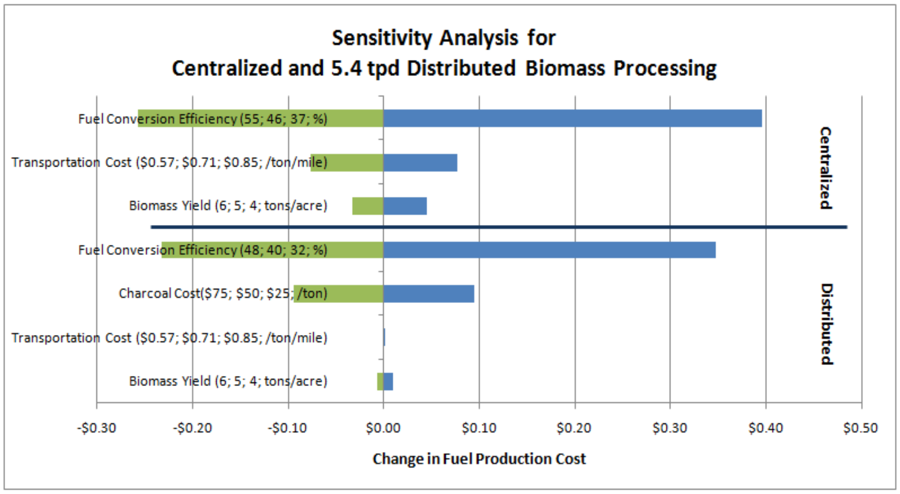

Figure 16 Sensitivity Analysis of 550 million gge for Centralized and 5.4 tpd Distributed Processing

As shown in Figure 16, there are various factors that can significantly affect the cost of biofuel production. Fuel conversion efficiency, a reflection of process performance, indicates that improving conversion efficiency from 46 to 55% can reduce fuel costs by $0.25 per gallon produced for centralized biomass processing. Due to the large biomass delivery distances that CBP would require, it is no surprise that a 20% increase in transportation costs can increase fuel production costs by $0.08 per gge (from $1.56 to $1.64 per gge). In this analysis, low crop yields would be require an increase in the area of cropland employed to grow biomass which would raise the biomass delivery distance and subsequently production costs. A 20% decrease in crop yields would raise fuel production costs by $0.04 per gge. DBP has a markedly lower sensitivity to transportation costs and biomass yields due to the reduction in average biomass delivery distances. In fact, a 20% increase in biomass delivery costs would only increase DBP fuel costs a bit more than a tenth of a cent per gge. DBP is affected by process efficiency with potential $0.23 per gge reduction in cost for 20% increase in process efficiency. Charcoal cost also stands to have a significant impact on fuel costs; a 50% variation in the cost of charcoal assumed here would alter fuel costs by $0.09 per gallon. These results underscore the importance of process efficiency as well as mark the vulnerability of a centralized biomass processing scenario to variations in the biomass harvesting and transportation system.

Conclusions

Distributed processing of biomass to bio-oil followed by gasification of the bio-oil and catalytic conversion of syngas to FTL offers production cost advantages over a more traditional system of centralized biomass gasification and F-T synthesis at fuel production capacities exceeding 550 million gge per year. Higher operation and biomass costs of the distributed processing system are off-set by much lower transportation costs of bio-oil compared to biomass. An additional advantage of distributed processing is a low sensitivity to variations in delivery costs and crop yields. This is important because delivery costs are hard to predict due to variations in transportation fuel costs, and regional considerations.

On the other hand, the distributed processing system comes at much higher capital cost than the centralized biomass processing system. Capital costs will be a major factor in future technology selection. Distributed processing incurs a large capital expense that will require solid financing and long-term commitments.

As shown in this analysis, large scale production of transportation fuel from biomass will require large investments in the order of billions of dollars. Distributed processing of biomass could be necessary at large production scales to lower fuel transportation costs, and reduction in capital investment expenses would allow for a faster implementation of these advanced biomass conversion pathways.

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General Conclusions

General Discussions

Advanced biorenewable technologies show great promise as a substitute to fossil-based transportation fuels. The low cost of petroleum has limited the development and adoption of biomass derived chemicals. Increases in the cost of petroleum as well as public awareness of the benefits of a biorenewable society are creating renewed opportunities for biofuels. If the rise in the price of oil, now over $90 a barrel, constitutes a long –term trend, investment in alternatives will increase. As the perceived value of the additional benefits of a biorenewable society increases, the adoption of alternatives could occur more rapidly than market conditions would dictate.

As shown in this study, advanced biorenewable plants require large capital investments. Without guarantees in the long –term price of oil, investors have been reluctant to invest these large amounts of money. A reduction in the capital costs would attract entrepreneurial interest. Reductions can be achieved through research and development as well as public policy. Current policies, such as the ethanol subsidy, favor the traditional biochemical approach and less capital intensive solutions. The adoption of advanced technologies with better efficiencies, environmental impacts, and economical returns will benefit from an appreciation of these benefits.

Other challenges exist in the adoption of biomass based fuels. Some of these challenges have been discussed in this study. Cost and availability of feedstock could become a problem as output capacity increases. Infrastructure challenges that include fuel delivery and engine compatibility will need to be addressed. Exploring the biofuel technoeconomic issues should help provide solutions that would advance the adoption of biorenewable technologies in a sustainable and responsible manner.

Recommendations

Biorenewable technologies continue to evolve and different pathways gain increased interest as new developments are discovered. These new developments will have to be compared to other technologies based on both their technical and economical merits. Some of the more recent developments include the hybrid concepts, new chemicals of interest, and scenarios such as various distributed systems. Due to the high risk inherent in the investment of unproven technologies, technoeconomic studies of promising solutions need to improve to better forecast the related costs and benefits.

Process design tools that model various technical and economical aspects of chemical processes are available. These tools are currently not optimized to deal with biomass based processes, but as research in this area increases these tools can be expected to improve. The accuracy in the results of technoeconomic studies will improve as additional information regarding biomass properties and conversion performance become available from both academia and industry.

The aim of this study was to provide a general framework for the discussion of biorenewable fuel technologies. The ±30% uncertainty in these kinds of analyses requires that specific applications be analyzed much further. On the other hand, general analysis can help shape public policy and guide investment in research. Publishing these tools in a variety of media could help increase awareness and usefulness of the results. For example, simple software packages that are made publically available for rapid comparison of available and new fuel technologies can be envisioned. It is possible to reach larger audiences, which are becoming more interested in alternatives to petroleum, by providing these studies in formats that are easy to understand and adopt.

Appendix

The appendix includes all the spreadsheet tables employed in this study and are arranged based on the studies supported by the results. Equations and calculations have been included in each of the articles.

Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms

Table 14 Summary of Capital Costs of Biorefineries (150 MMGPY gge)

Fuel Type	Base Size [gallons of gasoline equivalent/year]	Final Size [gallons of gasoline equivalent/year]	Base Total Capital Investment	Final Total Capital Investment (2005 $)	Final Total Capital Investment [$/bpd]
Grain Ethanol	16,666,667	150,000,000	$27,900,000	$126,272,390	$12,728
Cellulosic Ethanol	33,524,570	150,000,000	$294,000,000	$755,624,446	$76,167
Methanol	43,390,372	150,000,000	$254,350,000	$658,052,637	$66,332
Hydrogen	47,892,242	150,000,000	$244,320,000	$589,898,987	$59,462
Fischer-Tropsch	40,425,842	150,000,000	$341,000,000	$853,801,492	$86,063

Table 15 Summary of Operating Costs of Biorefineries (150 MMGPY gge)

Fuel Type	Fuel Cost [$/gallon of gasoline equivalent] 2005 Dollars	Capital Costs	Biomass	Operation and Management	Miscellaneous/Credits
Grain Ethanol	**$1.22**	$0.08	$1.27	$0.36	-$0.49
Cellulosic Ethanol	**$1.76**	$0.50	$1.06	$0.20	
Methanol	**$1.28**	$0.52	$0.79	$0.18	-$0.20
Hydrogen	**$1.05**	$0.39	$0.71	$0.16	-$0.21
Fischer-Tropsch	**$1.80**	$0.61	$0.90	$0.29	

Table 16 Summary of Base Case Operating Cost Components

Grain Ethanol	17 MMGPY	**Cellulosic Ethanol**	34 MMGPY
Shelled Corn	$17.0	Feedstock	$36.3
Other Raw Materials	$1.6	O&M Variable	$8.1
Denaturant	$0.6	O&M Fixed	$12.1
Utilities	$4.0	Capital	$36.3
Labor, Supplies, and Overhead Expenses	$3.1	Power	-$4.0
Depreciation of Capital	$2.8		
DDG Credit -	-$7.1		
Total Production Cost	$22.0		$88.7
Methanol	43 MMGPY	**Hydrogen**	48 MMGPY
Capital (MUS$)	$30.2	Capital (MUS$)	$29.0
O&M	$10.2	O&M	$9.8
Biomass	$24.8	Biomass	$24.7
Costs/income power	-$8.7	Costs/income power	-$9.9
Total Production Cost	$56.5		$53.6
Diesel	40 MMGPY		
Biomass	$29.2		
O&M	$14.6		
Investment Costs	$43.8		
Total Production Cost	$87.5		

Table 17 Grain Ethanol Base Case Costs

Base Size	25,000,000	25,000,000	gal Ethanol/year
Final Size	25,000,000	225,000,000	gal Ethanol/year
Base Total Capital Investment	$27,900,000	$27,900,000	
Final Total Capital Investment	$27,900,000	$111,372,248	
Scale Factor	0.63	0.63	
Shelled Corn	$17,000,000	$2.12	$167,368,421
Other Raw Materials	$1,600,000	$0.06	$13,500,000
Denaturant	$600,000	$0.03	$6,750,000
Utilities	$4,000,000	14%	$15,592,115
Labor, Supplies and Overhead Expenses	$3,100,000	11%	$12,250,947
Depreciation of Capital	$2,800,000	10%	$11,137,225
DDG Credit	-$7,100,000	-$0.29	-$65,250,000
Total Operating Cost	$22,000,000.00	$2.27	$161,348,708
Operating Cost	$0.88	$0.72	$/gallon of Ethanol
	$1.32	$1.08	$/gallon of gasoline eq
	$1.50	$1.22	(2005) $/gallon of gasoline equivalent
CPI (Base Year 2005)	0.882	0.882	2000

Table 18 Lignocellulosic Ethanol Capital and Operating Costs

Base Total Capital Investment	$294,000,000	
Final Total Capital Investment	$755,624,446	
Scale Factor	0.63	
Efficiency	35%	efficiency to fuel
Base capital cost	$2.10	$/W of ethanol
Base size	400,000,000	W
Final size	1,789,732,143	W
Base Biomass Input	2000	ton/day
Final Biomass Input	8949	ton/day
Biomass Cost	$158,531,945	
Operational Costs		
Maintenance	$22,668,733	0.03
Labour	$4,783,719	0.005
Gas Cleaning	$377,812	0.005
Insurance	$755,624	0.001
Sub-total	$28,585,889	
Consumables		
Dilute Acid	$7,338	$.82/tonne biomass input
Lime	$7,785	$.87/tonne biomass input
Cellulase	$515,137	$.013/L ethanol
Ammonia	$589,634	$.24/kg, consumption of .062kg/l ethanol
CSL	$681,566	$.20/kg, consumption of .086kg/l ethanol
Dolomite	$10,629	$50/tonne, consumption of .3kg/kg clean dry wood
Sub-total	$1,812,090	
Capital Cost	$75,562,445	
Total	$264,492,369	
Operating Cost	$1.18	$/gal of ethanol
	$1.76	2005 $/gal of gasoline equivalent
	$13.21	$/GJ
Biomass Cost	50	$/English ton
Conversions Factors		
1	0.907	English ton
1.5	1	gallon of gasoline
89,000,000	1	gallon of ethanol

Table 19 Methanol Capital and Operating Costs

Base total capital investment	254,350,000	254,350,000	
Final total capital investment		606,066,479	
Scale Factor		0.7	
Efficiency to fuel		45.3%	
Efficiency to power		8.5%	
Operation Time		8000	hr
Base size	400,000,000	400,000,000	W
Final size		1,382,795,254	W
Base Biomass Input	80	80	dry ton/hr
Final Biomass Input		277	dry ton/hr
Operational Costs			
Capital	$30,233,333	$72,051,769	Annual Capital cost calculated from Hamelinck
Operation and management	$10,166,667	$24,242,659	4% of total capital investment
Biomass	$24,666,667	$108,876,489	$50/English Ton
Costs/income power	-$8,633,333	-$28,043,088	$.03/kWh and 12.4% power efficiency
Total	$56,483,333	$177,127,829	$
Operating Cost		$0.59	$/gal of methanol
		$1.18	$/gal of gasoline eq
		$1.28	2005 $/gal of gasoline eq
	$10.37	$9.82	$/GJ of Fuel produced
Biomass cost	$50	dollars/English ton	
Power cost/credit	$0.03	dollars/kWh	
Conversions Factors			
1	tonne	0.907	English ton
56800	BTU	1	gallon of Methanol
114000	BTU	1	gallon of gasoline

1055	Joules	1	BTU
CPI		0.921	2002
59924000	1.107491857		
1.018708			

Table 20 Hydrogen Operating and Capital Costs

Base total capital investment	$244,320,000	$244,320,000	
Final total capital investment		$543,296,967	
Scale Factor		0.7	
Efficiency to fuel		50.0%	
		9.6%	
		8000	hr
Base size	400,000,000	400,000,000	W
Final size		1,252,812,500	W
Base Biomass Input		80	dry ton/hr
Final Biomass Input		251	dry ton/hr
Operational Costs			
Capital	$29,400,000	$54,329,697	Annual Capital cost calculated from Hamelinck
Operation and management	$9,760,000	$21,731,879	4% of total capital investment
Biomass	$24,700,000	$98,642,099	$50/English Ton
Costs/income power	-$9,880,000	-$28,985,070	$.03/kWh and 12.4% power eff.
Total	$53,580,000	$145,718,605	$
Operating Cost		$0.26	$/gal of hydrogen
		$0.97	$/gal of gasoline eq
		$1.05	2005 $/gal of gasoline eq
	$9.05	$8.08	$/GJ of Fuel produced
Biomass cost	$50	dollars/English ton	

Power cost/credit	$0.03	dollars/kWh	
Conversion Factors			
1	tonne	0.907	English ton
30000	BTU	1	gallon of hydrogen
114000	BTU	1	gallon of gasoline
1055	Joules	1	BTU
CPI		0.921	2002
31650000			
0.16458	0.178697068		

Table 21 Fischer-Tropsch Capital and Operating Costs

Base Total Capital Investment	341,000,000			
Final Total Capital Investment	853,801,492			
Scale Factor	0.7			
Efficiency to fuel	0.46			
Operation time	8000	h		
Base size	168,820,000	W	40,425,842	gal of gasoline/year
Final size	626,406,250	W	150,000,000	gal of gasoline equivalent/year
Base Biomass Input	367,000,000	W	684,386	English ton/year
Final Biomass Input	1,361,752,717	W	2,539,413	English ton/year
Basis	427000000	Watts input		
Annual Depreciation	$85,380,149	10% of Total capital investment		
Operational Costs				
Maintenance	$25,614,045	3% of Total capital investment		
Personnel	$8,192,840	0.7MUS$/100 MW	367 MW input for basis	
Dolomite	$3,905,560	$47.6/tonne	25728 tonne input for basis	
Waste-water treatment	$2,944,022	0.21MUS$/75 MW	367 MW input for basis	
ZnO	$33,300	33.3 KUS$/year		
FT cat. Consumption insurance	$853,801			
Operational Costs	$41,543,569			
Biomass	$126,970,666			

Total	$253,894,383.34			
Operating Cost	$1.95	$/gal of Diesel		
	$1.69	$/gal of gasoline equivalent		
	$1.80	2005 $/gal of gasoline eq.		
Biomass Cost	50	$/English Ton		
Conversion Factors				
131000	BTU/gal of Diesel			
114000	BTU/gal of gasoline			
0.94	CPI			

Establishing the Optimal Sizes of Different Kinds of Biorefineries

Table 22 Base Case Values for Optimal Plant Size Calculations

Fuel Type	**M_0**	**Biomass Input (million)**	**C_{Po} (million)**	**C_{Do} (million)**	**C_{Fo} (million)**	**C_T (million)**	**C_T/M_o**	**R**
Grain Ethanol	25.0	0.25	$5.0	$1.1	$18.6	$24.8	$0.99	0.23
Cellulosic Ethanol	69.6	0.93	$52.5	$20.4	$21.3	$94.2	$1.35	0.39
Methanol	88	0.64	$40.4	$14.1	$14.7	$69.2	$0.78	0.35
Hydrogen	182.0	0.64	$38.8	$14.1	$14.7	$67.6	$0.37	0.36
Fischer-Tropsch	35.2	0.59	$54.6	$12.9	$13.5	$81.0	$2.30	0.24
Fast Pyrolysis	1.0	7.50	$438.6	$165.0	$172.5	$776.1	$776.10	0.38

🟦 Squares can be varied

Fuel Type	**Transportation Cost [$/ton]**	Biomass Cost	**Plant Scale Factor (n)**	**Transportation Scale Factor (m)**	**Calculation Plant Start Size**	**Step Size**	**Largest Size Estimated**	
Grain Ethanol	$4.64	75.71	0.60	1.5	80	1	107	
Cellulosic Ethanol	$22.0	23	0.60	1.5	80	1	134	
Methanol	$22.0	23	0.60	1.5	80	3	242	
Hydrogen	$22.0	23	0.60	1.5	80	10	620	
Fischer-Tropsch	$22.0	23	0.60	1.5	80	3	242	
Fast Pyrolysis	$22.0	23	0.60	1.5	10	1	37	

Table 23Optimal Plant Sizes Results (Note: not same as published results)

Study Case

Grain Ethanol	100.5	0.99	$11.5	$9.2	$74.9	$95.6	$0.95
Cellulosic Ethanol	134.0	1.78	$77.8	$54.4	$41.0	$173.2	$1.29
Methanol	221.0	1.60	$70.1	$55.7	$36.8	$162.6	$0.74
Hydrogen	440.0	1.55	$65.9	$14.1	$35.6	$115.6	$0.26
Fischer-Tropsch	137.0	2.29	$123.3	$12.9	$52.6	$188.8	$1.38
Fast Pyrolysis	20.0	150.00	$2,646.6	$165.0	$3,450.0	$313.1	$2.01

Optimum Case

Fuel Type	**Mo**	**Biomass Input (million Ton)**	**Cpo (million)**	**Cdo (million)**	**Cfo (million)**	**Ct (million)**	**Ct/Mo ($/gal of gas eq.)**	
Grain Ethanol	101	0.99	$11.5	$9.2	$74.9	$20.7	$0.95	0.80
Cellulosic Ethanol	134	1.78	$77.8	$54.4	$41.0	$132.2	$1.29	0.70
Methanol	221	1.60	$70.1	$55.7	$36.8	$125.8	$0.74	0.80
Hydrogen	440	1.55	$65.9	$52.9	$35.6	$118.9	$0.35	0.80
Fischer-Tropsch	137	2.29	$123.3	$99.2	$52.6	$222.6	$2.01	0.80
Fast Pyrolysis	10	75.00	$1,746.1	$5,217.8	$1,725.0	$6,963.9	$696.39	2.99

Distributed Processing of Biomass to Bio-Oil for Subsequent Production of Fischer-Tropsch Liquids

Table 24 Summary Results of Distributed Biomass Processing and Central Gasification

Input

Case	**CG**	**DP550**	**DP55**	**DP5.4**	**DG**
Bio Energy Gasified [MW]	4986	5687	5687	5687	4986
Total Output [MMGPY gge]	**550.00**	**550.00**	**550.00**	**550.00**	**550.00**
Number of Plants		55	541	5502	1
Biomass Input (tpd per plant)		540	55	5.4	

Case	**CBG**	**DBP 550 tpd, n=0.6**	**DBP 55 tpd, n =1**	**DBP 5.4 tpd, n = 1**	
Transportation Cost	0.38	0.15	0.10	0.09	0.38
Capital Cost	0.39	0.34	0.34	0.34	0.39
Biomass Cost	0.59	0.72	0.72	0.72	0.59
O&M	0.20	0.39	0.39	0.39	0.20
Total Cost	1.56	1.60	1.55	1.53	
Capital Costs (billions)	$1.63	$4.05	$4.03	$4.03	$1.42

Table 25 Totals of Distributed Pyrolysis Units Operating Costs

Totals for	55	plants	
Biomass Cost	$396,141,814	0.72	
Biomass transportation	$38,418,243	0.07	
Operation and management	$125,770,935	0.23	
	$560,330,992	1.02	$/gal of FT Diesel
		0.37	$/gal of Bio-oil

Table 26 Centralized Gasification Operating and Capital Costs

Base Plant Size	367	MW
Plant Size	4986	MW
Plant Efficiency	0.46	
Plant operation time	8000	hr
FT Diesel	2293.545658	MW
	1,809,206,107	Liters Diesel/year
	550,000,000	gge
Biomass input	7,363,892,415	kg/year
	7,363,892	tonne/year
	8,117,344	English ton/year
Switchgrass production	3,200	tons/mi^2
	6,342	mi^2/year
Base Plant TCI	$341,000,000	$
Final Plant TCI	$1,631,565,358	$
Scale Factor	0.6	
Production Costs		
Biomass Cost	$324,693,773	40
Annual Depreciation	$212,103,496	
Maintenance	$48,946,961	
Personnel	$29,997,550	
Dolomite	$14,299,955	
Waste water treatment	$13,960,713	
ZnO consumption	$33,300	
FT cat. Insurance	$2,121,035	
Total	$ 646,156,782	100%
Transportation Cost		
Yield [Y]	3,200	tons/mile^2
Available land [a]	0.60	
average direct distance x	24.5	miles
average delivery distance x	36.68	miles
Birrell's Model	0.71	$/ton/mile
Operating Costs	1.17	$/gge
	9.78	$/GJ input
Conversion Factors		
36.51	MJ/l of Diesel	
3.78	liters/gal	
1055	BTU/J	
19.5	MJ/kg of Biomass	

Table 27 Distributed Pyrolysis Units Capital and Operating Costs

Energy Production per FP Plant	72.00	MW		
Number of plants	55			
Capital Cost	$4,048,408,677			
Plant operation time	8000	hr		
Base Plant Cost	$48,291,646			
Base Equipment Cost	$28,410,000			
Base Electricity Credit	$(209,620)			
Base Biomass Input	550	dry tons/day		
Base Bio-oil production	28,354,185	gallons/year	4.54	Bio-oil density [kg/gal]
Base Labor Cost	$1,340,920	1340920		
Plant Cost	$47,773,158	$ 2,627,523,689	0.6	Scale Factor
Equipment Cost	$28,104,973		0.6	Scale Factor
Biomass input [dry basis]	540.2	tons/day	180,064	tons/year
Bio-Oil production	27,848,624	gallons/year	16.4	MJ/kg of bio-oil
Char production	37814	tons/year	0.21	g/g of feed
Feedstock	$7,202,578	40	$/dry ton	
Water treatment	$982,170			
Electricity	$ (205,882)			
Labor	$1,326,523	0.6	Scale Factor	
Overhead	$795,914	0.6	60% of Labor	
Maintenance	$562,099	0.02	2% of Equip. Cost	
Insurance/taxes	$716,597	0.015	1.5% of TPI	
Char Credit	$ (1,890,677)	-50	$/ton	
Operating Cost	$2,286,744	100%		
Switchgrass	5	tons/acre	1,234.57	tons/km
	90,032	acres/year	0.40	Area Conservation Fraction
Yield [Y]	3,200	tons/mile^2		
Available land [a]	0.60			
average delivery distance x	5.5	miles	1.5	tortuosity
Birrell Cost	$698,514	0.71	$/ton/mile	

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