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Biomass and Bioenergy 31 (2007) 416–425
BIOMASS & BIOENERGY
www.elsevier.com/locate/biombioe

Grain and cellulosic ethanol: History, economics, and energy policy

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Received 27 April 2006; received in revised form 14 November 2006; accepted 30 January 2007
Available online 13 March 2007

Abstract

The United States (US) and Brazil have been the two leading producers of fuel ethanol since the 1970s. National policies have supported the production and use of ethanol from corn and sugarcane. US support in particular has included exemption from federal gasoline excise taxes, whole or partial exemption from road use (sales) taxes in nine states, a federal production tax credit, and a federal blender's credit. In the last decade the subsidization of grain-based ethanol has been increasingly criticized as economically inefficient and of questionable social benefit. In addition, much greater production of ethanol from corn may conflict with food production needs. A promising development is the acceleration of the technical readiness of cellulosic alcohol fuels, which can be produced from the woody parts of trees and plants, perennial grasses, or residues. This technology is now being commercialized and has greater long-term potential than grain ethanol. Cellulosic ethanol is projected to be much more cost-effective, environmentally beneficial, and have a greater energy output to input ratio than grain ethanol. The technology is being developed in North America, Brazil, Japan and Europe. In this paper, we will review the historical evolution of US federal and state energy policy support for and the currently attractive economics of the production and use of ethanol from biomass. The various energy and economic policies will be reviewed and assessed for their potential effects on cellulosic ethanol development relative to gasoline in the US.

Keywords: Biomass; Cellulosic ethanol; Corn; Energy Policy Act; Excise tax; Gasohol; MTBE

1. Introduction

While US interest in fuel ethanol has grown since the oil crises of the 1970s, its use in gasoline blends accounted for only 2.8 percent of total fuel use in motor vehicles in 2005 [1]. Although ethanol (i.e., ethyl alcohol) has the advantage of being derived from domestic resources, its use for fuel has often been criticized as technically, economically and environmentally undesirable (see e.g., [2]). Even so, interest in alternative transportation fuels is growing for two main reasons: oil supply insecurity and its impending peak, and the imperative to lower carbon dioxide (CO_2) emissions from fossil fuel use in order to stave off adverse global climatic change [3,4].

Several alternative fuels and engines for the transport sector have been assessed in detail in recent years [5]. These include electric and hybrid-electric vehicles (HEVs), compressed natural gas (CNG), hydrogen-fuel cells, and biomass fuels. While electric and CNG vehicles are available on a small scale their driving range is limited, severely restricting their consumer appeal. Hydrogen-fuel cell vehicles exist as prototypes, but they are extremely expensive and will be impractical for a decade or more [6]. This leaves HEVs and biomass fuels as the most cost-effective alternatives to oil in the near term (Table 1 below lists the various acronyms used in this paper and explains what each stands for). HEVs are attractive, as they increase fuel use efficiency and thus help to stretch petroleum resources and lower CO_2 emissions. Only sustainable biomass fuels however, such as ethanol and bio-diesel, can directly decrease oil reliance.

There are several ways to make biomass fuels, as well as alternative alcohol products. For example, in the 1970s methyl alcohol (methanol) received as much consideration as ethanol. Both fuels can be produced from food crops and biomass, as well as from fossil fuels [7]. While methanol can be made at a lower cost than ethanol, some

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doi:10.1016/j.biombioe.2007.01.023

Table 1
Explanation of acronyms used within text

Acronym	Explanation of acronym
$	United States dollars
ADM	Archer Daniels Midland Company
$c\,l^{-1}$	Cents per litre
$c\,gal^{-1}$	Cents per US gallon
CAFE	Corporate average fuel economy
CNG	Compressed natural gas
CO_2	Carbon dioxide
DDGS	Distiller's dried grains with solubles
E20, E85, E95	Volume percentage ethanol in fuel
EPA	United States Environmental Protection Agency
EPAct	United States Energy Policy Act of 2005
ETA	United States Energy Tax Act of 1978
ETBE	Ethyl tertiary butyl ether
Gal	US gallon = 3.78541
HEVs	Hybrid-electric vehicles
Kg	Kilogram
L	Litre
Mg	10^6 g or 1 tonne
MTBE	Methyl tertiary butyl ether
RFS	Renewable fuel standard
VEETC	Volumetric ethanol excise tax credit

refiners over-blended or used improper blending and handling techniques. This led to consumer and media problems and the eventual phase-out of almost all methanol/gasoline blends, with its use largely restricted to several auto races. Even here, the Indy Racing League announced in March 2005 that the Indianapolis 500 auto race plans to switch its cars from methanol to 100 percent ethanol fuel by 2007 [8]. Similarly, methanol caught on as a feedstock for production of methyl tertiary butyl ether (MTBE) under Clean Air Act requirements for 2.0–2.7 percent oxygen blends in ozone and carbon monoxide non-attainment areas. However, MTBE has been at least partially banned in half of the US states in the last several years because of groundwater toxicity problems, although over half of these states never used it [9,10]. Alternatively, interest has grown in coupling methanol with fuel cells as a transitional fuel until sufficient hydrogen production capacity becomes available [5]. Nonetheless, the main markets for methanol are for formaldehyde, acetic acid and other chemicals. Another promising option is biodiesel (FAME fatty acid methyl esters), which is made from vegetable oil or animal fats. Biodiesel has similar benefits as cellulosic ethanol, as noted below, but is limited to diesel engines.

There are two primary technologies to make ethanol fuel. The first option, in wide use today, is to convert the starchy part of foods such as corn into ethanol through the following seven steps: milling, liquefaction, saccharification, fermentation, distillation, dehydration and denaturing. When sugarcane is used (e.g. in Brazil) only four or five steps are required: milling, pressing, fermentation and distillation, plus dehydration in the case of alcohol blends. The other option is lignocellulosic or cellulosic ethanol, which is currently being commercialized. This process converts the woody part of trees, plants, grasses or residues into sugars and then ferments the sugars into ethanol.

Over 95 percent of ethanol production in the US comes from corn, with the rest made from wheat, barley, milo, cheese whey, and beverage residues [11]. This path to ethanol production has been criticized, often erroneously, for having an unfavorable net energy balance and significant arable land and water requirements [12]. While corn-based ethanol has several important environmental impacts, including soil erosion, loss of biodiversity, and higher volatile organic compound and NO_x pollution, it does result in a positive energy return on investment and a 10–15 percent reduction in CO_2 emissions (cf. [2,4,12–14]). These results are more favorable for sugarcane-based ethanol in Brazil [15]. Given land use concerns it is unlikely that grain ethanol can grow from its current US output of $19\,hm^3$ (5.1 Ggal (Giga = 10^9)) $year^{-1}$ to much more than three times that level, even with increased agricultural productivity [11]. For one thing, over half of the US corn crop is needed as feed grain for livestock as compared to 17 percent for ethanol [16].

Fortunately cellulosic ethanol has the potential to be superior on all of these dimensions except for conventional air pollution. Its advantages are that it can reduce net CO_2 emissions to almost zero, and that it can be derived from a diverse, widespread resource base (see e.g., [3]). For instance, it can be made from tree species such as hybrid poplar, willow, silver maple and black locust; wood residues including chips and sawdust; construction site residues, municipal residues (MSW), paper and sewage sludge; corn stover, corn and sugarcane processing residues; cereal straws such as wheat, oat, barley and rice; and grasses such as switchgrass, sorghum, reed canary grass, and miscanthus.

The purpose of this paper is to assess the progress and evolution of the ethanol industry from one based largely on corn and sugarcane to one that we expect will be increasingly based on cellulosic materials, and tracking ethanol's position in the US relative to gasoline. The next section traces the development of ethanol fuel from its consideration in the early stages of the automobile industry to its use as a substitute liquid fuel today in the US, Brazil and elsewhere. This will be followed by a review of the simple economics of ethanol fuel production. The next section will consider several federal and state policy instruments that have been used in the ethanol industry, including a variety of tax credits and the newly enacted US Renewable Fuel Standard. The paper will close with some preliminary conclusions about the future of ethanol development and use and the efficacy of public policies.

2. Historical development

Ethanol and ethanol–gasoline blends have a long history as automotive fuels [17,18]. In the late 1800s for example, Henry Ford, Nicholas Otto and others built engines and cars that could run on ethanol. Ford equipped his Model T in 1908 as a flexible fuel vehicle, with carburetors that could be adjusted to use alcohol, gasoline, or a "gasohol" mix. The need for fuel during World War I increased the demand for ethanol in the US to 0.19–0.23 hm^3 (550–60 Mgal) year^{-1}. Demand decreased after the War because gasoline became the motor fuel of choice, but there was a continued interest (e.g., from General Motors Corporation and DuPont) in ethanol as both an anti-knock agent (i.e., octane enhancer) and as a possible replacement for petroleum fuels. The discovery of the anti-knock properties of tetraethyl lead in 1921 dampened some of the enthusiasm for ethanol, and despite persistent health concerns, sales of leaded gasoline increased dramatically in subsequent years. Alcohol blended fuels enjoyed a brief resurgence in the mid 1930s as falling corn prices prompted Midwestern states to seek alternative uses for their farm products. During this period, various alcohol–gasoline blends were marketed under trademarked names such as Alcolene and Agrol. The latter brand, with blends ranging from 5 to 17.5 percent alcohol, was sold in over 2000 retails outlets from Indiana to South Dakota during the late 1930s. After World War II however, interest in ethanol waned because leaded gasoline proved cheaper and easier to produce while new oil discoveries reduced the perceived urgency of finding petroleum substitutes [18].

The fuel ethanol market was revived in the 1970s. First, Brazil developed a crash "Proalcool" Program in 1975 based on sugarcane in response to the 1973 OPEC Arab oil embargo. Over half of the cars in Brazil ran on 95 percent anhydrous ethanol (E95) in the late 1980s, though a late 1980s sugar shortage and price hikes have reduced that figure to where it is today, at 20 percent of flex-fuel cars. Still, all of the gasoline sold in Brazil today must have at least a 25 percent anhydrous alcohol blend (E20). Ethanol currently comprises about 40 percent of the total vehicle fuel used within the country [19]. Brazil also exported over 0.38 hm^3 (100 Mgal) of ethanol to both India and the US in 2005 [20].

Although the US rebuilt its fuel ethanol industry more gradually than Brazil, the two nations are today the world leaders in its production and usage (Table 2). The US Energy Tax Act of 1978 (ETA) officially defined gasohol as a blend of gasoline with at least 10 percent non-fossil fuel based ethanol by volume. The ETA exempted ethanol from the 1.1 $\mathrm{c\,l}^{-1}$ (4.0 $\mathrm{c\,gal}^{-1}$) excise tax on gasoline, which equaled a 10.5 $\mathrm{c\,l}^{-1}$ (40.0 $\mathrm{c\,gal}^{-1}$) subsidy for ethanol [7]. After peaking at 15.8 $\mathrm{c\,l}^{-1}$ (60.0 $\mathrm{c\,gal}^{-1}$) in the mid to late 1980s, this excise tax exemption was reduced to 13.4 $\mathrm{c\,l}^{-1}$ (51.0 $\mathrm{c\,gal}^{-1}$) of ethanol in 2005 [22].

Table 2
Top ten ethanol producing nations capacity in hm^3 (Ggal) year^{-1}

Nation	2004	2005
Brazil	15 (4)	16 (4.2)
US	13 (3.4)	15 (3.9)
China	3.7 (0.96)	3.8 (1.0)
India	1.8 (0.46)	1.7 (0.45)
France	0.84 (0.22)	0.91 (0.24)
Russia	0.76 (0.2)	0.76 (0.2)
Germany	0.27 (0.07)	0.43 (0.11)
South Africa	0.42 (0.11)	0.38 (0.10)
Spain	0.30 (0.08)	0.35 (0.09)
UK	0.42 (0.08)	0.35 (0.09)

Source: [21].

After the 1980s leaded gasoline phase-out by the US Environmental Protection Agency (EPA), interest increased in using ethanol as an octane booster and volume extender. However, MTBE dominated most oxygenated gasoline markets over ethyl tertiary butyl ether (ETBE) throughout the 1990s. While the commercial ethanol industry was small at this time, in 1980 Congress approved several more tax benefits, as well as loan and price guarantees, to support ethanol producers and blenders. The growth of this industry was again stymied by low gasoline prices following the oil price collapse of the mid 1980s.

The Energy Policy Act of 1992 contributed to increased usage of ethanol blends by requiring specified (primarily government-owned) car fleets to begin purchasing alternative fuel and flex-fuel vehicles. Such vehicles had to be capable of operating on E85, which is a blend of 85 percent ethanol and 15 percent gasoline. In the private sector, the production of alternative fuel vehicles was promoted by the Alternative Motor Fuels of Act of 1988, which provided auto companies with credits against their compliance requirements under the Corporate Average Fuel Economy (CAFE) standards for each flex-fuel or alternative fuel vehicle they produced [22]. In reality, the initiative had little effect on the use of alternative fuels because at the time few fuel retailers offered E85. For this reason, the program was frequently criticized as a mechanism for automakers to avoid CAFE requirements while being ineffective at supporting purchases of E85 [23]. Even today, the estimated five million of such vehicles on the road rely primarily on gasoline alone because only one thousand US retail outlets sell E85 [24]. Even so, US annual ethanol production passed the 3.8 hm^3 (1.0 billion gallon) mark in 1992 (Fig. 1). Continued low gasoline prices in the early 1990s, coupled with weak corn harvests and the doubling of corn prices, led several Midwestern states to approve new subsidies to keep the struggling ethanol industry solvent. In 1996 total ethanol production nonetheless declined by 1.1 hm^3 from the 1995 level, reducing output back to the 1992 level [25].

For the US ethanol industry the last decade has been far different. Ethanol production recovered, consolidated, and grew rapidly, with total 2005 output triple that of 1997 (Fig. 1). The industry today has a low four-firm concentration ratio of 32 percent although one firm, Archer Daniels Midland (ADM), accounts for 19 percent of total production (down from 75 percent in 1990). ADM operates distilleries in several Great Plains and North Central states. The facilities are close to large corn farms,

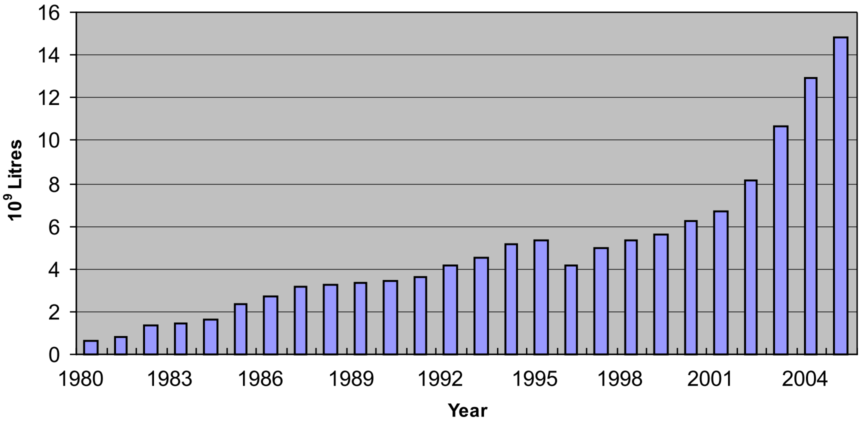

Fig. 1. US grain ethanol production, 1980–2005 [21].

Table 3
Leading ethanol producers in the US in 2006

Company	States(s)	Capacity hm^3 (Ggal) year^{-1}
Archer Daniels Midland	IL, IA, NE, MN, ND	4.1 (1.1)
VeraSun Energy	SD, IA	0.87 (0.23)[a]
Hawkeye Renewables	IA	0.84 (0.22)
Aventine Renewable Energy	IL, NE	0.57 (0.15)[b]
Cargill, Inc.	NE, IA	0.46 (0.12)
Abengoa Bioenergy	NE, KS, NM	0.42 (0.11)[c]
New Energy Corp.	IN	0.38 (0.10)
Global Ethanol/Midwest Grain Processors	IA, MI	0.36 (0.095)[d]
Total US Capacity		19.0 (5.1)

Source: [21].

[a] A 0.42 hm^3 year^{-1} expansion at a South Dakota plant is under construction.

[b] A 0.22 hm^3 year^{-1} expansion at an Illinois plant is under construction.

[c] A new 0.33 hm^3 year^{-1} plant in Nebraska is under construction.

[d] A 0.22 hm^3 year^{-1} plant in Michigan is under construction.

as well as most of the major ethanol consuming states outside of California (Tables 3 and 4). Conversely, 43 percent of the industry's 114 mills are owned by family-farm cooperatives [21].

The rapid growth in US ethanol production and use, especially since 2002, can be directly attributed to increasing restrictions on MTBE as a fuel oxygenate (Fig. 1 and Table 3). For example, MTBE bans in California, New York, and Connecticut, states that had accounted for a total of 42 percent of national MTBE consumption, took effect on January 1, 2004 [9]. In addition, the oxygen requirement for reformulated gasoline was repealed under the Energy Policy Act of 2005 (EPAct). Accelerated growth in ethanol production will continue at least through 2012 because of the Renewable Fuel Standard approved under EPAct, to be discussed below [27].

Table 4
Top ten ethanol-consuming states in the US capacity in hm^3 (Ggal) year^{-1}

State	2003	2004
California	2.2 (0.59)	3.4 (0.9)
Illinois	1.5 (0.39)	1.6 (0.42)
New York	0.084 (0.022)	1.2 (0.3)
Minnesota	1.0 (0.28)	1.1 (0.28)
Ohio	0.7 (0.18)	0.73 (0.19)
Michigan	0.57 (0.15)	0.63 (0.17)
Connecticut	0.076 (0.02)	0.6 (0.16)
Indiana	0.5 (0.13)	0.53 (0.14)
Iowa	0.4 (0.10)	0.44 (0.12)
Wisconsin	0.41 (0.11)	0.41 (0.11)

Source: [26].

3. Economics of ethanol production

Existing ethanol plants have varied in size from 1500 m^3 to 1.0 hm^3 (400,000 to 270 Mgal) year^{-1} of production capacity (ADM owns the largest plants, in Illinois and Iowa) and are highly capital-intensive. About 80 percent of production, including at all recent plants, occurs in anhydrous (dry grind) mills, with the rest made from wet mills [11]. The main cost components are capital and the feedstock supply. Given the proprietary nature of much ethanol corporate cost data, it is difficult to precisely model the production technology. This uncertainty extends to the degree of or lack of substitutability among factor inputs (i.e., capital, labor, energy, materials, water) and economies of scale, with the latter having been found to be highly variable in the dry mill industry [28]. Thus rather than modeling grain ethanol production technology with a Cobb-Douglas, Leontiff or CES format, we will posit a simpler equation [7]:

$$C_{\mathrm{A}} = \mathrm{C}_{\mathrm{C}}/2.75 + C_{\mathrm{K}} + C_{\mathrm{L}} + C_{\mathrm{E}} + C_{\mathrm{M}} + C_{\mathrm{O}} - (P_{\mathrm{DDGS}}(0.0005)(6.5)), \quad (1)$$

where C_A is the cost of ethyl alcohol production (\$ gal^{-1}); C_C the cost of corn (\$ bushel^{-1}); C_K the cost of capital investment; C_L the cost of labor; C_E the cost of energy; C_M the cost of raw materials; C_O the other costs, including maintenance, overhead, water, residue disposal, insurance, taxes, regulatory compliance; and P_{DDGS} the price of distiller's dried grains with solubles (DDGS) co-product to be sold (\$ short-ton^{-1}); and assuming 2.75 gal bushel^{-1} ethanol yield, i.e. 410 l t^{-1} for an anhydrous grain ethanol plant, with the coproduction of 0.8 kg l^{-1} (6.5 lb gal^{-1}) dried distillers grains and solubles (DDGS).

An average size, dry mill ethanol plant of 0.19 hm^3 (50 Mgal) year^{-1} requires about \$65–\$100 million in capital costs, employs 30–50 people and has \$45–60 million in annual operating costs [11]. The average wholesale, spot market price for grain ethanol in Illinois was 0.63 \$ l^{-1} (\$2.40 gal^{-1}) in August 2006 [29]. While this was 4.2 c l^{-1} (16.0 c gal^{-1}) higher than the August 2006 average oil refiner sales price of 0.59 \$ l^{-1} (\$2.24 gal^{-1}) for gasoline in the US [30], over 90 percent of ethanol production is sold under much lower long-term contract prices of around 0.37–0.39 \$ l^{-1} (\$1.40–1.50 gal^{-1}) [21]. Ethanol production in Brazil has been generally less expensive than in the US since the 1970s given the more simplified processing of sugarcane vs. grain, and the availability of free fuel in the form of bagasse (see e.g., [31]). The importation of cheap ethanol from Brazil into the US has been restricted since 1980, however, by a 14 c l^{-1} (54 c gal^{-1}) tariff on imports of foreign-produced ethanol. Even so, Brazil accounted for almost 90 percent of the ethanol imported into the US in 2005, most of it indirectly through Central American and Caribbean nations [21].

The potential supply of lignocellulosic biomass sources for ethanol is far greater than that of food crops, but development has been impeded by the greater recalcitrance of biomass materials to be hydrolyzed into sugars. However, recent developments by Genencor International and Novozymes Biotech have resulted in up to a 30-fold drop in the cost of enzymes for hydrolysis, to 2.6–5.3 c l^{-1} (10–20 c gal^{-1}) of ethanol [32, p. 62]. Thus, cellulosic ethanol has the potential to compete on a large scale with gasoline without subsidies in the next decade. Testing has occurred in over a dozen pilot plants and numerous commercial plants are being developed. While most of these facilities are in the US, several are being sited in Canada, Brazil, Europe and Japan (Tables 5 and 6).

Several technology configurations are being actively researched and developed to produce ethanol from cellulosic biomass. These include dilute sulfuric acid and enzymatic hydrolysis, gasification, fast pyrolysis, and concentrated acid processes [33]. Pretreatment is also needed to break apart the biomass structure to allow for efficient hydrolysis of cellulosic sugars, and several technologies can be employed. Based on Lynd [34], Wyman [35] and Hamelinck et al. [36] the reference technology assumed is dilute acid pretreatment and

Table 5
Cellulosic ethanol pilot and demonstration plants

Company	Location	Feedstock	Capacity or feed rate	Start date
Pilot plants				
Iogen	Ottawa, Canada	Wood chips	9.0×10^2 kg day^{-1}	1985
Iogen	Ottawa, Canada	Wheat straw	9.0×10^2 kg day^{-1}	1993
Masada/TVA	Muscle Shoals, AL	Wood	NA	1993
SunOpta	Norval, Canada	Various (non-woody)	4.5×10^2 kg h^{-1}	1995
Arkenol	Orange, CA	Various	9.0×10^2 kg day^{-1}	1995
Bioengineering Resources	Fayetteville, AR	Softwood & bark	NA	1998
NREL/DOE	Golden, CO	Corn stover, others	9.0×10^2 kg day^{-1}	2001
Pearson Technologies	Aberdeen, MS	Wood residues, rice straw	27 Mg day^{-1}	2001
NEDO	Izumi, Japan	Wood chips	3.0×10^2 l day^{-1}	2002
Dedini	Pirassununga, Brazil	Bagasse	1600 m^3 year^{-1}	2002
Tsukishima Kikai Co.	Ichikawa, Chiba, Japan	Wood residues	9.0×10^2 kg d^{-1}	2003
Etek EtanolTeknik	Ornskoldsvik, Sweden	Spruce sawdust	5.0×10^2 l day^{-1}	2004
PureVision	Ft. Lupton, CO	Corn stover, bagasse	9.0×10 kg day^{-1}	2004
Universal Entech	Phoenix, AZ	Municipal garbage	1.0×10^2 l day^{-1}	2004
Sicco A/S	Odense, Denmark	Wheat straw	1.0×10^2 kg h^{-1}	2005
Abengoa Bioenergy	York, NE	Corn stover (co-located with grain ethanol plant)	2000 m^3 year^{-1}	2006
Demonstration plants				
Iogen	Ottawa, Canada	Wheat, oat and barley straw	3000 m^3 year^{-1}	2004
ClearFuels Technology	Kauai, HI	Bagasse and wood residues	11,400 m^3 year^{-1}	2007
Celunol	Jennings, LA	Bagasse, rice hulls (co-located with grain ethanol plant)	5000 m^3 year^{-1}	2007
Etek EtanolTeknik	Sweden	Softwood residues (spruce and pine)	30,000 m^3 year^{-1}	2009

Source: [37].

Table 6
Near-term cellulosic ethanol commercial plants, capacity in $m^3\,year^{-1}$

Company	Location	Feedstock	Capacity	Date
Bioethanol Japan Kansai	Sakai, Japan	Construction wood residues	$1.4–4.0 \times 10^3$	2007
Abengoa Bioenergy & SunOpta	Babilafuente, Spain	Wheat straw (co-located w/grain ethanol plant)	5.0×10^3	2007
Iogen	Shelley, ID	Wheat, barley and rice straw	110×10^3	2008
Xethanol & Spring Hope	Spring Hope, NC	Hardwood chips, wood residues, other	130×10^3	2007
BioFuels Xethanol & Coastal	Augusta, GA	Wood residues, other	190×10^3	2007
Maui Ethanol	Kauai, HI	Bagasse	45×10^3	2007
Dedini	Brazil	Bagasse	20×10^3	2007
Colusa Biomass Energy	Colusa, CA	Rice straw and hulls, corn stover	38×10^3	2007
Future Fuels	Toms River, NJ	Wood residues, other	200×10^3	2008
Genahol	Orrville, OH	Municipal garbage	15×10^3	2008
Pencor-Masada OxyNol	Middletown, NY	Municipal garbage	34×10^3	2008

Source: [37].

enzymatic hydrolysis of cellulose, since it offers the best near-term potential for commercialization competitive with fuel ethanol from grain.

A revision of Eq. (1) for cellulosic ethanol can be expressed as:

$$C_A = C_B/95 + C_K + C_L + C_E + C_M + C_O - P_P, \tag{2}$$

where C_A is the cost of ethyl alcohol production ($\$\,gal^{-1}$); C_B the cost of the biomass feedstock ($\$$ dry short ton^{-1}); C_K the cost of capital investment; C_L the cost of labor; C_E the cost of energy; C_M the cost of raw materials; C_O the other costs, including maintenance, overhead, water, residue disposal, insurance, property taxes, regulatory compliance; and P_P the price of excess electric power byproduct to be sold ($cent\,kWh^{-1}$); and assuming $400\,l\,Mg^{-1}$ (95 gal dry short ton^{-1}) of biomass feedstock for an anhydrous cellulosic ethanol plant [33].

Earlier cost estimates and projections for cellulosic ethanol production have been modified and updated to 2006 dollars in Table 7 based on the $250 million capital investment projections of Iogen Corp. of Canada, which plans to build a $0.11\,hm^3$ (30 Mgal) $year^{-1}$ commercial plant in 2007–2008 in Eastern Idaho, US. An additional construction expense of $50+ million will be incurred since 500 construction workers will be needed to build the plant over 2 years. An economic lifetime of 15 years is assumed for the reference cellulosic ethanol mill. Given the lack of commercial experience thus far the capital cost may decrease over time, as scale economies are expected but yet unknown [33,36]. The largest capital cost components are for feedstock pretreatment, at 17 percent; simultaneous saccharification and fermentation, at 15 percent (which can also be done in separate vessels); and energy utilities, at 36 percent (for boilers and turbogenerators, although excess electricity production can be sold off-site).

For ethanol production the major wholesale cost components are the annualized capital charge, at 40 percent of the total; and the feedstock and other raw materials, at 46 percent. A total production cost of $6.3\,c\,l^{-1}$ ($24\,c\,g^{-1}$) below the spot price of grain ethanol and 8 cents below the gasoline price is calculated, at $0.57\ \$\ l^{-1}$ ($\$2.16\,gal^{-1}$) (Table 8). While this cost estimate has not been confirmed with commercial experience, this finding is encouraging.

Table 7
Estimated capital investment cost for a $220 \times 10^3\,m^3$ (58 Mg) $year^{-1}$ cellulosic ethanol plant[a]

Cost category	Million $ (2006)
Feedstock handling (wood or switchgrass)	12.7
Pretreatment	41.9
Xylose fermentation	10.9
Cellulase production	5.0
Simulataneous saccharification and fermentation	37.0
Ethanol recovery	7.1
Off-site tankage	7.2
Environmental systems	7.0
Utilities (steam, electricity, water)	90.0
Miscellaneous	8.5
Fixed capital investment	227.3
Start-up costs	11.4
Working capital	11.3
Total capital investment	250.0

Source: Adapted and updated from [35, Table 1, p. 199].

[a] The original study assumed a rather conservative ethanol production rate of $345\,l\,Mg^{-1}$ (83 gal dry short ton^{-1}) of wood based on a plant feed rate of 1.7 Gg day (1900 short ton day^{-1}).

Several factors could further lower the production cost of cellulosic ethanol. These include the use of cheap residues for biomass feedstocks lacking other markets, low-cost debt financing, or integration into a biorefinery platform to increase the product mix to include higher-value chemical co-products [35,38]. The latter option could potentially increase ethanol yields and further enhance economic competitiveness.

Table 8
Estimated cost of cellulosic ethanol production (year 2006 dollars)

Cost category	M\$ year^{-1}	c l^{-1} (c gal^{-1})
Feedstock (wood or switchgrass)[a]	39.85	18.2 (69.0)
Enzymes	11.50	5.3 (20.0)
Other raw materials (sulfuric acid, lime, glucose, nutrients)	5.67	2.6 (9.8)
Gypsum disposal	0.59	0.26 (1.0)
Electricity	(4.88)	−2.2 (−8.3)
Water	0.21	0.11 (0.4)
Labor/supervision	2.33	1.06 (4.0)
Maintenance	7.70	3.49 (13.2)
Direct overhead	1.42	0.63 (2.4)
General overhead	7.04	3.17 (12.0)
Insurance & property taxes	3.86	1.74 (6.6)
Total cash costs	75.29	34.37 (130.1)
Annualized capital charge[b]	50.00	22.59 (85.5)
Total production cost	125.29	56.96 (215.6)

Source: Adapted and updated from [35, Table 2, p. 200].

[a] The costs of the feedstock, other raw materials (except for enzymes), residue disposal, energy, water, and labor have been updated based on growth in the producer price index for pulp, paper and allied products between 1990 and 2006, calculated from [39]; all other cost categories have been updated based on the total capital investment requirements.

[b] 20 percent of total capital investment, and assuming a 10 percent after-tax rate of return on capital investment.

4. Federal and state energy policy instruments

Given the marginal economics but potentially large social benefits of ethanol development, government subsidies and other support mechanisms have been a consistent and essential part of the US ethanol industry for 30 years. Subsidies have taken several forms at the federal and state government levels, stimulating both supply and demand for the product, and sometimes prompting considerable criticism [2,40,41]. Because of the numerous support mechanisms that have been in effect since 1979 it is difficult to tease out the impact of any single policy instrument. The following discussion provides a brief history of US government support for ethanol, a more detailed look at some recent changes and, when possible, an assessment of the relative importance of these instruments.

4.1. Federal support

Three basic government initiatives fueled the early years of the modern fuel (i.e., corn) ethanol industry. The first and most important of these was a partial exemption from the federal gasoline excise tax for gasohol (a fuel containing at least a 10 percent component of biomass-derived ethanol). This exemption was instituted by the Energy Tax Act of 1978, and implemented in 1979 [7]. A fuel blender's tax credit and a pure alcohol fuel credit were added to the mix in 1980. These new initiatives were in essence the same subsidy as the fuel excise tax exemption, but recouped through a different system and available to a small number of companies who were unable to claim the fuel tax exemption. Through subsequent years, all three of the tax provisions were periodically renewed and altered in terms of the benefit magnitude, with changes in one being mirrored by changes in the others. For a variety of reasons, most notably its ease of use, the excise tax exemption has been by far the most widely used incentive (double crediting with the fuel blender's tax credit is not permitted) with total government revenue impacts estimated at between 16 and 56 times those of the other two tax credits combined [42]. Thus it was by far the most important of early ethanol support mechanisms and it remains of paramount importance to the ethanol industry.

Further federal support came in 1990 with passage of the Small Ethanol Producer Tax Credit, which provided small plants ($<0.11\,\mathrm{hm}^3$ (30 Mgal) year^{-1} production capacity) with an additional 0.026 \$ l^{-1} (\$0.10 gal^{-1}) income tax credit for volumes up to 57,000 m^3 (15 Mgal) year^{-1} [22]. The EP Act [27], discussed below, redefined small producers as those producing up to 0.23 hm^3 (60 Mgal) year^{-1}. In recent years the total combined federal support for ethanol has equaled a taxpayer subsidy of \$3.8 billion per year [42].

The period from 1978 to 2004 had little fundamental change to the main component of federal support, the excise tax exemption. Benefit levels increased and decreased several times, culminating in a progressive reduction from 0.14 \$ l^{-1} (\$0.54 gal^{-1}) to 0.13 \$ l^{-1} (\$0.51 gal^{-1}) of ethanol during 1998–2005 as a result of the Transportation Equity Act of 1998. In 2004 however, the basic mechanics of the subsidy were changed by the introduction of the Volumetric Ethanol Excise Tax Credit (VEETC). The VEETC streamlined the system by making it volume based rather than limited to specific blends, eliminated negative impacts on the Highway Trust Fund by taking the credit from general government revenues and renewed the subsidy until 2010 at 0.13 \$ l^{-1} of ethanol [21].

The EPAct has several important incentive provisions that will usher in a new era of renewable fuels, where *corn ethanol* is no longer synonymous with *ethanol* [27]. Cellulosic ethanol, although presently still in the pre-commercial stage, receives a considerable amount of attention from this legislation, garnering subsidies over and above that for traditional ethanol production. Even so, the most widely publicized provision of EPAct, the Renewable Fuel Standard (RFS), applies to both corn and cellulosic ethanol and will operate in the place of the now eliminated oxygenate requirement for reformulated gasoline. Implementation of the RFS begins in 2006 at 15 hm^3 (4.0 Ggal) year^{-1} (which was almost met in 2005), increasing to 28 hm^3 (7.5 Ggal) year^{-1} in 2012. In light of the current market for fuel ethanol EPAct provides only a modest boost to production. However the crediting procedure is unique in that it values residues and cellulose-derived ethanol at a ratio of 2.5:1 compared to corn ethanol, and requires a minimum of 0.95 hm^3 (250 Mgal) of the total be derived from cellulosic sources in 2013. Furthermore, the EPAct sets an annual production goal of 3.8 hm^3 of cellulosic ethanol by 2015, to be brought about in part by an additional production incentive (as yet undefined) separate from the VEETC [27].

Additional provisions are designed to improve commercialization prospects for the new technology through increased R&D funding in all aspects of the industry, including feedstock development, processing technology, co-product production, and systems optimization [43]. Project financing and funding, considered by many to be a major bottleneck [34,36,44], receives attention as well through a series of grants and loan guarantees for biorefinery development and commercialization [27]. The overall effect of the legislation is manifold, providing an essential short-term boost to accelerate commercialization and technological development, while also attempting to cement a place for the new technology in the longer-term ethanol market. Implicit in this is the assumption that cellulosic ethanol is capable of providing larger societal benefits than corn ethanol, although in the near future, corn ethanol will still dominate the market.

4.2. State support

During the revival of the US ethanol industry in the late 1970s over a dozen state governments were quick to approve partial or total gasohol exemptions from state road use taxes. These included producer states in the Midwest such as Iowa, but also southern states such as Louisiana, Arkansas and Oklahoma (Louisiana repealed its tax exemption in 1989). These state programs are generally similar to the federal programs, and as of 2004 thirty-six states were supporting ethanol development [22]. By 2005, nine states had some level of excise tax exemption (including Minnesota, which only offers the exemption for 85 percent fuel blends) [44]. Producer credits were offered in eleven additional states: a $2 million payment per plant is offered in Montana if state grains are used; and several other states offered grants, loan programs, or tax exemptions [22].

The policy environment in Minnesota has been heralded as especially effective, combining measures that support both production and consumption of ethanol. Instrumental to this has been a 1997 state requirement that all gasoline sold in the State must have a 10 percent ethanol content. An increase to a 20 percent mandate was approved in Minnesota in 2005 (which would take effect in 2012), pending EPA approval [44]. Similar laws that mandate a 10 percent ethanol-blended fuel were passed in Hawaii and Montana in 2005 (which took effect in 2006), and Missouri and Washington in 2006 (which will take effect in 2008–2009) [21]. Despite the pace of new policy development in other states, Minnesota continues to be far ahead of the field in most respects. By virtue of a state fuel tax exemption on E85 and an ethanol production payment of 0.05 $ l^{-1} ($0.20 gal^{-1}), it also boasts the most extensive E85 infrastructure in the country, with 300 retail outlets. Illinois has the second largest infrastructure, with almost half as many [24].

Additionally (as noted earlier), the 1990 Clean Air Act Amendments stimulated demand for ethanol by mandating the use of oxygenated fuels in many carbon monoxide and ozone non-attainment areas. In the several Midwestern states where ethanol production is concentrated, ethanol has become the primary oxygenate used for this purpose, while others such as California gravitated towards the more readily available MTBE [22]. Recent revelations about the toxic effects of MTBE and its accumulation in groundwater have led to it being partially or completely banned in half the states, including California and New York, further cementing the place of ethanol as a gasoline additive [10,21]. Moreover, the 2005 EPAct did *not* include liability protection for MTBE manufacturers. Thus, the future of ethanol production and use will depend upon a mix of federal and state support as well as technical and economic developments.

Table 9 summarizes the major components of government support for ethanol as of 2006. Through these

Table 9
Summary of current federal and state ethanol policy support mechanisms

Support mechanism	Description of subsidy
Fuel excise tax exemption (1978); replaced with VEETC (2004)	Currently renewed until 2010 at 0.13 $ l^{-1} ($0.51 gal^{-1}). The VEETC replaces the former fuel excise tax exemption, blender's credit, and pure alcohol fuel credit.
Small producer tax credit (1990)	Production credit of 2.6 $ l^{-1} ($0.10 gal^{-1}) for up to 5.7×10^4 m^3 (15 Mgal) for producers with annual production capacity of <0.23 hm^3 (60 Mgal).
Renewable fuel standard (2005)	Requires gasoline blending with 15 hm^3 (4.0 Ggal) ethanol in 2006, increasing gradually to 29 hm^3 (7.5 Ggal)) in 2012. Cellulosic and residue-derived ethanol credited at a ratio of 2.5:1.0 in relation to grain ethanol
Cellulosic ethanol production incentive (2005)	Magnitude undetermined but this incentive operates in addition to the VEETC
State incentives (variable) in 36 states	Excise tax exemptions, producer credits, producer payments, property tax exemptions, grants, loans, financing assistance, etc.
10% ethanol mandates	Minnesota (1997), Hawaii and Montana (2006), Missouri (2008), Washington (2009)
MTBE bans in 20 states (since 2004)	Bans in California, New York and Connecticut have stimulated the greatest demand for ethanol as a substitute fuel oxygenate

programs ethanol producers receive an indirect subsidy of 0.13 $ l^{-1} (\$0.51 gal^{-1}) on all ethanol production; a 0.03 $ l^{-1} (\$0.10 gal^{-1}) subsidy on a portion of their production if they meet the small producer's criteria; an additional as yet unspecified production incentive if they use residues or cellulosic feedstocks; and they may be eligible for state incentives depending on their location. The effect of the RFS is difficult to monetize, but by stimulating ethanol demand, it provides an additional subsidy in the form of increased ethanol sale prices. Again, cellulosic ethanol producers will benefit more than corn ethanol producers by virtue of its higher crediting ratio under the RFS.

5. Conclusions

Ethanol production has a long history. During this time, production has had many peaks and valleys, although it is currently at the highest ever production levels. Each time production rose or fell it responded to complex combinations of changes in demand for competing products, incentive programs, and government mandated production levels. Current production is highest in Brazil and the US. Brazil's experience illustrates that it is possible to successfully mandate large-scale shifts to ethanol use. MTBE bans in half the US states, including the major markets of California, New York and Connecticut, are contributing significantly to record demand for ethanol (Table 4 and Fig. 1).

The fuel is also experiencing unprecedented levels of attention due to its value as an *alternative* to gasoline, with its problematic links to climate change, peak oil supply, rising oil prices, and Middle Eastern political instability. Cellulosic ethanol production, in particular, can result in a fuel with a net energy yield that is close to CO_2 neutral [45]. This makes it increasingly desirable as a gasoline alternative. We therefore expect demand for ethanol to substantially grow in future years, but do not expect corn alone to meet this demand.

Corn remains the largest source of US ethanol production, however this is likely to change as demand for this feedstock is expected to exceed supply and technological improvements in processing converge to lower the cost of cellulosic ethanol production [46]. In some ways, the growth in grain ethanol production has laid the groundwork for a shift into cellulosic ethanol production. For instance, the political power of US farm interests has built support for ongoing state and federal subsidies of grain ethanol. These supports are currently in place for all feedstocks, and there will be additional federal support for emergent cellulosic ethanol production.

Our analysis estimates that cellulosic ethanol production costs could be 6.3 c l^{-1} (24 c gal^{-1}) lower than gasoline. Thus while cellulosic ethanol production is not yet commercial (due to higher capital costs and immature technology) its potential price would be competitive today. The technology may thus become especially attractive in the coastal states that produce only small corn or other grain crops. Moreover, cellulosic ethanol may experience further cost decreases due to the use of inexpensive farm and forestry residue feedstocks. Even so, it is important to emphasize that price supports remain critical. Subsidies that recognize the social value of grain and cellulosic ethanol as alternatives to gasoline and as a domestic product will be essential to market success, along with the need to substitute for MTBE. Additional policy solutions aimed at discouraging reliance on gasoline might similarly increase the competitiveness of both corn and cellulosic ethanol.

Acknowledgments

This research was supported by the Biocomplexity Program of the National Science Foundation under Grant #BE/MUSES-0524872.

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