Market Penetration of Ethanol

Kenneth R. Szulczyk[1*], Bruce A. McCarl[2], and Gerald Cornforth[3]

[1]School of Business, 1099 President's Drive, Arkadelphia, AR 71999

[2]Department of Agricultural Economics, 2124 TAMU, Texas A&M University, College Station, TX 77843

[3]Department of Agricultural Economics, 2124 TAMU, Texas A&M University, College Station, TX 77843

*Author to whom correspondence should be addressed; E-mail: kszulczyk@hotmail.com

Abstract.

This research examines in detail the technology and economics of substituting ethanol for gasoline. This endeavor examines three issues. First, the benefits of ethanol/gasoline blends are examined, and then the technical problems of large-scale implementation of ethanol. Second, ethanol production possibilities are examined in detail from a variety of feedstocks and technologies. The feedstocks are the starch/sugar crops and crop residues, while the technologies are corn wet mill, dry-grind, and lignocellulosic fermentation. Examining in detail the production possibilities allows the researchers to identity the extent of technological change, production costs, byproducts, and GHG emissions. Finally, a U.S. agricultural model, FASOMGHG, is updated which predicts the market penetration of ethanol given technological progress, variety of technologies and feedstocks, market interactions, energy prices, and GHG prices.

FASOMGHG has several interesting results. First, gasoline prices have a small expansionary impact on the U.S. ethanol industry. Both agricultural producers' income and cost both increase with higher energy prices. If wholesale gasoline is $4 per gallon, the predicted ethanol market penetration attains 53% of U.S. gasoline consumption in 2030. Second, the corn wet mill remains an important industry for ethanol production, because this industry also produces corn oil, which could be converted to biodiesel. Third, GHG prices expand the ethanol industry. However, the GHG price expands the corn wet mill, but has an ambiguous impact on lignocellulosic ethanol. Feedstocks for lignocellulosic fermentation can also be burned with coal to generate electricity. Both industries are quite GHG efficient. Finally, U.S. government subsidies on biofuels have an expansionary impact on ethanol production, but may only increase market penetration by an additional 1% in 2030, which is approximately 6 billion gallons.

Keywords: Agricultural Sector Model, Alternative Energy, Ethanol, Emission Trading, Carbon-Equivalent Price

Abbreviations: CAAA – Clean Air Act Amendments; DDGS – Distillers Dried Grains with Solubles; EPA – Environmental Protection Agency; FASOMGHG – Forest and Agricultural Sector Optimization Model Greenhouse Gas; GHG – Greenhouse Gas; GWP – Global Warming Potential; HHV – higher heating value; IPCC – International Panel on Climate

Change; LHV – lower heating value; MTBE – methyl tertiary-butyl ether; USDA – United States Department of Agriculture

1 INTRODUCTION

Gasoline and diesel fuels are significant sources of greenhouse gas (GHG) emissions particularly carbon dioxide (US EPA 2008). Such emissions contribute to the greenhouse effect and climate change. Biofuels, like ethanol and biodiesel, replace fossil fuels and reduce carbon dioxide emissions by recycling carbon from the atmosphere, thus mitigating climate change. Biofuels have the following benefits:

- Biofuels are renewable
- For countries that import petroleum, biofuels could reduce petroleum imports, improve the balance of payments, improve national energy security, and reduce the reliance on petroleum from unstable areas of the world.
- If biofuels could be produced on a large scale and supplied elastically to the market, then biofuels can reduce demands for fossil fuels and could potentially constrain the growth in fossil fuel prices.
- Biofuels recycle carbon dioxide from the atmosphere and have cleaner tail pipe emissions. Moreover, biofuels contain oxygen that reduces emissions from hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and sulfur dioxide (SO_2), but tend to increase NOX emissions (Canakci 2007; Duffield et al. 1998; Fukuda, Kondo, and Noda 2001; Gerpen et al. 2004; Graboski and McCormick 1998; Hewlett et al. 1983; Kadam 2000; Nevin 2005; Sheehan et al. 1998; Srivastava and Prasad 2000).
- Biofuels could create stronger demands for feedstocks, thus boosting agricultural prices and producers' incomes.

2 ANALYSIS OF ETHANOL MARKET PENETRATION

Increased ethanol production seems likely to emerge in the near future. Ethanol production rapidly expanded from about 1.7 billion gallons in 2001 to over 6 billion gallons in 2006 (Nelson 2006). Several forces are creating a strong demand for ethanol and the rapid growth of this industry.

- The Environmental Protection Agency (EPA) phased out the use of methyl tertiary-butyl ether (MTBE). MTBE is an oxygenate and used a fuel additive. However, MTBE is carcinogenic that could accumulate in the water supply. For every two gallons of MTBE removed from the market, approximately one gallon of ethanol is needed as a substitute (Reynolds 2000).
- High petroleum prices are stimulating ethanol production. Petroleum is a depletable resource with a strong demand. Thus, the gasoline price should follow Hotelling's (1931) prices and tend to increase over time, as petroleum is depleted.
- Government mandates, such as the provisions of the Energy Independence and Security Act of 2007 (U.S. Government Printing Office 2007), include mandates of up to 36 million gallons of biofuels. Furthermore, the U.S. government passed regulations requiring petroleum refiners to add oxygenates like ethanol to gasoline fuels.
- The public and government's concern over global warming. The U.S. government has discussed the use of GHG emission price in a cap and trade system, such as in the Lieberman-Warner Climate Security Act of 2008 (The Library of Congress 2008).

Clearly, the confluence of these forces cannot be observed in today's world as we have never seen such high petroleum prices or a trade and cap system for GHG. Consequently, we employ an agricultural model that incorporates:

- Lifecycle and more generalized procedures that calculate the GHG offsets of biofuels. Economic simulation helps predict the impact of carbon dioxide equivalent prices on biofuel production.
- The agricultural model allows gasoline prices to change. Higher fuel prices raise agricultural production, but create a higher price for ethanol fuel.
- The simulation model can predict the impact on biofuels if the U.S. government removed the federal subsidies on biofuel.
- The agricultural mode also contains other renewable fuels such as biodiesel and co-firing crop and wood residues to generate electricity.

In doing this we follow a number of previous studies and followed studies on:

- Lifecycle accounting as in Wang, Saricks, and Santini (1999) or Mann and Spath (1997) doing our own analysis of GHG consequences
- Ways agriculture might modify production patterns in the face of GHG mitigation alternatives as in Adams et al. (1993), Callaway and McCarl (1996), McCarl and Schneider (2001), Antle et al. (2001), Lewandrowski et al. (2004), Lee, McCarl, and Gillig (2005), and US EPA (2005);
- Agriculture might alter production patterns in the face of higher energy prices as analyzed in Francl (1997), McCarl, Gowen and Yeats(1997), USDA Office of the Chief Economist (1999), Antle et al (1999), Konyar and Howitt (2000), and Schneider and McCarl (2003, 2005); and
- Agriculture might react to biofuel activities Tyner et al. (1979), McCarl et al. (2000), Schneider and McCarl (2005), Lee, McCarl, and Gillig (2005), and US EPA (2005).

3 ETHANOL FUEL AS A GASOLINE SUBSTITUE

Ethanol is not a perfect substitute for gasoline and hence this section examines the compatibility between these fuels. One of the most important properties for gasoline is a high vapor pressure. Vapor pressure is important for starting a cold engine, because some of the fuel has to vaporize easily and combusted in an engine (Leffler 1985, pp. 86-89). From Table 1, pure ethanol has a lower vapor pressure than gasoline (Gallagher et al. 2003; Lugar and Woolsey 1999). However, ethanol-gasoline blends have a complex vapor pressure relationship. E22 blends and below have a higher vapor pressure and easily evaporates into the atmosphere, thus these blends allow easy start up of engines (Lugar and Woolsey 1999; Gnansounou, Dauriat, and Wyman 2005; Nevin 2005; Reynolds 2000). However, the U.S. EPA sets a maximum vapor pressure for gasoline fuels. Blending ethanol with gasoline could increase vapor pressure above EPA's maximum. Consequently, gas distributors would have to purchase a more expensive lower vapor pressure gasoline in the summer, increasing gasoline costs[1] (Reynolds 2000).

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[1] Vapor pressure increases as the ambient temperature increases.

Table 1. Ethanol and Gasoline Fuel Properties

	Units	Gasoline	Pure Ethanol
Octane Number	100%	85 to 94	112.5 to 114
Reid Vapor Pressure	PSI	7.0 to 15.0	2.3
Higher Heating Value	BTU / Gal.	125,000	84,600
Lower Heating Value	BTU / Gal.	112,00 to 116,000	75,670 to 76,100

Sources: Davis and Diegel 2006; Gallagher et al. 2003; Reynolds 2000; Sheehan et al. 2004

Octane rating is another important fuel property. Octane rating is a measure of how much pressure and temperature is needed to ignite the fuel/air mixture. A low-octane gasoline causes premature fuel ignition, which places stress on engine parts and in some cases could damage the engine (Leffler 1985, pp. 90-95). From Table 1, pure ethanol has a higher octane level than gasoline. Moreover, petroleum refineries could reduce costs by producing a lower grade octane gasoline and mixing it with ethanol to increase octane rating (Gallagher et al. 2003; Hewlett et al. 1983; Reynolds 2000).

Ethanol contains less energy than gasoline. The lower energy content reduces torque, acceleration, and miles per gallon (Nevin 2005; Reynolds 2000). Car manufacturers may have to increase fuel tank sizes to compensate. Researchers use two energy values. The higher heating value (HHV) is the combustion energy including the energy to vaporize water, while the lower heating value (LHV) only includes the combustion energy (Gerpen et al. 2004; Hammerschlag 2006). The lower heating value is used, because the energy from vaporized water performs no work in the engine. From Table 1, one gallon of ethanol contains from 65.5% to 67.9% less energy than one gallon of gasoline.

Another restriction for ethanol is the current design of automobile engines. Ethanol could be blended with gasoline up to E15 without engine modification, whereas flexible fuel vehicles (which have modified engines) could use up to E85. (The "E" is for ethanol and the number refers to ethanol percentage by volume). Thus at this time, ethanol could never completely eliminate gasoline as a fuel.

Ethanol has three more potential problems. First, ethanol-gasoline blends separate in the presence of water and are difficult to remix (Nevin 2005; Reynolds 2000; Zerbe 1992), making ethanol blends difficult to store and transport, especially through pipelines (American Petroleum Institute 2006). Second, ethanol-gasoline blends can degrade some types of rubber and plastics, and may degrade some engine seals, especially in the fuel system (Nevin 2005). Finally, ethanol-gasoline blends dissolve carcinogenic substances from gasoline like benzene, toluene, ethylbenzene, and xylenes. The ethanol could steep from fuel lines at filling stations, carrying these substances with it potentially contaminating nearby soil. Moreover, ethanol-gasoline plumes tend to spread over a longer distance (Nevin 2005).

Despite some disadvantageous of using ethanol for a transportation fuel, it is also used as an oxygenate. The federal Clean Air Act Amendments (CAAA) of 1990 requires cities with high ozone concentrations or carbon monoxide emissions to add oxygenates to gasoline, because oxygenated gasoline have cleaner emissions (Gallagher et al. 2003; Nevin 2005; Rask 1998; Reynolds 2000; Zerbe 1992).

4 SECTORAL MODELING APPROACH

The agriculture sector is complex and highly interrelated. Previous analyses reveal a number of features that are needed in any analytical approach to reasonably assess biofuel production and associated GHG mitigation potential. Among these are

Biofuel production market and production interrelationships. Biofuel industry has impacts on other agricultural markets. For example, biofuel production levels influence cattle feeds for livestock production as well as how agricultural producers allocate land. This study utilizes an analytical approach that simultaneously depicts crop and livestock production, biofuel processing, the feeding of crop products to livestock, grazing, product substitution, competition for land, exports, imports and market price formation among other factors across the agricultural sector.

Representing Ethanol Production Possibilities. Different technologies exist to produce ethanol. The differences involve the way sugar is separated and created from the feedstock.

Multiple gas implications. Each stage in agricultural production either release or sequester greenhouse gases. The greenhouse gases are carbon dioxide, nitrous oxide, and methane.

Co-Benefits. Agricultural mitigation alternatives are frequently cited as win-win approaches as a number of the strategies generate GHG offsets while at the same time as achieving environmental quality gains in terms of reduced erosion and improved water quality.

Market/welfare implications. U.S. agriculture produces large quantities of a number of commodities relative to domestic needs and total global market volume. Variation in US production influences prices in these markets. Thus it is possible that US GHG mitigation policies will also affect domestic and world market prices along with the welfare of producers and consumers in those markets. The analytical approach used here includes a representation of domestic agricultural markets and their links to foreign markets.

The approach used to address these issues identified above is to simulate them in an agricultural model. The model used in this research is the Forest and Agricultural Sector Optimization Model Greenhouse Gas, hereafter referred to as FASOMGHG. This model has greenhouse gas accounting unified with a detailed representation of the possible mitigation strategies in the agricultural sector as adapted from Schneider (2000), Lee (2002) and McCarl and Schneider (2001) in addition to a number of recent updates that have improved the depiction of biofuel production possibilities.

FASOMGHG is a large mathematical programming, price endogenous model, and consists of approximately 120,000 variables, 800 nonlinear variables, and 9,500 constraints. FASOMGHG is written in the General Algebraic Modeling System (GAMS) and the GAMS solver, CPLEX, finds the optimal market prices that maximize the welfare from consumer' plus producers' surpluses for each market. FASOMGHG uses the Law of One Price, where any price differences between markets originate from transportation costs. With a large number of markets, FASOMGHG accounts for the opportunity costs and byproducts of biofuel production (Adams et al. 2005; McCarl et al. 2000).

The U.S. is devided into 63 agricultural production regions in FASOMGHG. Each region has unique climate and different economic opportunities. The producers in each region process the agricultural commodities into 56 primary crop and livestock products, which are listed in Table 2. Furthermore, the producers can process the primary commodities into 39 secondary products and shown in Table 3. The primary and secondary activities are aggregated into 11 regions and ethanol production could occur in any region (Adams et al. 2005; McCarl et al. 2000)

Table 2. Primary Crops and Livestock

Category	Activity
Primary Crops	Barley, citrus, corn, cotton, hay, oats, potatoes, rice, silage, sorghum, soybeans, sugar beets, sugarcane, tomatoes, and wheat
Energy Crops	Hydrid poplar, switchgrass, and willow
Livestock	Beef cattle, dairy cattle, hogs, horses and mules, poultry, and sheep
Misc.	Eggs

Source: Adams et al. (2005)

Table 3. Major Secondary Products

Category	Activity
Animal products	Beef, chicken, edible tallow, non-edible tallow, pork, turkey, and wool
Bio-energy	Biodiesel, ethanol, and electricity
Corn wet mill	Corn oil, corn starch, corn syrup, dextrose, high fructose corn syrup, and gluten feed
Dairy products	American cheese, butter, cream, cottage cheese, ice cream, and milk
Potato products	Dried potatoes, frozen potatoes, and potato chips
Processed citrus products	Grapefruit and orange jc8uice
Refined sugar items	Refined cane sugar and refined sugar
Soybeans	Soybean meal and soybean oil
Sweetened products	Baking, beverages, confection, and canning

Source: Adams et al. (2005)

FASOMGHG includes an international sector and decomposes the world into 27 trade regions and U.S. trade depends on the commodity and region of the world. All the sugar and starch crops are imported and exported, except sugar beets. Moreover, ethanol and crop residues are not traded internationally and no international possibilities are included for these commodities (Adams et al. 2005).

5 ETHANOL PRODUCTION POSSIBILITIES

The technology determines which feedstocks are used and which byproducts are created. This section reviews the technology and how the markets are linked in FASOMGHG.

5.1 Corn Wet Mill

The first technology is the corn wet mill and the production possibilities coefficients are shown in Table 4. The input is corn and the output is starch, corn oil, corn gluten feed, and corn gluten meal. The starch could be converted into corn syrup, dextrose, ethanol, or high fructose corn syrup. The analysis in this paper includes markets for all these products. Furthermore, the corn wet mill has an annual technological improvement of 0.77% over 30 years and is further explained in Section 5.4.

Table 4. Corn Wet Mill Possibilities

Input	Output
1 bushel corn	31.5 lbs of starch or 2.5 gallons of ethanol And 1.5 lbs of corn oil And 2.6 lbs of corn gluten meal And 13.5 lbs of corn gluten feed
1 pound of starch	1.3 lbs of corn syrup or 1.19 lbs of dextrose or 1.41 – 1.54 lbs high fructose corn syrup (HFCS)

Sources: National Corn Growers Association 2007; Rausch and Belyea 2006; Light 2007

Note: HFCS comes in two types. The sweeter HFCS-55 is used in carbonated drinks while the less sweet HFCS-42 is used in everything else.

5.2 Dry Grind Possibilities

The second technology is the dry grind production budgets for barley, corn, sorghum, oats, rice, sugar beats, sugarcane, sweet sorghum, and wheat. The dry grind has two chemical processes which are sugar and starch fermentation.

Sugar fermentation process converts simple sugars into ethanol using the chemical reaction as shown in Equation 1 (Hamelinck, Hooijdonk, and Faaij 2005; Hewlett et al. 1983). If all sugar is converted into ethanol, then one ton of pure sugar theoretically yields 154.9 gallons of ethanol. The theoretically yield will be adjusted to reflect the practical yield in the industry. Further, this conversion applies to sugar extracted from sugarcane, sugar beets, and sweet sorghum. The chemical conversion is approximate, because density changes with temperature.

$$\begin{array}{ccccc} C_6H_{12}O_6 & \rightarrow & 2C_2H_5OH & + & 2CO_2 \\ 180kg & & 92kg & & 88kg \end{array} \quad (1)$$

Starch fermentation is similar to sugar fermentation. Starch is a polymer and is composed of molecules that are similar to glucose. The molecules can link linearly and is called amylase, or the molecules can form branches and is called amylopectin. Both amylase and amylopectin are summed collectively as starch. A hydrolysis reaction causes the starch to react with water, creating a solution of glucose. Hydrolysis uses either an enzyme or acid to facilitate the reaction (Carver Research Foundation 1985; Hewlett et al. 1983). One kilogram of starch yields theoretically 1.11 kg of glucose[2] (Koutinas, Wang, and Webb 2004; Stenzel et al. 1980). Thus, one ton of pure starch theoretically yields 172.0 gallons of ethanol.

The theoretical chemical yields are shown in Table 5 and contains the feedstock source, whether the feedstock uses starch or sugar fermentation, the sugar or starch content, and the theoretical ethanol yield from one ton of feedstock.

Table 5. Theoretical Ethanol Chemical Yields

Source	Fermentation Type	Sugar or Starch Content %	Theoretical Ethanol Yield Gal/ton of feedstock
Barley	Starch	50.0 to 55.0	86.0 to 94.6
Corn	Starch	72.0	123.8
Grain sorghum	Starch	67.0 to 73.8	115.2 to 126.9
Oats	Starch	64.0	110.1
Pure sugar	Sugar	100.0	154.9
Rice grain	Starch	74.5	128.1
Sugar beet	Sugar	16.0 to 17.3	24.8 to 26.9
Sugarcane	Sugar	10.0 to 12.0	15.5 to 18.6
Sweet Sorghum	Sugar	13.0	20.1
Wheat	Starch	57.9	99.5

Sources: Agricultural Research Center 2005; Committee on Animal Nutrition et al. 1981, p.16; Food and Agricultural Organization 2002; Gnansounou, Dauriat, and Wyman 2005; Haley, Kelch, and Jerardo 2006; Pardee 1998; Stenzel et al. 1980; Wallace et al. 2005; Xie et al. 2002

Note: Some starch feedstocks may contain trace amounts of sugar.

The ethanol chemical yields are lower than the theoretical yield, due to extraction, conversion, and recovery efficiencies. The extraction efficiency is the amount of sugar or starch that can be extracted from the feedstock given current technology and is shown in Table 6. The conversion efficiency is the percentage of sugar that is chemically converted to ethanol. Research indicates the conversion efficiency ranges from 92 to 92.5% (Hamelinck, Hooijdonk, and Faaij 2005; Stenzel et al. 1980). The recovery efficiency is the percentage of ethanol that can be recovered from the chemical mixture. The recovery efficiency is set at 99%, because ethanol uses the two-stage distillation process. The first stage distills ethanol to a 95.6%

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[2] The biorefinery does not create matter. The increased mass resulted from the chemical reaction between starch and water.

concentration (Committee on Animal Nutrition et al. 1981, p. 11; Gerpen et al. 2004), while the second stage uses denaturants or desiccants to remove the remaining water (Hewlett et al. 1983).

The practical ethanol chemical yields are shown in Table 6 with the extraction efficiencies, amount of Distillers Dried Grains with Solubles (DDGS) produced, and technological growth rate. The extraction efficiencies are either from the literature or calculated from known chemical yields in the literature. DDGS is the yeast and crop residues leftover from the fermentation. DDGS is a high-protein source that can be blended with animal feeds and sold to the animal feed markets. DDGS is included in the agricultural model. The derivation of the technological growth rate is described in Section 5.4.

Table 6. Extraction Efficiencies, Chemical Yields, DDGS for Feedstocks, and Technology

Feedstock	Extraction Efficiency %	Ethanol Yield Gal./ton of feedstock	DDGS lbs/gal. of ethanol	Technological Growth Rate %/year
Barley	89.5	70.1 to 77.5		0.311
Corn (dried grind)	86.9	98.0 to 98.6	5.9 to 6.1	0.409
Corn (wet milled)	78.8	88.8 to 89.3	-	0.738
Grain sorghum	78.0 to 90.4	81.8 to 105.1	7.9	0.279
Oats	89.5	89.7 to 90.2	9.9	0.311
Pure sugar	100	141.1 to 141.9	-	-
Rice grain	89.5	104.5 to 105.0	5.3	0.277
Sugar beet	87.9	19.8 to 21.6	14.2	0.372
Sugarcane	93.1 to 97	15.5 to 18.6	14.9	0.181
Sweet Sorghum	86.9	15.9 to 16.0	7.9	0.410
Wheat	95 to 97.3	86.1 to 88.7	7.3 to 9.2	0.033

Sources: Haley, Kelch, and Jerardo 2006; Kim and Dale 2004; Raush and Belyea 2006; Stenzel et al. 1980; Sweden Biobase 1999; Szulczyk 2007; Wallace et al. 2005; Xie et al. 2002

Note: Barley, oats, and rice grain use the average extraction efficiency for starch crops.

The ethanol industry also produces CO2 as a byproduct (Hamelinck, Hooijdonk, and Faaij 2005; Hewlett et al. 1983). The food industry uses liquefied CO2 to freeze, chill, and preserve food, or uses CO2 to carbonate beverages. FASSOMGHG does not include a CO2 market, because a large ethanol industry could easily saturate the CO2 market, causing the market price to drop significantly. The CO2 market was 5.6 million tons in 1995 with a 3 to 4 percent per year growth rate (Chemical Marketing Reporter 1995). An ethanol industry with 36 ethanol refineries with production capacity of 50 million gallons per year could supply this market. However, the CO2 emissions were included the life-cycle GHG emissions.

5.3 Lignocellulosic Fermentation

The last technology is lignocellulosic fermentation, which uses crop residues for the input. Crop residues do not have an official market, but they serve two purposes in the agricultural model. First, crop residues provide surface cover that prevents soil erosion and provides nutrients and organic matter for the soil, which are critical for future crop yields (Gallagher and Johnson 1999; Kadam and McMillan 2003; Kim and Dale 2004; Kim and Dale 2005; Sheehan et al. 2004; Wallace et al. 2005). Thus, FASOMGHG restricts the amount of crop residues that can be removed from the land. Second, crop residues could be co-fired with coal to generate electricity, which is also included in FASOMGHG FASOMGHG contains lignocellulosic production possibilities for bagasse, barley, straw, corn stover, oat straw, rice straw, sorghum straw, and wheat straw.

Lignocellulosic fermentation is more complex than sugar/starch fermentation. Plant residues contain cellulose and hemicellulose. Cellulose is the largest component and is composed of glucan, while hemicellulose is composed of arabinan, galactan, mannan, and xylan. These five components can be broken down into two categories of sugar using either an acid or enzyme hydrolysis. The sugar category refers to the number of carbon (C) atoms contained in the sugar molecule. The C6 sugars are glucose, galactose and mannose, which originate from glucan, galactan and mannan, while the C5 sugars are arabinose and xylose, which originate from arabinan and xylan. Microorganisms can ferment all sugars into ethanol. The variety of sugars requires multiple processing stages, increasing capital and operating costs (Hamelinck, Hooijdonk, and Faaij 2005; Gnansounou, Dauriat, and Wyman 2005; Kadam 2000; Kaylen et al. 2000; Sheenan et al. 2005; Tshiteya and Tshiteya 1998).

The composition of crop residues is shown in Table 7. The C6 polymers are similar to starch, whereas one ton of glucan, galactan,or mannan yields 1.11 tons of C6 sugars (Energy Efficiency and Renewable Energy 2006b) and could be fermented theoretically into 172.0 gallons of ethanol. One ton of arabinan or xylan yields 1.14 tons of C5 sugars (Energy Efficiency and Renewable Energy 2006b) and could be fermented theoretically into 176.0 gallons of ethanol. The reaction is similar to Equation 1. The feedstock also contains lignin, which is a fiber. Lignin has to be removed, because it interferes with the fermentation process (Hamelinck, Hooijdonk, and Faaij 2005).

Table 7. Crop Residue Composition

Feedstock	Glucan % wt	Galactan % wt	Mannan % wt	Arabinan % wt	Xylan % wt	Lignin % wt	Theoretical Chemical Yield Gal/ton of feedstock
Bagasse	40.6	0.8	0.2	1.7	20	25.5	109.7
Corn Stover	40.9	1	0	1.8	21.5	16.7	113.1
Rice Straw	34.2	0	0	0	24.5	11.9	101.9
Sorghum straw	34.01	0.52	0.2	1.65	14.1	16.1	87.4
Wheat Straw	38.2	0.7	0.3	2.5	21.2	23.4	109.1

Sources: Energy Efficiency and Renewable Energy 2006a; Kadam 2000; Kim 2004, p. 33; Tshiteya and Tshiteya 1998

The extraction, conversion, and recovery efficiencies cause the ethanol chemical yields to be lower than the theoretical. The efficiencies are defined similarly as the sugar and starch fermentations and are listed in Table 8 for each sugar.

Table 8. Extraction, Conversion, and Recovery Efficiencies

Sugar	Extraction Efficiency %	Conversion Efficiency %	Recovery Efficiency %
Arabinose	75 to 90	59 to 90	99
Galactose	82	90	99
Glucose	50 to 90	92 to 92.5	99
Mannose	89	90	99
Xylose	75 to 90	59 to 92	99

Source: Hamelinck, Hooijdonk, and Faaij 2005

Note - The extraction efficiency is unknown for arabinose, thus the xylose efficiency is used.

Note – Extraction efficiencies are based on acid hydrolysis.

The ethanol industry does not currently use lignocellulosic fermentation. However, the practical ethanol chemical yields are shown in Table 9 and include the impact of the three efficiencies from Table 8. The mid-range values are used for the FASOMGHG. The mid-range values are close to what is cited in the literature and are included in Table 9 for a comparison. The crop residue to crop ratio and technological growth rates are also included in Table 8 and are explained in Section 5.4.

Table 9. Ethanol Chemical Yields

Feedstock	Crop residue to crop ratio	Practical Ethanol Chemical Yield Gal./ton of feedstock	Ethanol Chemical Yields from Literature Gal./ton of feedstock	Tech. Growth Rate %/year
Bagasse	0.60	49.80 to 90.07	67.2 to 71.88	1.15
Barley straw	1.20		60.00 to 74.4	1.15
Corn Stover	1.00	51.25 to 92.78	56.5 to 79.2	1.15
Oat straw	1.30		60.00 to 62.4	1.64
Rice Straw	1.35 to 1.40	45.67 to 83.81	60.00 to 67.2	1.16
Sorghum straw	1.30	39.70 to 71.79	64.60 to 64.8	1.15
Wheat Straw	1.30	49.47 to 89.54	57.6 to 70.00	1.15

Sources: Kadam, Forrest, and Jacobson 2000; Kadam and McMillan 2003; Kim and Dale 2004; Mann and Bryan 2001; Sheehan et al. 2004; Wallace et al. 2005; White, John G.

Note: Barley straw and oat straw use the wheat straw chemical yields and technological growth rate, because they are in the grass family.

Lignin is produced from lignocellulosic fermentation as a byproduct and could be burned to produce electricity and heat in FASOMGHG. The high heating value (HHV) is used to calculate the heating value for lignin, because the vaporization of water performs work in an electric generating facility. Each ton of lignin with 33% moisture content yields 18,222,000 BTUs of heat energy (Domalski, Jobe, and Milne 1986). The efficiency for lignin-electricity generation starts with a 32% energy efficiency (Spath, Mann, and Kerr 1999). The energy efficiency is the percentage of heat energy that is converted to electricity.

FASOMGHG does not contain the following byproducts for lignocellulosic fermentation: CO2, furfural, gypsum, and biogas. The reason is because these markets are small, and a large ethanol industry would cause the market price to fall. Further, these byproducts could require expensive capital upgrades. Carbon dioxide is released from the fermentation process and this CO2 is included in the life-cycle emissions. Furfural is created from the breakdown of hemicellulose, and could be used to make carpet fibers (Kadam and McMillan 2003; Kaylen et al. 2000). Gypsum is a byproduct from neutralizing the acid used in hydrolysis (Easterly Consulting 2002; Hamelinck, Hooijdonk, and Faaij 2005). Finally, biogas is created from anaerobic fermentation in the biorefinery’s wastewater and contains 75% methane. An ethanol refinery could collect and burn this gas for heat and electricity (Easterly Consulting 2002; Hamelinck, Hooijdonk, and Faaij 2005; Gnansounou, Dauriat, and Wyman 2005; Kaylen et al. 2000; Ortiz-Canavate 1994; Wallace et al. 2005).

5.4 Incorporating Technological Progress

High energy prices and GHG prices are likely to induce technical change where ethanol production yields given an amount of feedstock, feedstock yields per acre and the cost of ethanol processing are likely to change over time particularly for cellulosic ethanol. In our framework these are depicted by having

- Crop yields increase over time at rates forecasted by USDA (Interagency Agricultural Projections Committee 2008).
- Ethanol yields increasing over time where ethanol producers are assumed to attain 90% of theoretical chemical yield in 30 years, where the conversion, extraction, and recovery efficiencies results in a total efficiency of 90%. The annual growth rates are shown in Tables 6 and 9.
- The efficiency for lignin-electricity generation increases to 42% (Spath, Mann, and Kerr 1999), increasing 1.09% annually. The 42% energy efficiency occurs as producers upgrade or build new electric generation facilities.

Technological improvement can also be incorporated by having production costs decrease over time or genetic engineering improves sugar/starch content in crops. However, these alternatives were not examined because this paper is already quite lengthy.

5.5 Greenhouse Gas Efficiency

Researchers like Pimentel (1991) and Searchinger et al. (2008), have criticized ethanol for being energy and GHG inefficient. However, the GHG emissions and energy efficiency not only depend on the production and consumption of ethanol, but all of ethanol's byproducts and inputs. For example, crops absorb carbon from the atmosphere and energy from the sun. As producers convert plants into fuel, they release greenhouse gases and consume energy. The producers harvest, haul, ferment, and distill the feedstock into ethanol, and then combust the ethanol in a car engine. Thus, energy and GHG efficiency depends on ethanol conversion rates, crop yields, fertilizer manufacturing and application, byproduct analysis, and amount of energy used in each process (Hammerschlag 2006; Shapouri, Duffield, and Graboski 1995). For example, life-cycle analysis includes byproducts like DDGS that displaces corn in feeding and thus the attendant GHG emissions and energy inherent therein. Thus, FASOMGHG accounts for these GHG emissions and allows producers to alter their activities as if there was a carbon equivalent price.

Biofuels are not equal in their GHG efficiency and creating an institution of a GHG emission based cap and trade system will allow biofuel production to move towards more GHG efficient forms. Estimates of ethanol GHG efficiency from various feedstocks considering GHGs used in crop production, manufacturing of crop production inputs, hauling of feedstocks, processing plant transformation and byproduct offsets are given in Table 10. These results show among other things that the current major U.S. source of ethanol – corn is relatively GHG inefficient while sugarcane and cellulosic ethanol sources are much more efficient. In addition one should note that this does not account for offsite leakage as discussed in Murry, McCarl, and Lee (2004), Searchinger et al. (2008) or Fargione et al. (2008).

Table 10. Percentage Offset of Net GHG Emissions from the Usage of a Biofeedstock

	Form of Bioenergy				
	Liquid Fuels			**Electricity**	
Feedstock Commodity	Crop Ethanol (%)	Cellulosic Ethanol (%)	Biodiesel (%)	Cofire at 5 % (%)	Fire with 100% biomass (%)
Corn	30.5				
Hard Red Win. Wheat	31.5				
Sorghum	38.5				
Sugarcane	64.8				
Softwood Residue		80.0		99.2	97.4
Hardwood Residue		79.9		99.0	96.5
Corn Residue		75.1		93.7	88.1
Sugarcane Bagasse		90.1		100.0	100.0
Wheat Residue		73.8		95.6	91.4
Switch Grass		68.6		94.3	89.5
Hybrid Poplar		61.9		94.1	89.1
Willow		67.7		96.6	93.7
Lignin				91	86
Cattle Manure				99.6	96.5
Soybean Oil			70.9		
Corn Oil			55.0		

6 ECONOMIC COST OF ETHANOL PRODUCTION

The total cost of ethanol production is composed of two types of costs: Endogenous and exogenous. The feedstock costs and hauling costs are endogenous and determined within the FASOMGHG, while the production costs, capital costs, and transportation costs are exogenous.

The hauling costs are the cost of harvesting and transporting the feedstocks to the biorefinery, and include processing for use. Hauling costs are computed by French's (1960) approximation, where a biorefinery is in a center of a circular region, surrounded by a square grid layout of roads and defined by Equations 3. The feedstock is hauled an average distance of $\overline{D}$ miles, *S* is the amount of feedstock input for a biorefinery in tons, *Y* is the crop density in tons per acre, and 640 is acres-per-square-mile conversion. The hauling costs per ton of feedstock is defined as H, where b_0 is the fixed loading charge, b_1 is the rate charge, L is the truck load size, and the 2 indicates a return trip to the biorefinery. The hauling costs and parameters are defined in Table 11. Even though the ethanol production budgets have fixed capital (fixed *S*), hauling costs are updated in the FASOMGHG to reflect changes in crop yields, because crop yields differ by region and time.

$$\overline{D} = 0.4714\sqrt{\frac{S}{640Y}} \quad \text{and} \quad H = \frac{b_0 + 2b_1\overline{D}}{L} \qquad (3)$$

Table 11. Feedstock Hauling Costs and Parameters

Feedstock	Hauling Costs ($ per ton)	b_0 ($)	b_1 ($ per mile)	Load Size (tons)
Barley		45	1.10	60
Corn (dry grind)		45	1.10	60
Corn (wet mill)		45	1.10	60
Crop Residues		90	2.20	20
Lignin	5	-	-	-
Oats		45	1.10	60
Pure Sugar		90	2.20	25
Rice		45	1.10	60
Rice Straw	13.54	-	-	-
Sorghum		45	1.10	60
Sweet Sorghum		90	2.20	20
Wheat		45	1.10	60

Note: Lignin and rice straw is used near the biorefinery. The hauling costs are preparing feedstocks for use.

The operating costs are defined for the ethanol dry grind refineries, ethanol wet mill, and ethanol lignocellulosic, and shown in Table 12. Operating costs include labor, materials, insurance, utilities, and taxes for operating the facility. The operating costs for burning lignin depend which percentage of cofiring lignin with coal and are shown separately in Table 13. FASOMGHG has production budgets for burning 100% lignin, or co-firing the lignin with coal from 5% to 20%. Lignin contains little sulfur and co-firing with coal can reduce sulfur dioxide emissions, lowering the need to purchase sulfur dioxide credits. However, at this point, sulfur dioxide credits are not included in the production possibilities budget.

Table 12. Economic Costs of Ethanol Production in 2000 Dollars

Type	Wet Mill ($ per gallon)	Dry Grind ($ per gallon)	Lignocellulosic ($ per gallon)
Feedstock costs	Endogeneous	Endogeneous	Endogeneous
Hauling costs	Endogeneous	Endogeneous	Endogeneous
Operating costs	$0.46	$0.3958	$1.31
Capital costs	0.1165	0.0832	0.315
Transportation and storage costs	0.05	0.05	0.05

Sources: Energy Information Administration 2007, Shapouri and Gallagher 2005, and Wallace et al. 2005

Table 13. 100 MW per Year Production and Capital Costs for Lignin-Electricity Generation

Type	Production Costs ($)	Capital Costs ($)
Pure Lignin	13,363,330.00	45,625,000
5% Lignin Co-fire	51,486.40	1,573,880
10% Lignin Co-fire	101,134.00	3,200,320
15% Lignin Co-fire	154,459.20	4,882,240
20% Lignin Co-fire	209,623.20	6,621,100

Sources: Hughes 2000; Markiewicz, Rose, and Wolfram. 2004; Qin et al. 2006.

The lignocellulosic facilities and sweet sorghum facilities are fixed at 20 million gallons, while the other production budgets are based on 40 million gallon facilities. The capital budgets were derived from Gallagher, Brubaker, and Shapouri (2005) and Wallace et al. (2005). The assumption is capital has a 10-year life with a discount rate of 8%. Using continuous compounding, the real capital depreciation cost is $0.0832 per gallon for the dry grind, $0.1165 for the wet mill, and $0.315 per ethanol gallon for lignocellulosic fermentation. The capital costs for electricity generation are shown in Table 13. The capital cost for burning 100% lignin to create electricity is the whole 100 MW generating facility, while for co-firing, the capital is the upgrade to equipment that process and feed the lignin to the steam boilers. Moreover, the electric and ethanol facilities are assumed to be located near each other.

The last cost is transporting the ethanol to the retail market. The ethanol refinery transports ethanol by truck to petroleum product terminals and ethanol is stored in its own tank. When ethanol is ready to be transported to the retail market, it is blended with gasoline and transported by truck. Consequently, this analysis uses a real cost of 5 cents per gallon to transport and store the ethanol (Reynolds 2000).

7 ETHANOL MARKET PENETRATION

FASOMGHG is used to predict the U.S. market penetration for ethanol. Two important assumptions are made about market penetration. First, the gasoline markets remain the same size. Thus, any increases in ethanol production reflect increased market penetration. Second, no problems are encountered when the ethanol is blended with petroleum-based fuels, such as gasoline-ethanol blends exceeding E15.

Ethanol producers receive federal and state subsidies. The state subsidies vary, but the federal ethanol subsidy is $0.51 per gallon (U.S. Government Printing Office 2002, 2004). The production period ranges from 2000 to 2030 with five-year increments. The wholesale gasoline price is exogenous and ranges from $1.00 to $4.00 per gallon, using the 25-year energy price forecasts from the National Energy Modeling System (Office of Integrated Analysis and Forecasting 2006). Further, the ethanol price is adjusted for the lower energy content of the fuel. FASOMGHG is used to examine three scenarios: Varying fossil fuel prices, carbon equivalent price for greenhouse gases, and the removal of U.S. federal government subsidies.

7.1 Varying Energy Prices

FASOMGHG predicts the U.S. ethanol market penetration in Figure 1. The U.S. production is in millions of gallons and the ethanol price is adjusted for the lower energy content. FASOMGHG clearly shows that ethanol producers supply approximately the same level of ethanol production independent from the gasoline price. The reason is gasoline prices raise both revenues from ethanol and feedstock costs. The estimated ethanol production is approximately 75 billion gallons of equivalent fuel in 2030, when gasoline is $4 per gallon. With an annual U.S. gasoline supply of approximately 142.4 billion gallons in 2007 (Energy Information

Administration 2008), U.S. ethanol production attains a maximum predicted market penetration of 53%.

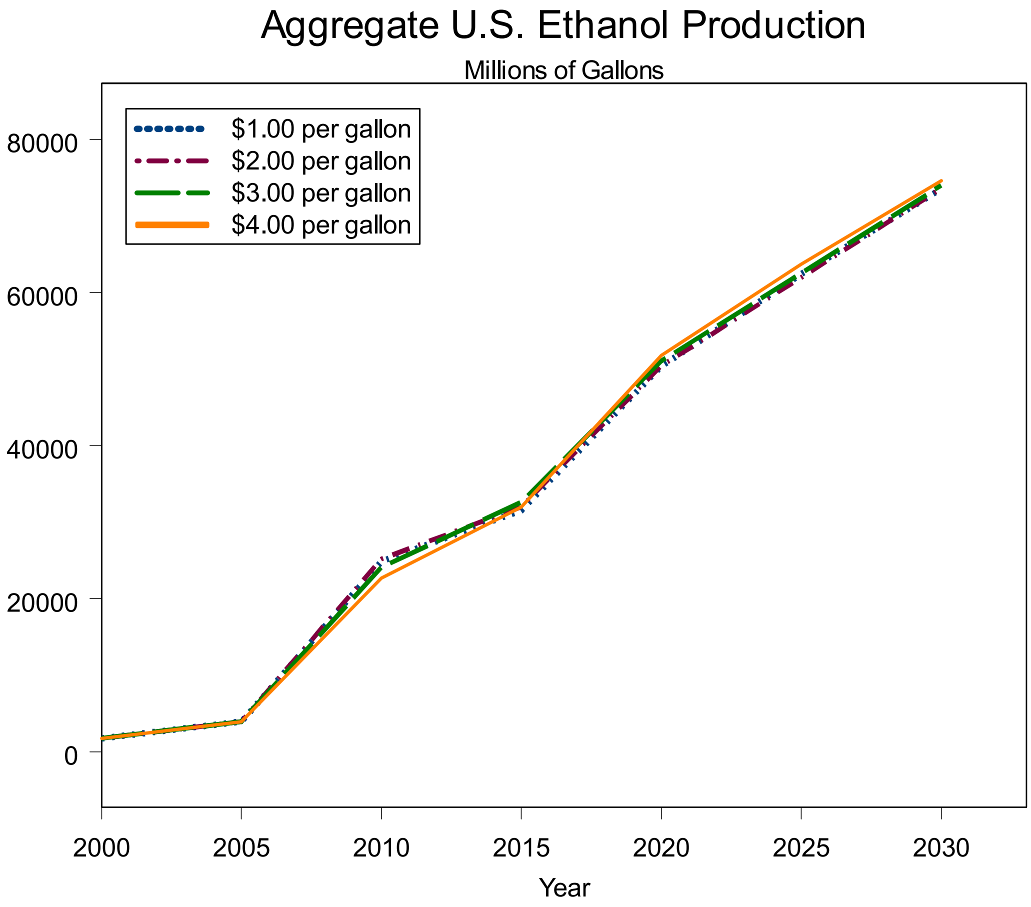

Figure 1. Aggregate Ethanol Production

FASOMGHG predicts the sources for ethanol and is shown in Figure 2 when the gasoline price is set at $2 per gallon and quantity is in millions of gallons of ethanol. The primary source of ethanol is from the corn wet mills, because the wet mills produce other valuable byproducts like corn oil, which can produce biodiesel. The second largest ethanol source quickly grows over time and uses lignocellulosic fermentation from bagasse, corn stover, and soft wood pulp. Ethanol producers also use some energy crops, such as hydrid poplar and switchgrass. Unfortunately, ethanol produced from the dry grind industry does not show any increase over time. The feedstocks are barley, wheat, sorghum, and sweet sorghum, which are also used in the animal feeds and/or human food.

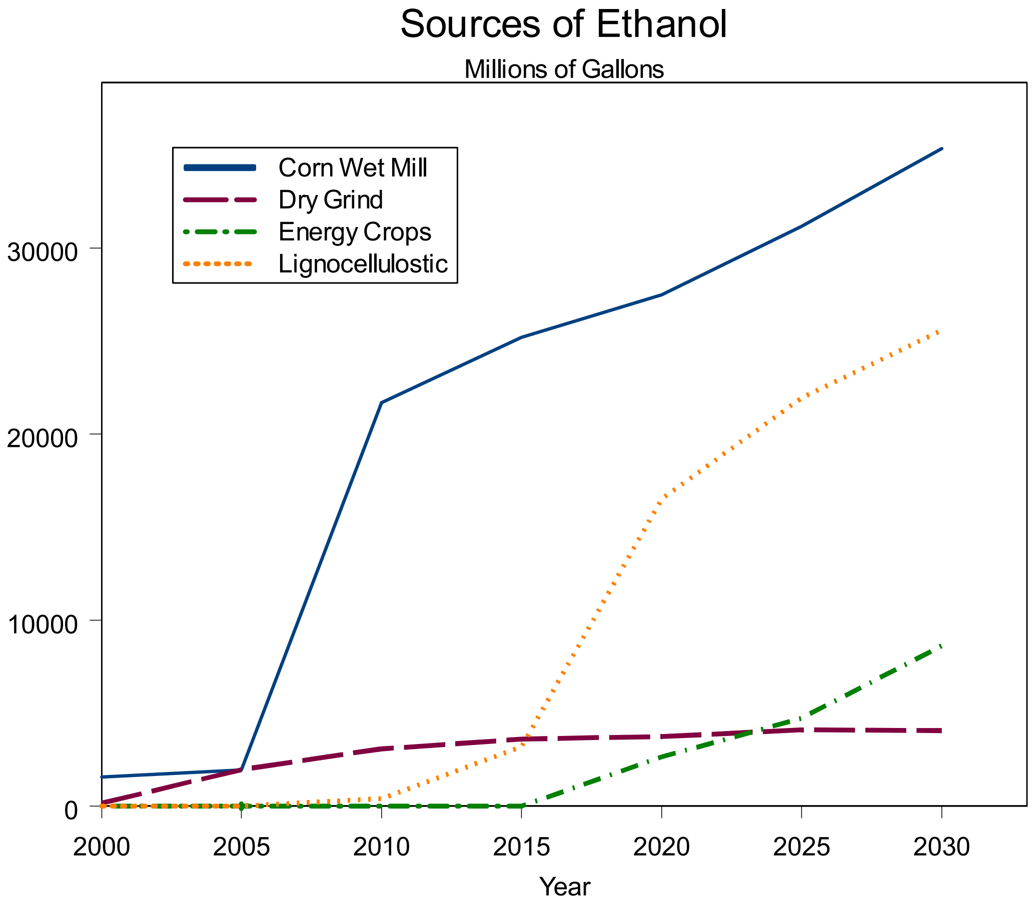

Figure 2. Sources of Ethanol

7.2 Varying GHG Offset Prices

FASOMGHG was used to predict the market penetration of ethanol given if a market price existed for GHG emissions. The GHG price uses the IPCC 100-year Global Warming Potential (GWP) as an exchange rate among GHGs (Cole et al. 1996, pp. 726-71). The GWP defines carbon dioxide equals 1, methane as 21, and nitrous oxide as 310 (Adams et al. p. 114, 2005; Kadam 2000). The carbon equivalent price ranged from $0 to $100 per metric ton, because Schneider and McCarl (2003) have shown this price range to be effective in reducing greenhouse gas emissions.

The model predicts the U.S. aggregate ethanol production for various carbon dioxide equivalent prices. The results are shown in Figure 3 and the gasoline price was fixed at $2 per gallon. FASOMGHG predicts all ethanol production time paths are increasing and a carbon equivalent price has an expansionary impact on this industry. Additionally, the feedstock sources change with a carbon price. A higher carbon equivalent price boosts the corn wet mill industry, because this industry supplies corn oil which is used to produce biodiesel. However, carbon equivalent prices are ambiguous for lignocellulosic ethanol. Lignocellulosic feedstocks like crop residues and energy crops like hybrid poplar, switchgrass, and willow can also be co-fired with coal to generate electricity. FASOMGHG switches the feedstocks between the ethanol and electricity industries, because both are quite GHG efficient.

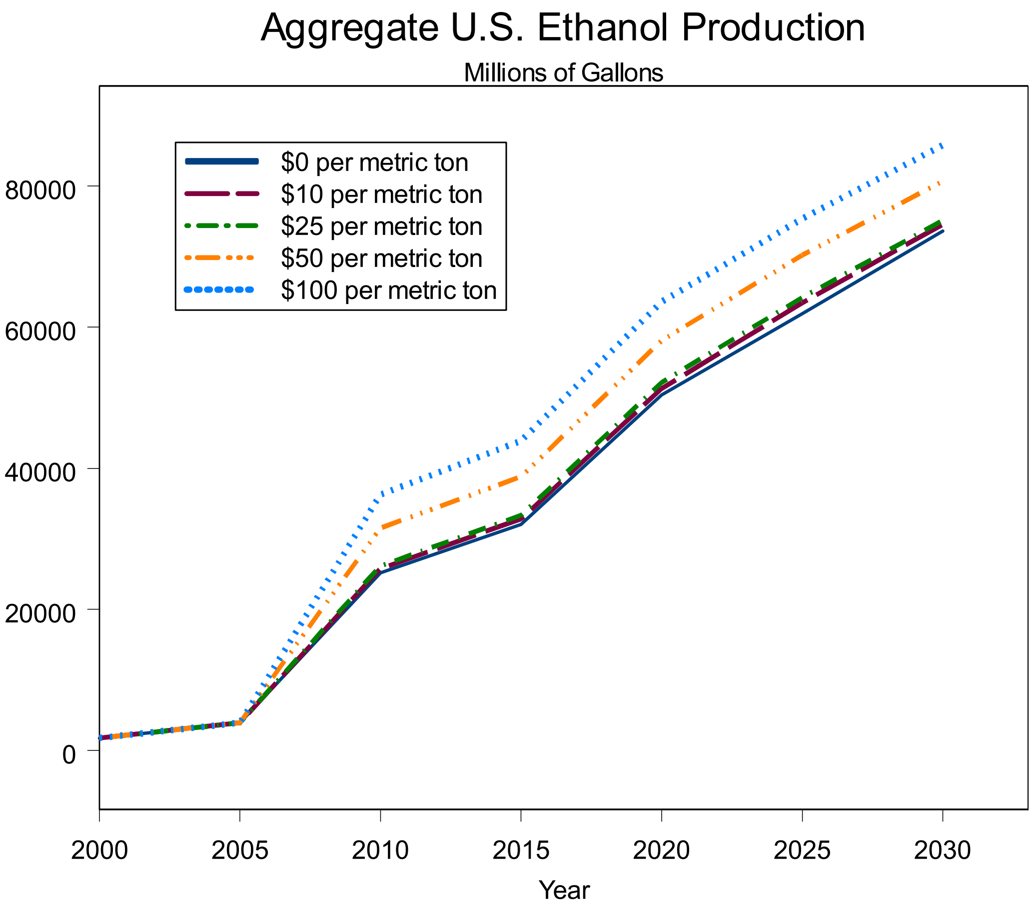

Figure 3. Aggregate Ethanol Production for Various Carbon Equivalent Prices

7.3 Federal Subsidies

Subsidies for ethanol (and biodiesel) are set to expire on ethanol in December 2008. Consequently, FASOMGHG was used to predict the U.S. market penetration for ethanol, if U.S. government subsidiaries were removed. The results are shown in Figure 4. Without question, the U.S. government subsidies expand the ethanol industry. If the $0.51 subsidy is removed, FASOMGHG predicts in 2030 that ethanol industry produces 3 billion less gallons of ethanol for low gasoline prices and 6 billion gallons less for high gasoline prices. The predicted maximum ethanol production is approximately 75 billion equivalent gallons and occurs in 2030 when the gasoline price is $4 per gallon, resulting in a market penetration of 52%. Thus, U.S. federal subsidies help expand the market penetration by approximately 1% in 2030.

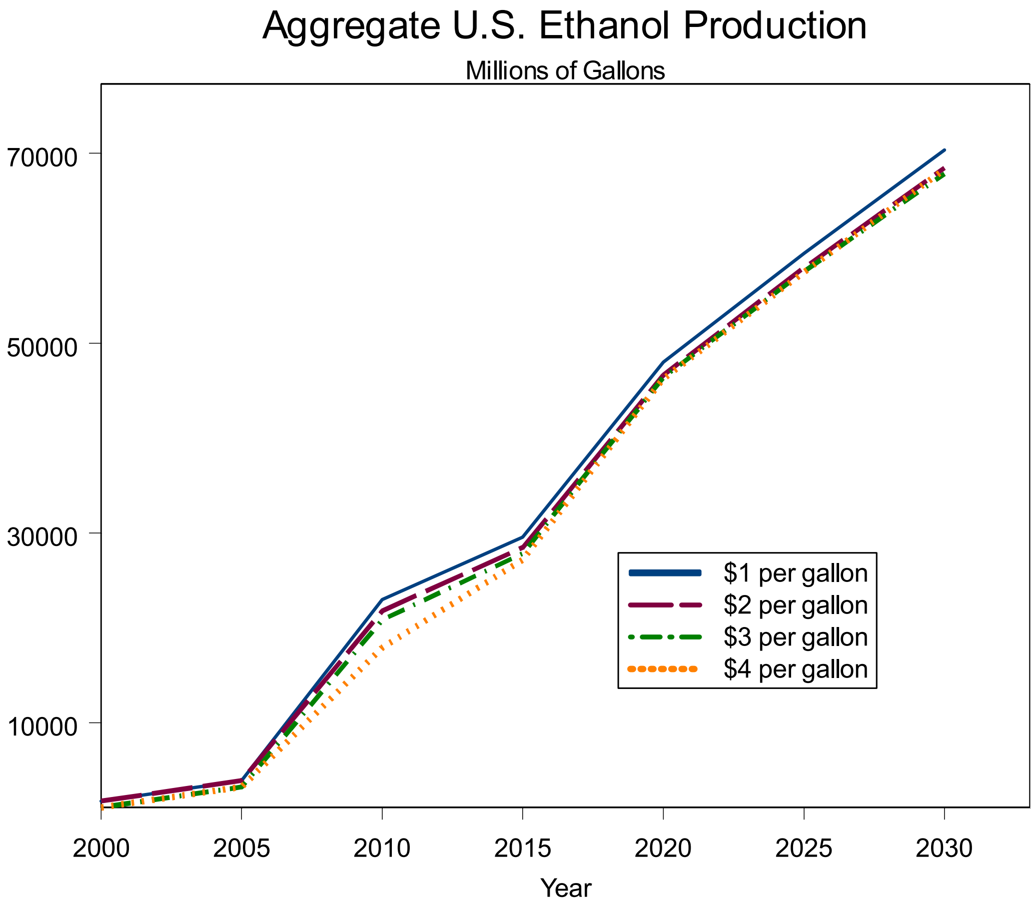

Figure 4. Aggregate Ethanol Production with No Government Subsidies

8 CONCLUSIONS

This research indicates the ethanol can become an important source for a transportation fuel. However, the predictions from FASOMGHG are optimistic, because the price for gasoline is fixed at one level. Thus, producers have no uncertainty about the future price of fossil fuels. Further, for ethanol to become important, several problems have to be overcome:

- All cars sold in the United States will have to be flexible fuel vehicles. Otherwise, the ethanol industry could not supply more than 21 billions gallons of ethanol, which is 15% of the current U.S. gasoline consumption.
- The ethanol industry will have to develop an additive that prevents gasoline and ethanol blends from separating when contaminated with water. This would allow ethanol to be transported through pipelines and reduce storage costs.

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