MARKET PENETRATION OF BIODIESEL AND ETHANOL

A Dissertation

by

KENNETH RAY SZULCZYK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

May 2007

Major Subject: Agricultural Economics

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Approved by:

Chair of Committee,	Bruce A. McCarl
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ABSTRACT

Market Penetration of Biodiesel and Ethanol. (May 2007)

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This dissertation examines the influence that economic and technological factors have on the penetration of biodiesel and ethanol into the transportation fuels market. This dissertation focuses on four aspects. The first involves the influence of fossil fuel prices, because biofuels are substitutes and have to compete in price. The second involves biofuel manufacturing technology, principally the feedstock-to-biofuel conversion rates, and the biofuel manufacturing costs. The third involves prices for greenhouse gas offsets. The fourth involves the agricultural commodity markets for feedstocks, and biofuel byproducts. This dissertation uses the Forest and Agricultural Sector Optimization Model-Greenhouse Gas (FASOM-GHG) to quantitatively examine these issues and calculates equilibrium prices and quantities, given market interactions, fossil fuel prices, carbon dioxide equivalent prices, government biofuel subsidies, technological improvement, and crop yield gains.

The results indicate that for the ranges studied, gasoline prices have a major impact on aggregate ethanol production but only at low prices. At higher prices, one runs into a capacity constraint that limits expansion on the capacity of ethanol production. Aggregate biodiesel production is highly responsive to gasoline prices and increases over time. (Diesel fuel price is proportional to the gasoline price). Carbon dioxide equivalent prices expand the biodiesel industry, but have no impact on ethanol aggregate production when gasoline prices are high again because of refinery capacity expansion. Improvement of crop yields shows a similar pattern, expanding ethanol production when the gasoline price is low and expanding biodiesel. Technological improvement, where biorefinery production costs decrease over time, had minimal impact on aggregate ethanol and biodiesel production. Finally, U.S. government subsidies have a large expansionary impact on aggregate biodiesel production, but only expand the ethanol industry at low gasoline prices. All of these factors increase agricultural welfare with most expanding producer surplus and mixed effects on consumers.

DEDICATION

To my boys, Anvar and Arthur

ACKNOWLEDGEMENTS

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Much appreciation and gratitude goes to Dr. Jerry Cornforth for helping the author understand FASOM-GHG, and its application to this research endeavor. In addition, the author also thanks the Agricultural Economics Department at Texas A&M University, U.S. Department of Agriculture and U.S. Department of Energy for financing his doctoral education.

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1. INTRODUCTION

Biofuel production is an ancient endeavor that diminished in importance during the twenty-first century, because of “cheap” petroleum. Recent rises in petroleum prices have caused a biofuels revival with production increasing more than five fold between 2000 and 2006. The degree of future penetration of biofuels into the energy market depends on five issues.

- The market price for fossil fuels, because biofuels are substitutes for fossil fuels.
- The degree, to which technological innovation increases crop yields, causes growth in energy production per unit of feedstock, or decreases biofuel manufacturing and crop production costs.
- Interactions of biofuel production and agricultural markets, for factors, resources, and biofuel byproduct markets.
- The level of greenhouse gas (GHG) offset prices. Agriculture and forestry are sources and sinks for GHGs. Biofuels reduce life-cycle emissions of GHGs relative to fossil fuel, and consequently, high GHG prices would increase biofuel market penetration. Moreover, GHG reductions and climate change mitigation may provide income-earning opportunities for agriculture as agricultural producers sequester GHGs.
- Government regulations, taxes, and subsidies.

The next sections provide more background on the ethanol and biodiesel industries and their recent resurgence.

This dissertation follows the reference style of the *American Journal of Agricultural Economics*.

1.1. Ethanol

The ethanol industry is expanding rapidly in the U.S. This industry started to produce ethanol from corn in the early 1980's, and by 2005 had expanded to a 3.9 billion gallon per year industry (Renewable Fuels Association 2005b). Furthermore, the expansion reached approximately 6 billion gallons during 2006 (Nelson 2006).

The sources of growth are from government subsidies, environmental regulations and surging gasoline prices. The subsidies vary by state, but the current federal subsidy is $0.51 per gallon tax credit (U.S. Government Printing Office 2002, 2004).

Another important stimulus comes from the federal Clean Air Act Amendments (CAAA) of 1990. The CAAA requires cities with high ozone concentrations or carbon monoxide emissions to add oxygenates to gasoline[1], because oxygenated gasoline have cleaner emissions (Gallagher et al. 2003; Nevin 2005; Rask 1998; Reynolds 2000; Zerbe 1992). Two widely used oxygenates are ethanol and methyl tertiary-butyl ether (MTBE). The Environmental Protection Agency (EPA) is currently phasing out MTBE, because MTBE is found to be a carcinogen that in cases accumulates in water supplies (Reynolds 2000). The MTBE phase out will strengthen the demand for ethanol. For instance, for every two gallons of MTBE removed from the market, approximately one gallon of ethanol is needed as a substitute. Ethanol contains approximately twice the oxygen content as MTBE (Reynolds 2000).

1.2. Biodiesel

The rapidly growing U.S. biodiesel industry is a younger industry than ethanol. The U.S. biodiesel industry produced 75 million gallons in 2005, a 50 million gallon increase compared to the production level in 2004 (National Biodiesel Board 2006). The federal government also subsidizes biodiesel. Biodiesel originating from agricultural

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[1] The Energy Policy Act of 2005 phases out the oxygenate requirement for reformulated gasoline, giving petroleum refiners greater flexibility in meeting air quality standards (U.S. Government Printing Office 2005).

sources receives a \$1.00 per gallon subsidy while other biodiesel sources receive \$0.50 per gallon (U.S. Government Printing Office 2004).

1.3. International GHG Reduction Efforts

Public awareness of GHG emissions and their link to climate change is fueling interest in ethanol and biodiesel. As of April 2006, 163 countries have ratified the Kyoto Protocol, which is an agreement to reduce signatory GHG emissions to below 1990 levels. Currently, two large economies that were party to the agreement have chosen not to ratify it, namely Australia and the U.S. The Kyoto Protocol and GHG reduction are based on the precautionary principal. Most scientists believe GHG emissions are accumulating in the earth's atmosphere, trapping more of the sun's radiation, and causing the earth to become warmer. The six man made GHGs are carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs (Wikipedia-Kyoto Protocol 2006).

Gasoline and diesel fuels are significant source of GHG emissions particularly carbon dioxide (CO2) as shown in Davis and Diegel (2006, Table 11.4). For example, combusted diesel fuel creates approximately 22.384 pounds of CO2 per gallon, while combusted gasoline creates approximately 19.564 pounds of CO2 per gallon (Energy Information Administration 2005b). On the other hand, the combustion of biofuels does not increase net CO2 emissions, because plants remove carbon from the atmosphere as they grow and store it as cellulose, hemicellulose, oils, starches, and sugars. In turn, the carbon is emitted when these substances are processed into fuels, and then are burned. The carbon recycling is not 100%, because the biofeedstock production, transport and biofuel manufacturing uses fossil fuels and thus releases GHGs. Thus, biofuels mitigate global warming by recycling carbon from the atmosphere, helping countries to reduce GHG emission levels (Barnwal and Sharma 2005; Beer et al. 2002; Carver Research Foundation 1985; Encinar et al. 2002; Gallagher et al. 2003; Gerpen et al. 2004; Hammerschlag 2006; Lugar and Woolsey 1999; McCarl et al. 2000; Ortiz-Canavate 1994; Shay 1993; Sheehan et al. 1998).

1.4. Market Forces

Market forces cause the biofuels industry to compete with the agricultural markets for feedstocks, to compete with the petroleum industry to supply consumers with fuel, and to compete for the prices of a number of byproducts. Under a market system, producers maximize their profits by allocating resources to the production of their most profitable commodity alternatives, whereas consumers maximize their utility by purchasing a bundle of goods given their income. Hence, the market approach uses market prices to determine the biofuel industry size, given other markets, GHG and gasoline prices, biofuel costs, and government biofuel subsidies.

1.5. Technology

Advances in technology increase the amount of biofuel that biorefineries can obtain from a given quantity of feedstock or reduce per unit processing cost. The actual chemical processes can be complex. Here technology is treated in terms of four independent, exogenous factors.

- Crop chemical composition determines the maximum amount of the crop that a biorefinery could convert to biofuel. Crop breeding and DNA manipulation technology can alter crop chemistry namely cellulose, hemicellulose, sugar, starch, and oil content.
- Technological advances in growing and cultivating crops increase the amount of crops harvested per unit of land, lowering cost of feedstock crop production.
- Biorefinery processing cost could decrease over time, as it becomes more efficient at producing biofuel.
- Potential advances in feedstock-to-biofuel chemical yields increase biofuel production from cellulose, oil, starch, or sugar.

1.6. Research Problem / Objective

The research objective is to examine the economic and technological factors that influence the penetration of biodiesel and ethanol[2] into the transportation fuels market. The essential steps to accomplish this objective are:

1. Examine the current situation for biodiesel and ethanol production, including societal benefits and technological issues that could hinder biofuel market penetration.
2. Examine the future likely levels of fossil fuel prices relying on the U.S. Department of Energy's 25-year energy market price forecasts.
3. Examine the current levels for feedstock-to-biofuel chemical yields for ethanol and biodiesel production using chemical formulas along with the potential for enhancements.
4. Estimate the costs for biodiesel and ethanol production including feedstocks, hauling, and processing costs as well as byproduct production rates.
5. Update the FASOM-GHG model to include all needed byproduct and feedstock markets plus data for feedstock production, hauling, processing, and energy price.
6. Use FASOM-GHG to investigate the potential market penetration of biodiesel and ethanol, given various gasoline prices, GHG prices, government subsidies, and technological improvement.

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[2] Any references to ethanol refer to ethanol made from agricultural sources and not by the petroleum industry.

2. ECONOMICS OF MARKET PENETRATION

Many ideas are examined in this dissertation, spanning from economics to technical information. This section brings these ideas together and examines the simple theoretical relationships between energy prices, technological progress, biofuel subsidies, and GHG prices as they influence biofuel penetration.

2.1. Higher Energy Prices

The first graphical analysis examines the economic impact of higher petroleum fuel prices on the markets and is depicted in Figure 2.1. The black lines indicate the initial market equilibrium. The agricultural market is depicted in the upper left corner. The agricultural producers create the feedstock, representing the supply function, while industries that use that feedstock represent the demand. The agricultural producers can export their commodities. The exports are represented by the excess supply function; the excess demand function is the aggregation of countries who import from the U.S.

The three markets on the bottom panel are the biofuel, byproduct, and fossil fuel markets. Biorefineries produce biofuel and represent the supply function in the biofuel market, while the petroleum fuel distributors that blend the biofuel with fossil fuel represent the demand function. Biorefineries also produce a byproduct, indicated by the supply function in the byproduct market whereas firms using that byproduct represent the demand. The petroleum distributors supply fossil fuel in the fossil fuel market while consumers use the fossil fuels in vehicles, representing the fossil fuel demand function.

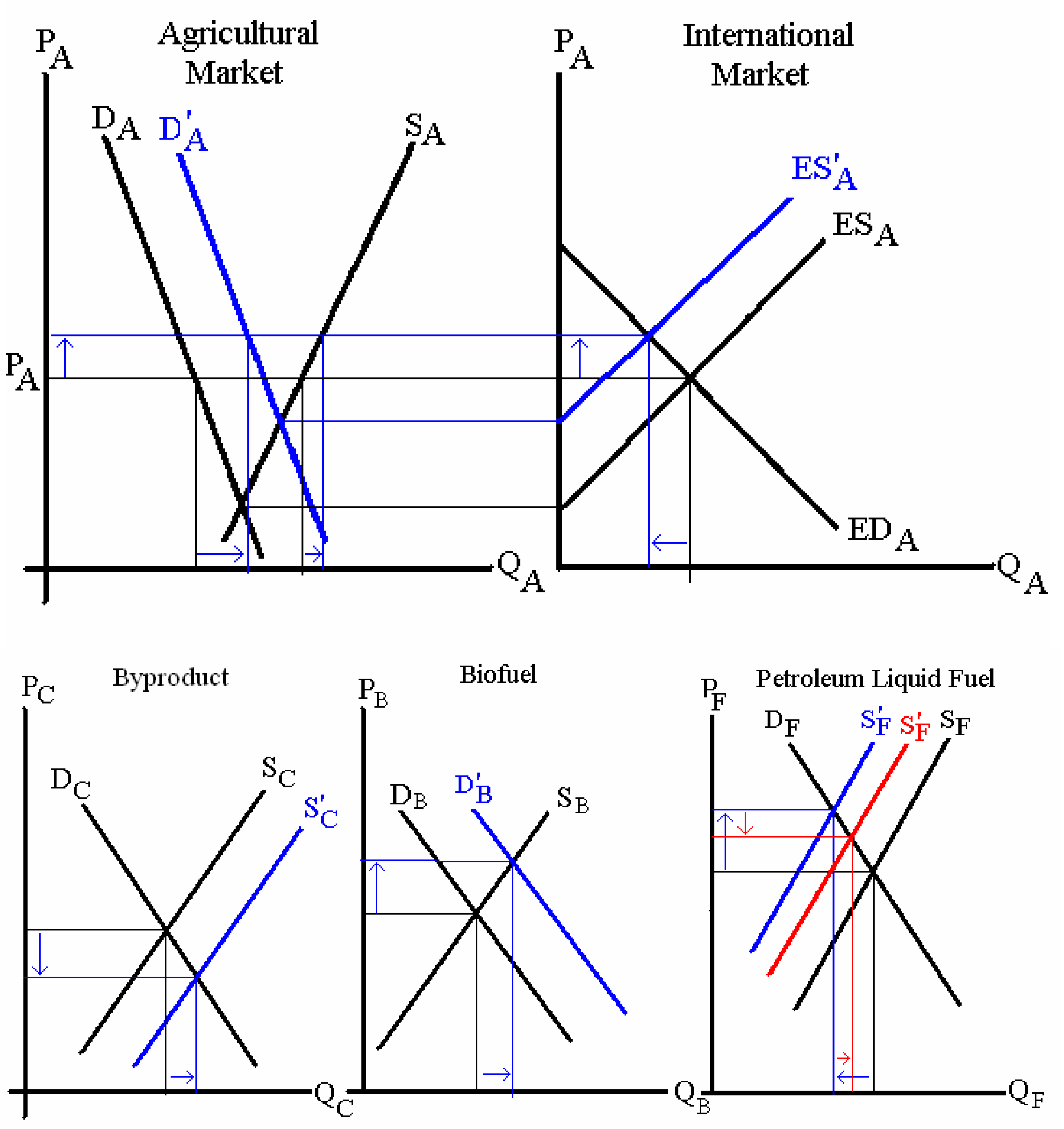

Figure 2.1. Economic impact of higher energy prices

A decreasing petroleum supply causes a higher petroleum liquid fuel price and lower market quantity. The blue lines indicate equilibrium changes. The higher fuel prices create a higher demand for biofuels, increasing the biofuel price. Biorefineries increase biofuel quantity supplied, and produce more byproducts. Expanded biorefinery production requires more feedstocks, increasing the demand for feedstocks in the agricultural market. As this demand increases, feedstock prices and quantities both increase. An increasing agricultural demand causes the excess supply function to decrease, causing U.S. exports to fall.

Biorefineries are producing more biofuel, and fossil fuel distributors blend this biofuel to their fossil fuels. The fossil fuel supply increases, causing fossil price to fall and quantities to increase. The red line indicates the equilibrium change. One assumes the fossil fuel price does not fall below the original market price. Moreover, a higher biofuel production increases the supply of byproducts, causing byproduct market price to fall and quantity to increase.

This analysis is further complicated, because energy prices raise the cost of agricultural production. Furthermore, a higher demand for petroleum fuel will have a similar impact on the agricultural and biofuel markets.

2.2. Technological Progress

Technological progress improves the chemical yield coefficients, allowing biofuel producers to produce more biofuel given the same level of inputs. The market system is shown in Figure 2.2 and the black lines are the initial market equilibrium. The supply and demand functions are defined the same way as in the higher energy price scenario.

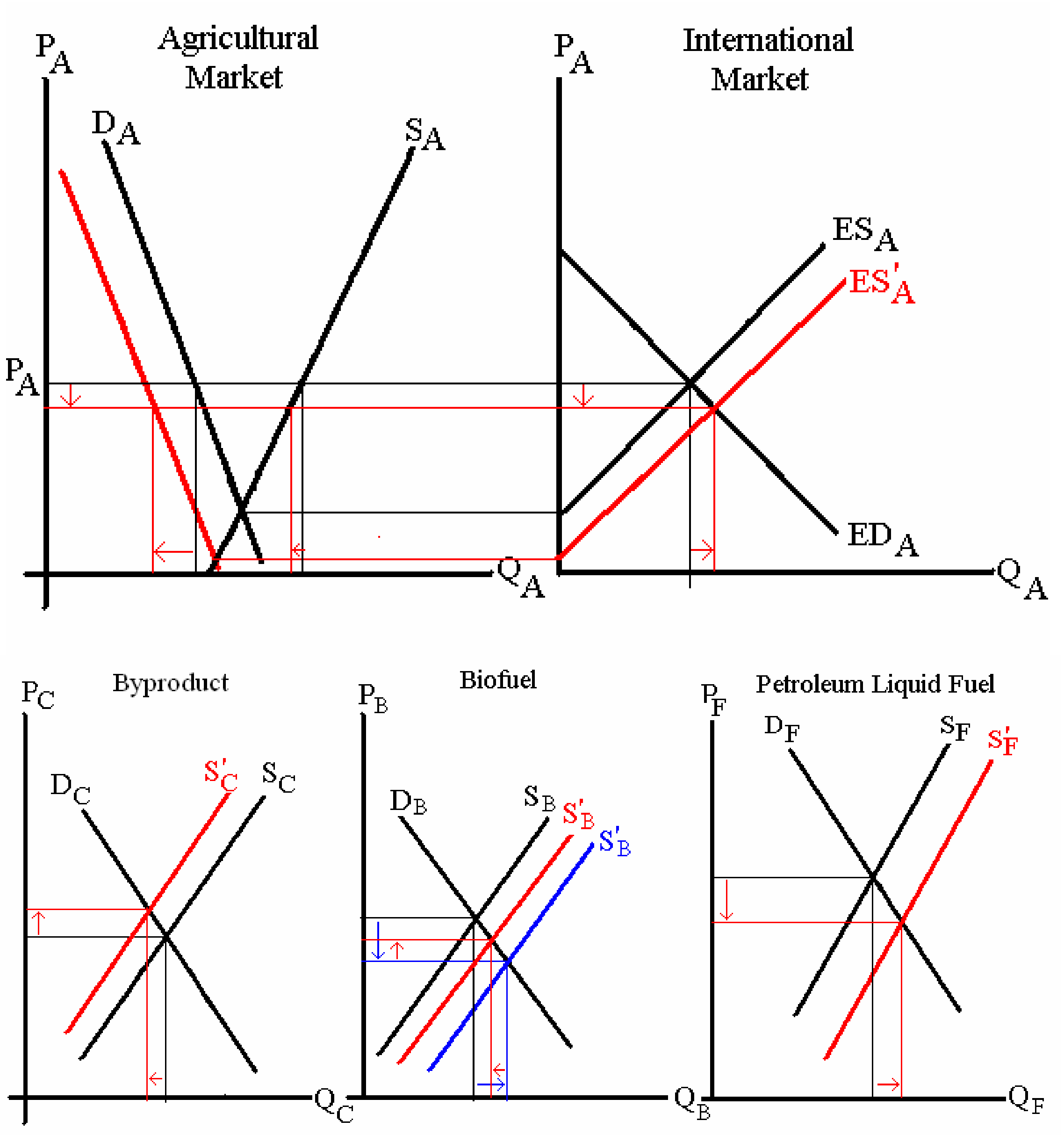

Figure 2.2. Economic impact of technological progress

Technological progress causes the biofuel supply function to shift to the right, causing the biofuel price to decrease for any given quantity as represented by the blue line. However, the biofuel price relative to the feedstock price decreases, causing the biorefineries to decrease supply. The biorefineries still produce more biofuel with lower market prices and higher quantity, but they decrease their demand for feedstock. The red lines are the final equilibrium. The demand for the agricultural feedstock decreases, causing a lower feedstock price. The excess demand increases, causing more of the agricultural commodity to be exported. The biorefineries process less feedstock, decreasing their supply of byproducts. The byproduct's price increases and quantity decreases. Moreover, the petroleum distributors blend more biofuel with fossil fuels because of the lower biofuel price. Fossil fuel supply function increases, causing fossil fuel price to fall and quantity to increase.

The same results apply, if technological improvement causes production costs to decline over time. On the other hand, crop yield improvement changes the analysis. If crop yields increase, then the supply function in the agricultural market increases, causing the agricultural price to fall and the U.S. exports more agricultural product. The feedstock price is lower, causing biorefineries to expand production. More biofuel and byproducts are produced. Consequently, the supply function increases for the byproducts, biofuel, and fossil fuel markets, increasing equilibrium quantities and decreasing prices.

2.3. Government Subsidies

Government subsidies expand biofuel production and the market system is shown in Figure 2.3. The black lines are the initial market equilibrium.

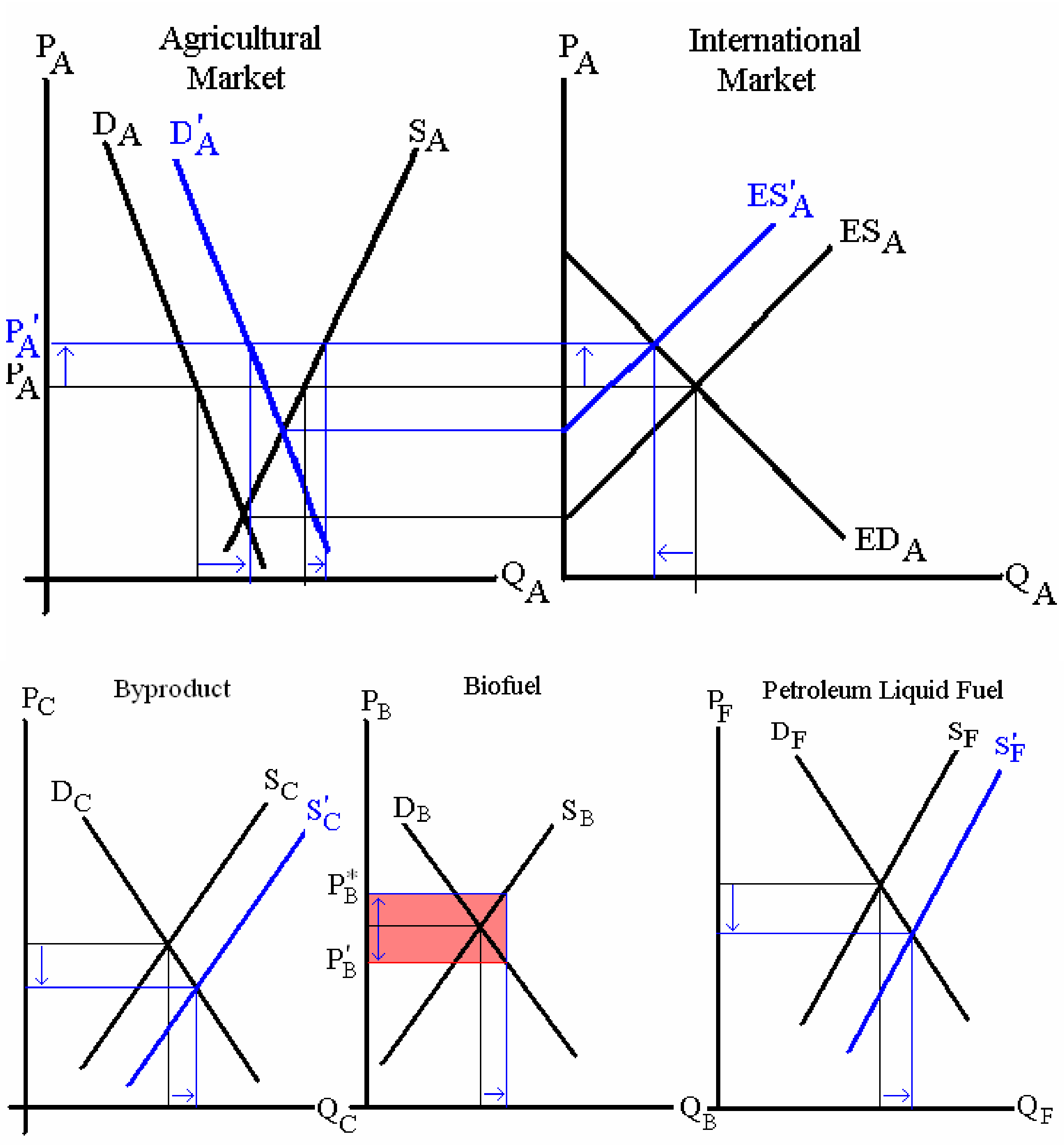

Figure 2.3. Economic impact of a government subsidy

The government grants a biofuel subsidy as depicted by the reddish box in the biofuel market and the blue lines are equilibrium changes. The subsidy creates a price wedge with the market price being P_B^* while petroleum refiners pay $P_B^{'}$. As biorefineries produce more biofuel, the byproduct's supply function and petroleum fuel supply function both increase. The market prices decrease and market quantities increase in these markets. For biorefineries to produce more biofuel, they increase their demand for feedstocks. The biofuels industry increases their demand for feedstocks, increasing the demand function in the agricultural market and decreasing the excess supply function. The market price for the agricultural commodity is higher and the U.S. exports less.

2.4. GHG Offset Prices / Carbon Dioxide Equivalent Taxes

The no-government policy for regulating GHGs is not necessarily the most efficient policy, because market failure results from nonpoint pollution and a transboundary externality. Nonpoint pollution is extremely difficult for a government to monitor and regulate, because millions of sources like cars and trucks are emitters. Consequently, polluters can take advantage and pollute more. For the transboundary externality, once society emits GHG into the atmosphere, the whole planet is impacted. The Kyoto Protocol is an attempt to address transboundary pollution.

If the Kyoto Protocol were to come fully into force, it is likely that there would be a price for GHG emissions. The GHG price is more complicated to analyze than the previous scenarios. The market system is shown in Figure 2.4 and the black lines are the initial market equilibrium. The petroleum and biorefineries emit GHGs into the atmosphere mainly in the form of CO2 and thus the GHG price becomes a tax on CO2 emissions. The producers are more likely to purchase the emission permits, because the number of consumers far exceed the number of sellers.

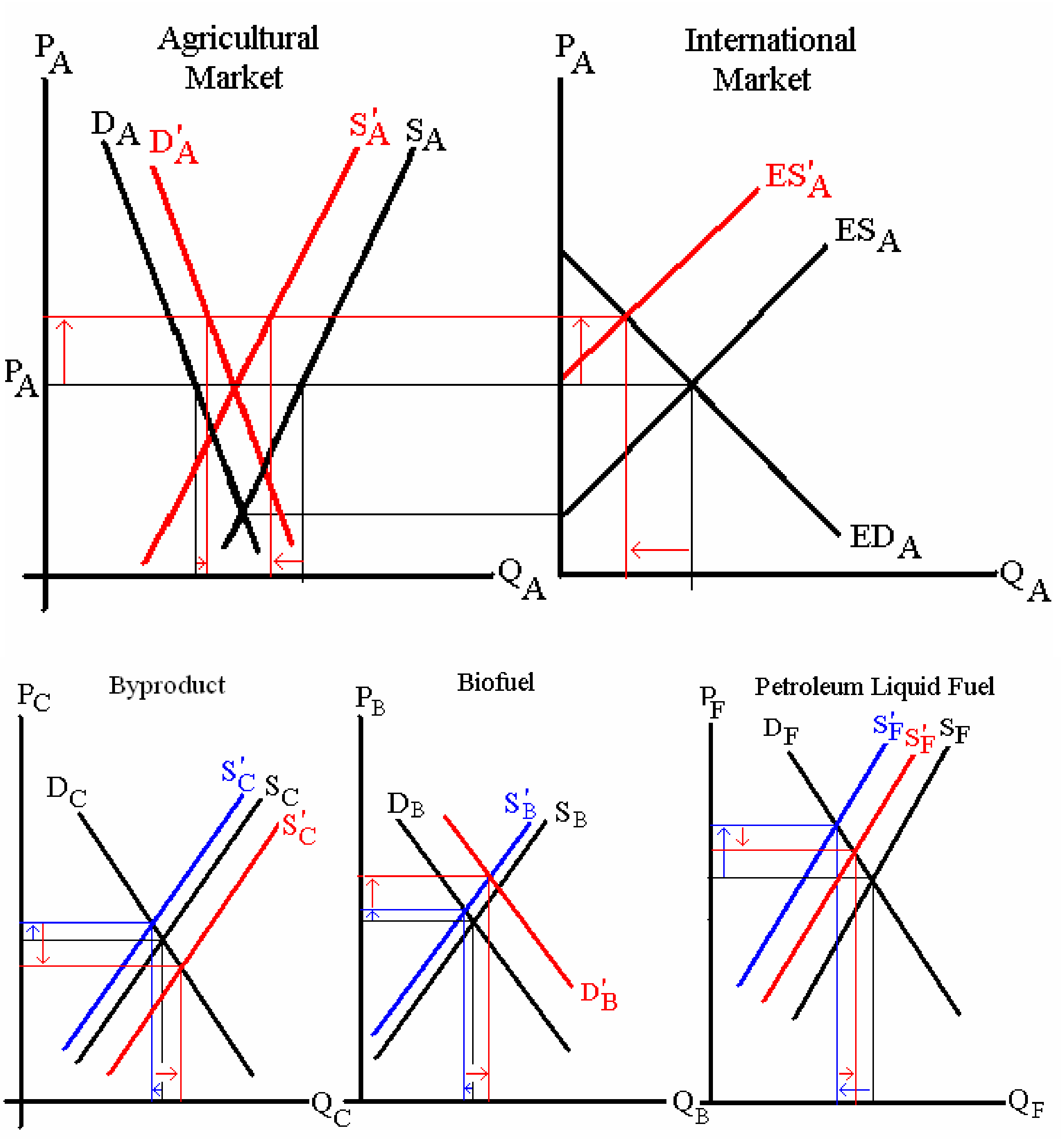

Figure 2.4. Economic impact of carbon dioxide equivalent price

The GHG price causes the petroleum fuel supply and biofuel functions to decrease. The blues lines indicate the market changes. When less biofuel is produces, less byproducts are supplied to the market. The market quantities decrease and prices increase in these three markets. An important assumption is biofuel supply function decreases less than the liquid fuels market, because GHG emissions are smaller. If this were not the case, then biofuel market quantity becomes indeterminate.

Biofuels become relatively cheaper than fossil fuels, and petroleum distributors increase their demand for biofuels and blend the biofuel, increasing the petroleum supply. The red lines indicate the final market equilibrium. After all market adjustments, the petroleum and biofuel market prices are higher. However, petroleum fuel market quantity is lower and biofuel quantity is higher than the original market condition. The biofuel industry increases it demand for agricultural feedstocks, increasing the agricultural demand function. With biorefineries producing more biofuel, more byproduct is supplied to the market, lowering the price and increasing the quantity.

The supply function of the agricultural commodity also decreases, because some producers switch land use into forests. Trees sequester carbon dioxide from the atmosphere and are thus a sink for GHGs. Therefore, GHG prices would be a subsidy in this case. The supply function decreases, making less land available for crops and the excess supply function decreases. The agricultural commodity price increases, agricultural market quantity becomes indeterminate, and the U.S. exports fewer commodities.

3. BACKGROUND ON BIOFUELS

This section discusses the societal benefits of biodiesel and ethanol blended gasoline, and their compatibility with their respective fossil fuels.

3.1. Societal Benefits of Biodiesel and Ethanol

Biodiesel and ethanol have six characteristics that are beneficial for the U.S. economy.

- Biofuels are renewable and increase the demand for agricultural commodities, thus potentially boosting agricultural producers' income and prices[3].
- Biofuels could be produced domestically in the U.S., reducing petroleum imports, improving the balance of payments, improving national energy security, and reducing the reliance on petroleum from unstable areas of the world.
- Petroleum prices are volatile and projected to increase over time. However, biofuels are a backstop technology, potentially constraining the growth in petroleum prices.
- Biofuels recycle carbon from the atmosphere and have cleaner emissions, thus reducing GHG emissions and mitigating climate change.
- Petroleum distributors could easily blend biofuels with fossil fuels, and consumers could currently use the blended fuels in automobiles. Thus, society can easily phase in biofuels without the costly upgrades and engine replacements.

Each of these is further discussed below.

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[3] Higher commodity prices reduce U.S. consumer welfare and U.S. exports, which is shown in Section 8.1.

3.1.1. Additional Source of Income

A large biofuels industry could increase prices and income for the agricultural sector (Duffield et al. 1998; Gallagher et al. 2003; McCarl et al. 2000; Schneider and McCarl 2003; Sheehan et al. 1998; Yahya et al. 2004). Agricultural producers are subject to low commodity prices, largely inelastic demand, and many unpredictable events. The unpredictable events originate from the weather, biological problems like destructive viruses, fungi, or insects, volatile commodity prices and yields, business cycles causing shifting demand for agricultural products over time, and unstable export demand. The low commodity prices and unpredictable events cause farmers' income and wealth accumulation to be low and variable (Mishra et al. 2002). However, a large energy industry provides an elastic demand for biofuels and if biofuel industry is large this in turn creates a large demand for agricultural feedstocks, increasing agricultural prices and incomes. Further, biofuels could help farmers hedge against agricultural fluctuating prices, because a farmer could grow a variety of crops, and still able to supply renewable energy.

A large biofuels industry has other benefits, which include reductions in government subsidies to farmers (Shapouri et al. 1995), movement of dormant agricultural land into production (Ortiz-Canavate 1994; Van Dyne, Weber, and Braschler 1996), and increases in rural employment (Shay 1993; Stenzel et al. 1980; Van Dyne, Weber, and Braschler 1996). For instance, farmers hire more workers to grow more energy crops and biorefineries hire more workers to convert energy crops into biofuel. The biorefineries are expected to be located close to the agricultural producers, because hauling costs increase exponentially the further the feedstocks are transported. Finally, the biofuels industry is capital intensive, expanding the tax base for rural governments (Stenzel et al. 1980; Van Dyne, Weber, and Braschler 1996).

3.1.2. Reduced Reliance on Foreign Oil

Petroleum imports are growing over time and currently, the U.S. imported approximately 69% of U.S. petroleum consumption in 2004 (Energy Information

Administration 2005a). A country that imports a large share of its petroleum needs usually suffer from significant trade deficits (Gnansounou, Dauriat, and Wyman 2005). A biofuels industry could help the U.S. import less petroleum, because producers grow and manufacture the biofuels domestically (Durbin et al. 2000; Fukuda, Kondo, and Noda 2001; Hewlett et al. 1983; Sheehan et al. 1998; Van Dyne, Weber, and Braschler 1996; Wang et al. 2000; Zhang et al. 2003a).

Importing large quantities of oil especially from the Middle East, Nigeria, and Venezuela creates two problems. First, these regions are politically volatile and exporting oil leads to large exchange earnings that can be used to acquire military hardware equipment, posing security issues (Lugar and Woolsey 1999). Second, less reliance on the Middle East for oil allows the U.S. to decrease its military presence in the Gulf States. Thus, a biofuels industry could enhance national security (Duffield et al. 1998; Durbin et al. 2000; Gallagher et al. 2003; Lugar and Woolsey 1999; McCarl et al. 2000).

3.1.3. Price Stabilization

Petroleum prices are expected to be volatile and continuously increase over time. The Middle East is the source of the crude oil spikes in 1973, 1979, and 1990 (Lee and Ni 2002; Lugar and Woolsey 1999; OPEC 2006). Furthermore, both the Chinese and Indian economies are growing fast, increasing global energy demand and petroleum prices. For example, China switched from a net exporter of petroleum to a net importer in 1993, and today is building more complex refineries that can process sour crude oil (high sulfur content) from the Middle East (Wang 1995; Haijang 1995). Moreover, India imported approximately 74% of its petroleum needs in 2002 (Rao 2002).

A biofuels industry could constrain the growth of petroleum prices, because biofuels are a backstop technology. If petroleum prices increase too rapidly, then society substitutes biofuels for petroleum. If biofuel prices increase too rapidly, then farmers expand their production of energy crops, decreasing the biofuel’s market price.

3.1.4. Reduce GHG and Other Pollution Emissions

As ready mentioned earlier, biofuels mitigate global warming by recycling carbon from the atmosphere and reduce most tail-pipe pollution from compression engines. However, tail-pipe emissions are variable and depend on the engine design, manufacturer, engine age, and engine maintenance. Biofuels contain little sulfur and no mercury. Therefore, sulfur dioxide and mercury emissions decrease when biofuels are blended with diesel and gasoline (Barnwal and Sharma 2005; Encinar et al. 2002; Fukuda, Kondo, and Noda 2001; Kadam 2000; Shay 1993; Sheehan et al. 1998; Srivastava and Prasad 2000; Wang et al. 2000).

Biodiesel and ethanol are oxygenates while diesel fuel and gasoline contain almost zero oxygen. Pure biodiesel contains 10-12 % oxygen on a weight basis (Barnwal and Sharma 2005; Canakci 2007; Duffield et al. 1998; Encinar et al. 2002; Fukuda, Kondo, and Noda 2001; Graboski and McCormick 1998; Srivastava and Prasad 2000; Wang et al. 2000) while ethanol contains 35% oxygen (Nevin 2005; Rask 1998; Shapouri et al. 2002). The presence of oxygen allows more complete combustion, which reduces emissions from hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Unfortunately, for both fuels, the higher oxygen content increases NOX emissions (Barnwal and Sharma 2005; Canakci 2007; Duffield et al. 1998; Fukuda, Kondo, and Noda 2001; Graboski and McCormick 1998; Hewlett et al. 1983; Kadam 2000; Nevin 2005; Sheehan et al. 1998; Srivastava and Prasad 2000; Wang et al. 2000).

3.1.5. Compatibility with Current Cars

The U.S. auto and truck fleet can use biodiesel and ethanol. Namely,

- Biodiesel could be blended with diesel fuel with any percentage while ethanol could be blended up to 15% with gasoline with little or no modification to engines (Canakci 2007; Duffield et al. 1998; Hewlett et al. 1983; Tshiteya and Tshiteya 1998; Wang et al. 2000). When producers blend biofuels with fossil fuels, the concentration of ethanol is always written as

EXX and biodiesel is written as BXX. For instance, E10 means the fuel is 90% gasoline and 10% ethanol by volume.

- Car manufacturers are offering flexible fuel vehicles that can use up to E85 (Gnansounou, Dauriat, and Wyman 2005; Lugar and Woolsey 1999).

In addition, the Energy Policy Act of 2005 mandates a fuel standard for biodiesel and ethanol. A fuel standard requires car manufacturers to design engines and extend warranties to a known, standardized fuel (U.S. Government Printing Office 2005).

3.2. Compatibility between Biofuels and Fossil Fuels

Biofuels are not perfect substitutes for petroleum-based fuels. Biofuels have additional benefits and costs, which are likely to cause the consumers to value biofuels differently and therefore, change consumer's willingness to pay for biofuels. Biodiesel is discussed first, and then ethanol.

3.2.1. Biodiesel Compatibility

To address fuel compatibility one must make assumptions about fuel manufacturing practices. The following discussion assumes biorefineries use methanol to produce biodiesel, because methanol is the cheapest alcohol and the most widely researched (Gerpen et al. 2004; Sheehan et al. 1998; Zhang et al. 2003a). Biorefineries could make biodiesel from ethanol and other alcohols, but this changes some of the fuel properties (Encinar et al. 2002; Gerpen et al. 2004).

The cetane number is the most important property of diesel fuel. Diesel engines do not have spark plugs. The engine's piston compresses the fuel and air mixture until heat and pressure ignite the mixture. This ignition point is identified by the cetane number. Diesel fuel has a cetane number that ranges between 40 and 45, with higher quality diesel fuels having higher cetane numbers (Gerpen et al. 2005; Leffler 1985, pp.104-106).

Biodiesel has comparable cetane numbers to conventional diesel, but varies with the feedstock and the alcohol used in the chemical conversion. For instance, biodiesel made from saturated oils, such as lard and tallow have higher cetane numbers than biodiesel produced from vegetable oils (Duffield et al. 1998; Gerpen et al. 2004).

Biodiesel has two benefits when compared to number 2 diesel. First, biodiesel has a higher flash point than diesel. The flash point is the minimum temperature the fuel must be heated to ignite the vapor and air (Duffield et al. 1998; Gerpen et al. 2004; Graboski and McCormick 1998; Srivastava and Prasad 2000). The U.S. Department of Transportation defines a nonhazardous fuel with a flash point higher than 90 ^{0}C. Number 2 diesel has a flashpoint of 71 ^{0}C while pure soydiesel with no impurities has a flash point over 100 ^{0}C, making soydiesel nonhazardous (Duffield et al. 1998; Graboski and McCormick 1998). Second, pure biodiesel has better lubrication properties than number 2 diesel. Biodiesel lubricates the fuel pump and fuel injectors, which could extend engine life (Duffield et al. 1998; Gerpen et al. 2004; Graboski and McCormick 1998). Ag Processors, Inc. are exploiting this property of soydiesel and marketing SoyGold as a diesel fuel additive (Duffield et al. 1998).

Biodiesel also has undesirable properties that could prevent market penetration. Two important properties are the biodiesel's cloud and pour points. Cloud point is the temperature that causes the fuel to form wax on the fuel filter, thus clogging it, whereas pour point is the temperature the fuel turns into a gel, impeding fuel flow. The cloud point and pour point for biodiesel fuels made from unsaturated oil tend to be 0^{0} C and -5^{0} C, while number 2 diesel has a cloud point ranging from -15 to 5^{0} C and a pour point ranging from -35 to -15 ^{0} C (Barnwal and Sharma 2005; Duffield et al. 1998; Graboski and McCormick 1998; Tyson et al. 2004; Srivastava and Prasad 2000). If biorefineries produce biodiesel from saturated oils like tallow and lard, then the cold flow properties are worse. Cloud and pour points are approximately 14^{0}C and 10^{0}C (Barnwal and Sharma 2005; Duffield et al. 1998; Graboski and McCormick 1998; Tyson et al. 2004). Thus, biodiesel may not be usable during winter where temperatures dip below freezing.

Four more problems are associated with biodiesel. First, biodiesel contains lower energy than diesel. The lower energy content reduces torque, acceleration, and miles per gallon rating of the vehicle (Gerpen et al. 2004; Graboski and McCormick 1998; Tyson et al. 2004). The lower energy content may require vehicles to have larger fuel tanks, increasing vehicle cost. Second, biodiesel made from unsaturated oils tends to oxidize and degrade over time while biodiesel made from tallow and lard degrades less (Canakci 2007; Duffield et al. 1998). The chemical reactivity depends whether the chemical bonds in the source oil are saturated or unsaturated (Canakci 2007; Duffield et al. 1998; Graboski and McCormick 1998). Third, if water is dissolved in the biodiesel, the water encourages microbial growth (Gerpen et al. 2004). Finally, biodiesel could cause engine problems like engine deposits (Graboski and McCormick 1998), and degrade engine gaskets and seals (Tyson et al. 2004; Graboski and McCormick 1998; Shay 1993).

Producers may also have difficulties transporting biodiesel through pipelines. First, biodiesel dissolves the impurity buildup from diesel fuel, becoming contaminated. Second, biodiesel contains oxygen and the oxygen could react with the impurities in diesel fuel, forming insoluble gums and buildup in the pipeline (Duffield et al. 1998; Graboski and McCormick 1998). Finally, biodiesel freezes around -5 ^{0}C. The biodiesel could gel and impede flow through the pipeline during winter in northern states.

The biodiesel cold flow properties have to improve for large-scale penetration of biodiesel. Researchers are searching for biodiesel additives that could improve the cold flow properties, because B20 blends may still have cloud point problems (Duffield et al. 1998; Graboski and McCormick 1998; Srivastava and Prasad 2000).

3.2.2. Ethanol Compatibility

The two most important properties for gasoline are vapor pressure and octane rating. Vapor pressure is important for starting a cold engine. When the car engine is cold, some of the fuel has to vaporize easily, so the fuel can be mixed with air and combusted in the engine. Once the engine is warm, the other components of the fuel will easily vaporize. Further the composition of gasoline changes with the season and climate. Gasoline needs a higher vapor pressure in the winter than summer, which helps start the car engine in colder temperatures (Leffler 1985, pp. 86-89).

The second important property is octane rating. Octane rating is a measure of how much pressure and temperature is needed to ignite the fuel/air mixture and is the opposite of the cetane number[4]. A high-octane gasoline is preferred, because premature fuel ignition in the engine causes a pinging sound, which places stress on engine parts and in some cases could damage the engine. Petroleum refiners produce several grades of gasoline with different octane ratings to meet car manufacturers' minimum octane rating for the vehicle (Leffler 1985, pp. 90-95).

Ethanol has three benefits, which makes it compatible with gasoline. First, pure ethanol has an octane rating between 112.5-114 (Gallagher et al. 2003; Reynolds 2000). Thus, the 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). Second, 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[5] (Lugar and Woolsey 1999; Gnansounou, Dauriat, and Wyman 2005; Nevin 2005; Reynolds 2000). Finally, pure ethanol is environmentally friendly. Accidental spillage of pure ethanol into the sea would cause minimal damage. Part of the ethanol would evaporate and the other part would dissolve in water, possibly causing intoxicated sea animals (Gnansounou, Dauriat, and Wyman 2005; Lugar and Woolsey 1999; Reynolds 2000). However, ethanol has problems, which could mitigate its benefits.

Ethanol has four disadvantages. First, 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

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[4] Engineers designed diesel engines to use heat and pressure to ignite the fuel/air mixture. However, this property is not desirable in gasoline engines. The gasoline engines use spark plugs to ignite the fuel at a precise point in the power stroke.

[5] Gasoline distributors, who use ethanol, would have to purchase lower vapor pressure gasoline in the summer, thus increasing gasoline costs (Reynolds 2000).

compensate. Second, 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. Third, 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. Over time the soil around filling stations could become contaminated (Nevin 2005). These problems with ethanol also cause problems in storing and transporting ethanol to the retail markets, especially through the pipeline.

Producers cannot transport ethanol and ethanol blends through pipelines for three reasons. First, moisture could accumulate in the pipeline, causing ethanol and water to mix. Second, ethanol and ethanol blends are corrosive to the pipeline, especially at the welded joints, and dissolves the impurity buildup in the pipeline. The impurities may be harmful to engines. As a result, producers would have to refit pipelines with noncorrosive liners (American Petroleum Institute 2006). Finally, pipelines originate from the south and transport petroleum products north, northeast, and northwest while current U.S. ethanol production is in the Midwest and flows in the opposite direction (Reynolds 2000).

Some researchers criticized ethanol for being energy inefficient. Researchers use the life-cycle energy efficiency, which is the ratio between energy output and energy input when manufacturing the fuel. A fuel is energy efficient if the ratio is greater than one. The amount of energy contained in one gallon of ethanol is the output while all energy sources used to produce that one gallon are the inputs. Energy efficiency is difficult to analyze, because it depends on ethanol conversion rate, crop yields, fertilizer manufacturing and application, byproduct analysis, and amount of energy used in each process (Hammerschlag 2006; Shapouri et al. 1995). Some researchers, like Pimentel (1991), argued that ethanol production is energy inefficient, because producers use more energy to grow, process, ferment, and distill the ethanol than the energy content of ethanol. With current technology, Shapouri et al. (1995) estimated the energy efficiency from corn ethanol including the byproducts as 1.24. If byproducts are removed from the analysis, the energy efficiency is closer to 1. When other life-cycle energy efficiencies are examined, soy-biodiesel is 0.8055, while diesel fuel is 0.8328, making them less efficient than corn ethanol (Sheenhan et al. 1998).

An alternative measure is the fossil-fuel energy efficiency, where the ratio is between energy output and the total amount of fossil fuel energy used in the input production process (Hammerschlag 2006; Sheenhan et al. 1998). Shapouri et al. (1995) estimated the fossil-fuel energy efficiency for ethanol as 7.09.

Some researchers criticized ethanol for increasing life-cycle GHG emissions. Again, the analysis for life-cycle emissions is similar to ethanol's energy efficiency. The energy crop absorbs carbon from the atmosphere, and producers release GHGs when they harvest, haul, ferment, and distill the feedstock into ethanol, and combusted into a car engine. The GHG emissions depend on a host of factors including fertilizer manufacturing and application, technology to produce and distill ethanol, byproduct processing, and tail pipe emission. The most variable is tail-pipe emissions, because the emissions depend on engine design, car maintenance, and driver's usage. Consequently, no studies are cited or referenced that pertain to GHG emissions.

If biodiesel and ethanol penetrate the liquid fuels markets, then car manufacturers may re-design the compression engines to over come some of these difficulties. Gasoline and diesel fuel contains hundreds of compounds while biodiesel contains less than ten (Gerpen et al. 2004) while ethanol contains only one compound. (Ethanol could include water if using pure ethanol as a fuel). Re-engineered engines may be better tailored to biofuels, because biofuels are chemically simpler than their petroleum counterparts.

3.3. Biofuel and Fossil Fuel Energy Differences

Biofuels contain less energy than their respective petroleum-based fuel and hence, energy content provides a basis to adjust the price and quantity of biofuels to comparable units of fossil fuels.

Researchers use two measures of energy content. The first is the higher heating value (HHV), which is the combustion energy including the energy to vaporize water while the second energy measure is the lower heating value (LHV), which only includes the combustion energy (Gerpen et al. 2004; Hammerschlag 2006). The lower heating values (LHV) are reported in Table 3.1, because the vaporization of water does not perform any work in the engine. Instead, water vapor exits the engine through the exhaust system.

One calculates the energy ratio coefficients by dividing the LHV for the biofuel into its respective petroleum liquid fuel, yielding the energy ratio coefficients as Equation 3.1. A range of LHV exists for all fuels, so the minimum and maximum ratios were computed and shown as an interval. The market ethanol price in FASOM-GHG is the gasoline price multiplied by 0.6609, while the biodiesel price is the diesel price multiplied by 0.9182.

Equation 3.1. Energy Ratio Coefficient for Biofuels

$$1 \text{ gallon biodiesel} = \left[0.8871,\ 0.9182\right] \text{ gallons of diesel fuel}$$

$$1 \text{ gallon bioethanol} = \left[0.6557,\ 0.6609\right] \text{ gallons of gasoline}$$

Table 3.1. Energy Content of Fuels

Fuel	Lower Heating Value (BTUs/gallon)
Gasoline	115,000[d] - 115,400[a]
Diesel fuel	128,700[a] - 132,000[b]
Ethanol	75,670[a] - 76,000[d]
Biodiesel	117,093[a] - 118,170[b,c]

Sources:

a. Davis and Diegel 2006, Table B.4
b. Duffield et al. 1998
c. Gerpen et al. 2004
d. Sheehan et al. 2004

4. FUTURE ENERGY PRICES

Energy prices are potentially a key factor in forecasting biofuel market penetration. Thus, this section examines the basic economic and engineering issues that relate to fossil fuel prices. For a biorefinery to supply biofuel to the market, the price of the petroleum fuel must be greater than or equal to the cost of producing the biofuel, when market price and quantity are in comparable units. If petroleum fuel prices remained as high as they were in summer 2006 or rise even further, then firms could supply biofuels competitively. Of course, if fuel prices decrease substantially, then biofuels may never penetrate the fuels market. Moreover, FASOM-GHG does not contain petroleum markets, causing the fossil fuel prices to be perfectly elastic to the biorefineries. The ideas in this section could allow future researchers to add more fossil fuel price dynamics to FASOM-GHG.

4.1. The U.S. Petroleum Market System

The U.S. petroleum industry is a large, vertically integrated industry that extracts petroleum from the ground, transports the oil to the refineries through pipelines, and the refineries produce a variety of liquid fuels and chemicals (Gallagher et al. 2003; Ortiz-Canavate 1994). Furthermore, the petroleum companies sell the liquid fuels directly to the consumers through franchises.

A simplified view of the U.S. petroleum market system is graphically shown in Figure 4.1 and the black lines define the original market equilibrium. The oil companies extract crude oil from the ground, and represent the petroleum supply function, while the U.S. refineries use petroleum as an input, representing petroleum demand. The excess demand function indicates the U.S. imports petroleum and the excess supply function is the aggregation of all countries that export oil to the U.S. The petroleum refineries produce gasoline and diesel fuel as the two largest commodities. The U.S. refineries represent the supply functions, while the consumers who use the fossil fuels represent the demand functions for the gasoline and diesel fuel. The U.S. refineries have a production constraint, where the supply function becomes vertical when production reaches Q_{max} for each petroleum fuel. Moreover, the import and export markets are small for liquid fuels and no international markets are incorporated into the graphs.

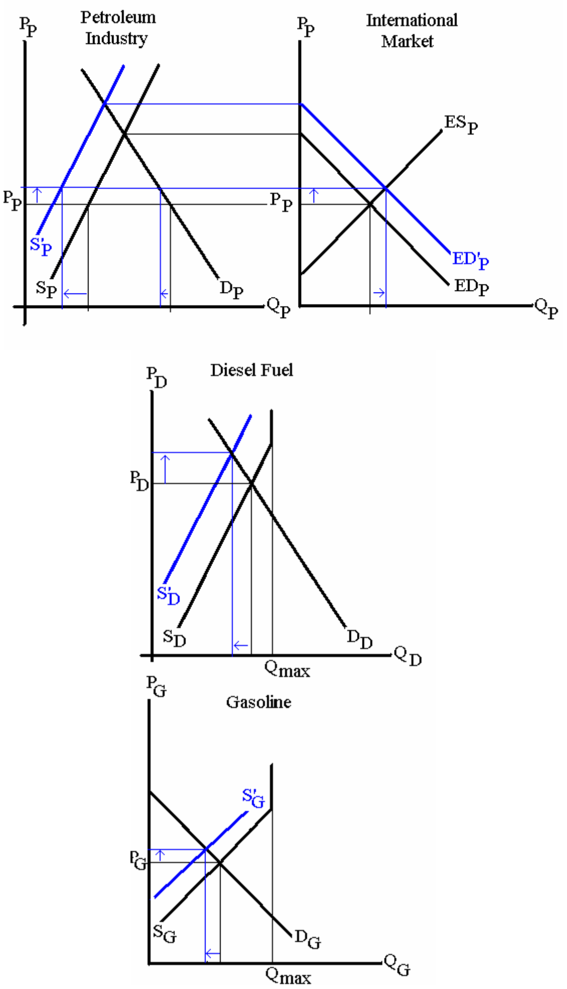

Figure 4.1 Market impact of declining petroleum reserves

Petroleum is a depletable resource and each barrel extracted today leaves less petroleum for the future. The blue lines indicate changes in market equilibrium in Figure 4.1. As petroleum is depleted, the domestic supply of petroleum decreases.

Moreover, the excess demand function increases, causing the market price to increase, domestic quantity supplied to decrease, and the quantity of imports to increase. U.S. refineries have less oil to process, thus the supply functions for gasoline and diesel fuel decrease, causing the market price for fuels to increase and quantity supplied to decrease.

Another scenario is the demands for gasoline and diesel fuel both increase, and is shown in Figure 4.2. The initial market conditions and specifications are the same as the last example and the black lines indicate the initial market equilibrium. Both the demand functions increase in the gasoline and diesel fuel markets, and are indicated by the red lines. The higher demand causes higher market prices and refineries increase quantity supplied. For the U.S. refineries to produce more, they increase their demand for petroleum, causing the petroleum demand function and excess supply functions to both increase. The petroleum market price increases, petroleum companies extract and import more petroleum. If demand for liquid fuels keeps increasing until refineries reach their maximum production capacity, then market quantity is constrained at the maximum and only the gasoline and diesel fuel prices increase.

4.2. Petroleum Production Possibilities

This section gives a brief overview of petroleum refining and some of the characteristics involved. Petroleum refining involves two processes. The first process is to separate each component from petroleum into finished and intermediary products and the process is called fractional distillation. Refineries heat the crude oil until each substance in crude oil vaporizes and rises in a distillation tower. Each substance has a different condensation temperature and condenses at different points in the tower, allowing the refinery to separate the substances. Lighter hydrocarbons condense at higher points in the tower (Leffler 1985, pp.6-8; Office of Integrated Analysis and Forecasting 2006). The second process is to chemically convert the intermediary products into finished products. The key inputs to the petroleum refining industry are petroleum and natural gas while the key outputs are gasoline and diesel fuel[6]. Moreover, the refineries manufacture many other chemicals such as jet fuel, liquid petroleum gases, asphalt, and chemicals to manufacture plastics.

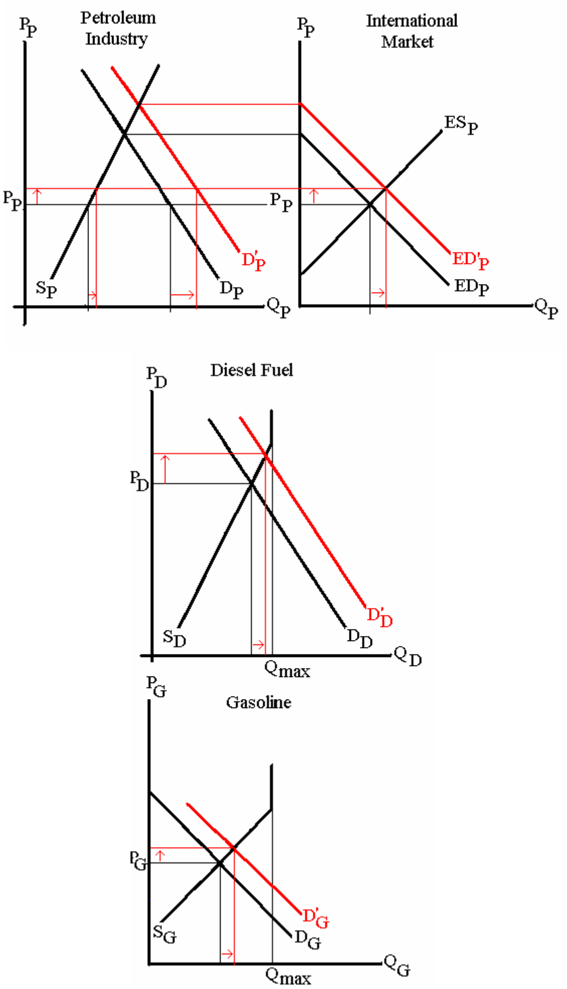

Figure 4.2. Market impact of increasing fossil fuel demands

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[6] Diesel fuel is also called distillate fuel oil.

The first characteristic is diesel, gasoline, and petroleum are not homogeneous commodities. The composition of gasoline and diesel fuel changes with the season and crude oil source.

- Petroleum is composed of many compounds that span from methane (CH_4) to complex hydrocarbons like $C_{85}H_{60}$ (Gallagher et al. 2003; Leffler 1985, p.4) and petroleum's composition varies from well to well. Moreover, petroleum contains different levels of sulfur. Sour crude contains high levels of sulfur while sweet crude refers to low sulfur content. The output yields depend on the petroleum's composition and sulfur content.
- Gasoline contains hydrocarbons that range in length from C_4 to C_{12} (Waddams 1968, p. 15) and boils between 90 and 220^0 F (Leffler 1985, p.6). Moreover, refineries sell three levels of octane gasoline with different gasoline additives.
- Diesel fuel contains hydrocarbons that range in length from C_{12} to C_{25} (Srivastava and Prasad 2000; Waddams 1968, p. 15) and boils between 450 and 800^0 F (Leffler 1985, p.6). Moreover, diesel fuel comes as Number 1, Number 2, and Number 4 with a variety of sulfur levels. The transportation sector uses number 2 diesel and any future references to diesel fuel in this dissertation refer to Number 2 diesel (Gerpen et al. 2004).

The second characteristic is processing gain. Refineries do not create or destroy matter, but the volume changes as density changes. Heavier hydrocarbons have higher densities then lighter hydrocarbons. As refineries convert the heavier hydrocarbons into lighter ones, the lighter substances have lower densities, causing the substance to have more volume. Refiners refer to this phenomenon as "fluff up the barrel" by having the output chemicals having higher volumes than the input chemicals (Leffler 1985, p. 45). The average processing gain of using one barrel of crude oil in 2004 resulted in a gain 0f 1.068 barrels of products, which is a gain of 6.8% (Energy Information Administration 2005a). If the petroleum industry and society used a weight measure, then one could ignore processing gain.

The third characteristic is petroleum-refining technology is not a Leontief technology. Refineries have the flexibility to alter the production possibilities between diesel fuel and gasoline (Gallagher et al. 2003; Srivastava and Prasad 2000). Moreover, diesel fuel has a higher density than gasoline, thus, a refinery could convert one gallon of diesel fuel into more than one gallon of gasoline (Leffler 1985, p. 28). The production possibilities vary over a narrow range at the U.S. aggregate level and only the last 20 years are examined to minimize the impact of technological change. During 1984 and 2004, a barrel of petroleum input yielded 0.228 barrels of diesel fuel and 0.530 barrels of gasoline. The standard deviation is 0.0098 for diesel fuel and 0.0069 for gasoline (Energy Information Administration 2005a). Despite the refinery's ability to alter the production between gasoline and diesel fuel, the U.S. refinery industry produce a narrow range for these fuels.

The fourth characteristic is U.S. refineries use different technologies to create gasoline. The technologies are important, because ethanol-gasoline blends allow refiners to produce a lower octane gasoline, lowering the refiner's costs. Only four technologies are briefly discussed. The simplest technology is catalytic cracking (cat cracking) that subjects the heavier oils to high temperatures around 900 ^{0}F, high pressure, and a catalyst, which cause the oils to break down into simpler hydrocarbons used in gasoline (Leffler 1985, p. 39). The second technology is hydrocracking. This process is similar to cat cracking except refineries add hydrogen gas to the chemical reaction. The hydrogen saturates all the chemical bonds, resulting in high-octane gasoline (Leffler 1985, pp. 80-84). The third technology is alkylation and is the opposite of cracking. The refinery transforms small-chained hydrocarbons like propylene and butylene into heavier hydrocarbons used in gasoline (Leffler 1985, p. 59). Finally, the last technology is catalytic reforming that chemically transforms low octane gasoline components into higher octane ones (Leffler 1985, p 71).

The last characteristic is the constrained petroleum refining capacity. Petroleum companies gradually expanded the refining capacity in the U.S. for the last 30 years, because of government environmental regulations (Gallagher et al. 2003; Office of

Integrated Analysis and Forecasting 2006). The number of petroleum refineries in the U.S. was 149 in 2004, down by 127 refineries since 1976. During the same period, the refinery capacity increased 0.37% annually with refineries operating at 93% capacity in 2004 (Energy Information Administration 2005a). Consequently, refiners may not be able to increase gasoline and diesel fuel production, if prices for these commodities increase.

4.3. Increasing Energy Demand

U.S. society is increasing its demand for energy as shown in Figure 4.3[7]. Petroleum is the largest energy source, and then followed by natural gas and coal. If one converts petroleum consumption to a percentage, petroleum comprised approximately 40% of the U.S. energy consumption for the last 50 years (Energy Information Administration 2005a).

Renewable energy and nuclear energy are slowly growing over time. Renewable energy is energy derived from hydroelectric, wood, alcohol, geothermal, solar, and wind. If one converts renewable to a percentage, then renewable energy has consistently comprised only 10% of energy consumption during the last 30 years. On the other hand, nuclear energy remained roughly zero until the late 1960s and rose to 10% of energy consumption (Energy Information Administration 2005a). Many do not consider nuclear energy a significant backstop technology, because of the legal and regulatory barriers that prevent construction of nuclear power plants and the environmental hazard of storing nuclear waste for thousands of years.

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[7] All energy sources are converted to British Thermal Units (BTUs), allowing the comparison of different energy sources.

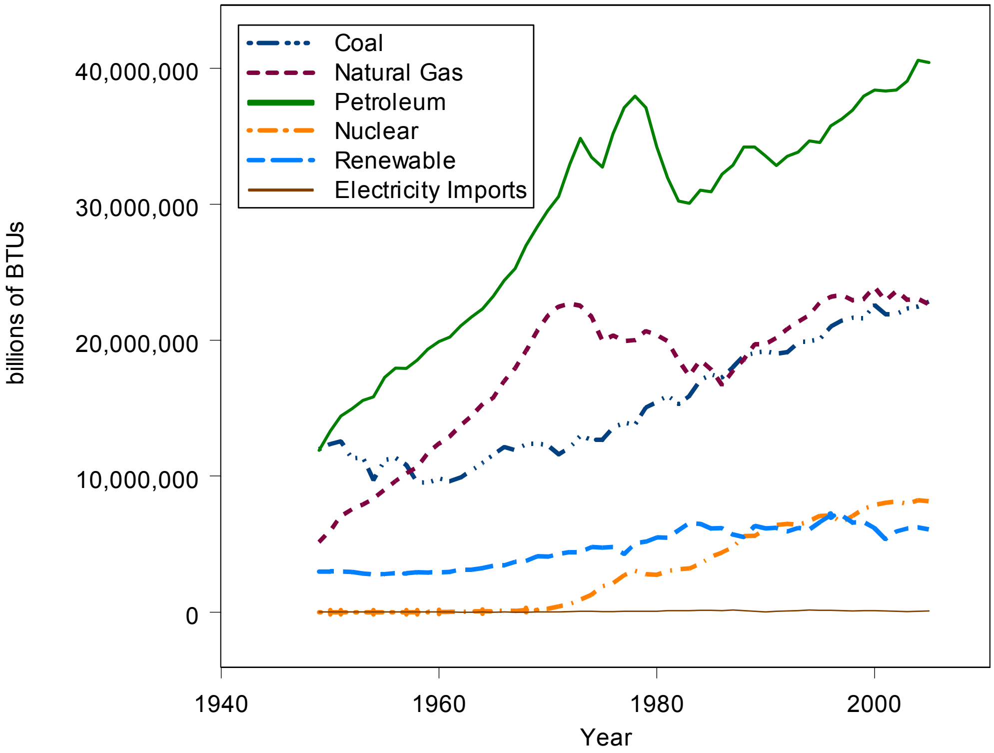

Figure 4.3. U.S. energy consumption

The last energy source is electricity and U.S. production of electricity is not included in Figure 4.3. Electricity is defined as a secondary energy source, because electric utility companies use other energy sources to create it. However, electricity imports are included, because a foreign country uses their primary energy sources to create electricity and sell its excess supply to the U.S. In Figure 4.3, electricity imports are small compared to the other sources.

4.4. U.S. Petroleum Imports

The U.S. imported 69% of its petroleum consumption in 2004 (Energy Information Administration 2005a). Moreover, petroleum imports are growing over time from both the Organization of Petroleum Exporting Countries (OPEC) and non-OPEC countries, and are shown in Figure 4.4. When examining the liquid fuels markets, the U.S. imports are small. In 2004, the U.S. imported 346.6 million barrels of gasoline and gasoline blending components while the U.S. imported 119.1 million barrels of diesel fuel. When compared to the U.S. market, the U.S. refineries produce 3 billion barrels of gasoline and 1.3 billion barrels[8] of diesel fuel (Energy Information Administration 2005a).

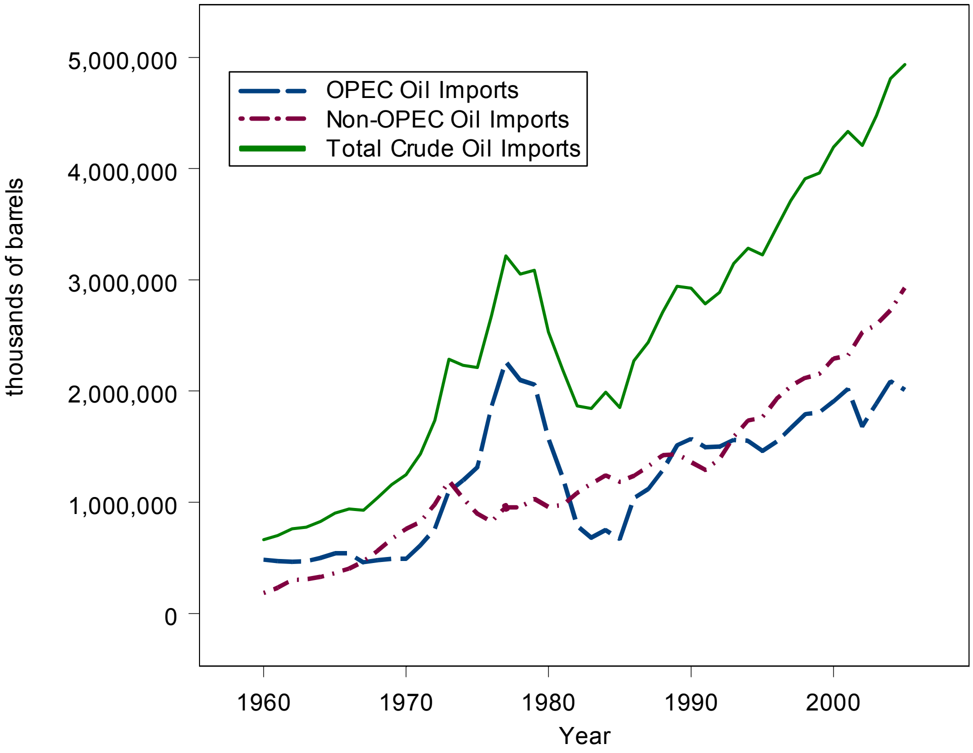

Figure 4.4. Annual total U.S. petroleum imports

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[8] Use the conversion 1 barrel = 42 gallons to convert units into gallons.

The U.S. relies on petroleum as a major energy source and imports a large share of its petroleum needs. Rapidly growing imports could present the U.S. with future political problems. As Figure 4.5 shows, non-OPEC countries hold a small portion of the world's petroleum reserves while collectively, OPEC holds the world's largest petroleum reserves with Saudi Arabia controlling approximately 1/3. Eventually, as non-OPEC nation's reserves are exhausted, the U.S. will eventually import a significant share of petroleum from OPEC, indirectly granting OPEC a large amount of economic and political power (Energy Information Administration 2005a).

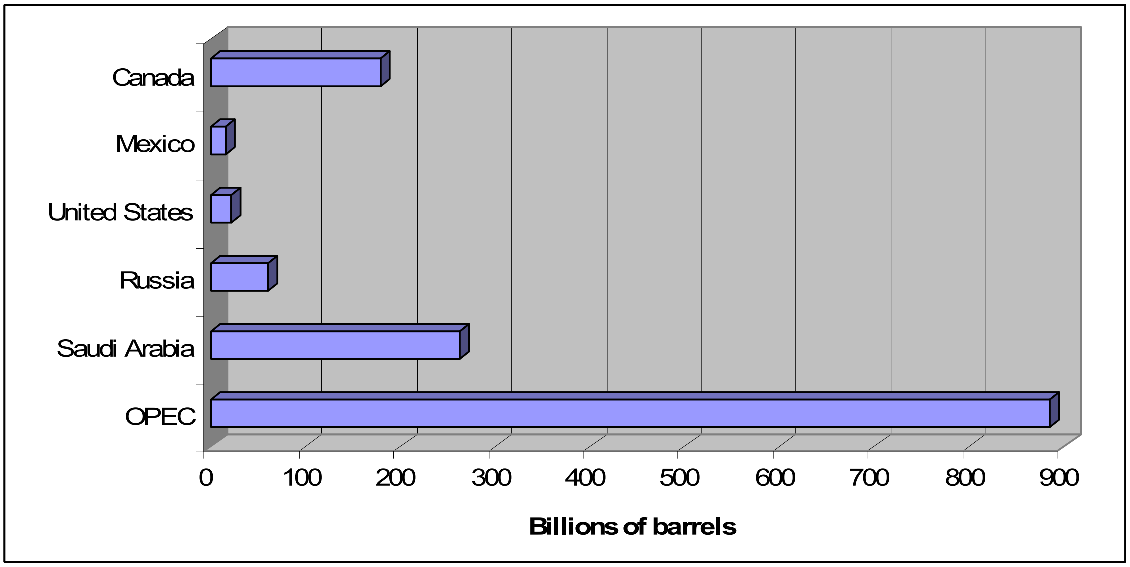

Figure 4.5: Proven petroleum reserves as of January 1, 2005

4.5. Hotelling's Rule

Petroleum is an exhaustible resource and the economic and geophysical characteristics of petroleum extraction suggest petroleum market prices follow

Hotelling's (1931) rule. First, as petroleum reserves are exhausted, ceterius paribus, the petroleum supply decreases over time, causing the market price to increase. Second, as the petroleum reserves are depleted, wellhead pressure decreases and crude oil viscosity increases, increasing marginal extraction costs (Banks 2004; Black and LaFrance 1998; Gray 1914; Faber and Proops 1993; Hartwick 1993; Heal and Barrow 1981; Pindyck 1981). Finally, as the low-cost petroleum reserves are depleted, firms extract petroleum from higher cost wells, like extracting petroleum from the deep waters of the Gulf of Mexico or the cold Alaskan climate (Pindyck 1981; Solow and Wan 1976). Consequently, higher marginal extraction costs and supply depletion lead to higher petroleum prices over time.

Hotelling's (1931) rule in a purely competitive market with zero extraction costs yields Equation 4.1, where $\dot{P}_t$ is the change in petroleum price over time, P_t is the price at time t, and r is the discount rate. The differential equation is solved for the time path, yielding $P_t = P_0 e^{rt}$. The time path indicates the petroleum price increases over time.

Equation 4.1. Hotelling's Rule

$$\frac{\dot{P}_t}{P_t} = r$$

The real U.S. petroleum price in dollars per barrel is shown in Figure 4.6. The price time path clearly shows petroleum prices are not following Hotelling's (1931) rule (Energy Information Administration 2005a).

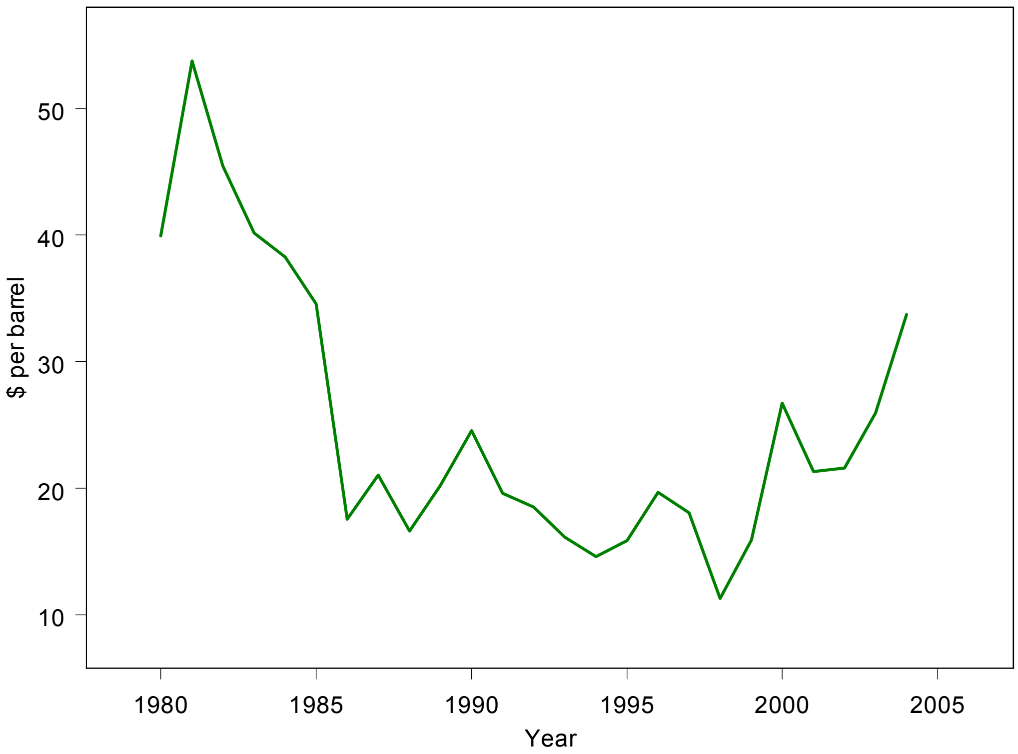

Figure 4.6. Real petroleum price

One can convert Hotelling's (1931) price rule into a quantity extraction rule. Assume a well-behaved demand function $Q_t = f(P_t, \mathbf{x_t})$ with Q_t as quantity demanded, P_t is market price, and $\mathbf{x_t}$ is a vector of variables that influence demand and is not a function of time. The Law of Demand is $\partial f / \partial P_t < 0$ and Hotelling's (1931) rule is solved for quantity, yielding $Q_t = f(P_0 e^{rt}, \mathbf{x_t})$. The change in the extraction path over time is the partial derivative $\frac{\partial Q_t}{\partial t} = P_0 r e^{rt} \frac{\partial f}{\partial P_t}$. The partial derivative is negative, because of the Law of Demand. Hotelling's quantity rule implies the quantity of petroleum extraction should decrease over time. However, the U.S. petroleum extraction is a parabola shape in Figure 4.7 (Energy Information Administration 2005a). The U.S. petroleum production reached its peak in the 1970s and has been declining ever since.

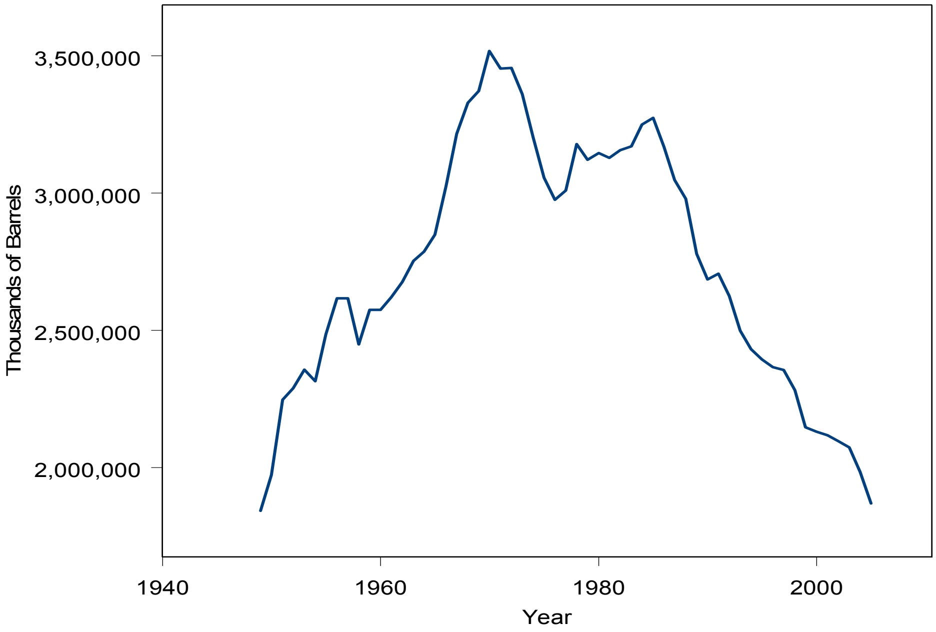

Figure 4.7. U.S. petroleum production

Another indicator for petroleum depletion is well productivity and is shown in Figure 4.8 (Energy Information Administration 2005a). The average well productivity is measured in thousands of barrels per well, and has been declining since the early 1970s. Moreover, the number of producing wells in the U.S. is approximately 560,000 with a standard deviation of 40,000 (Energy Information Administration 2005a). Collectively these data show that petroleum is being depleted in the U.S. and new wells are not coming into operation.

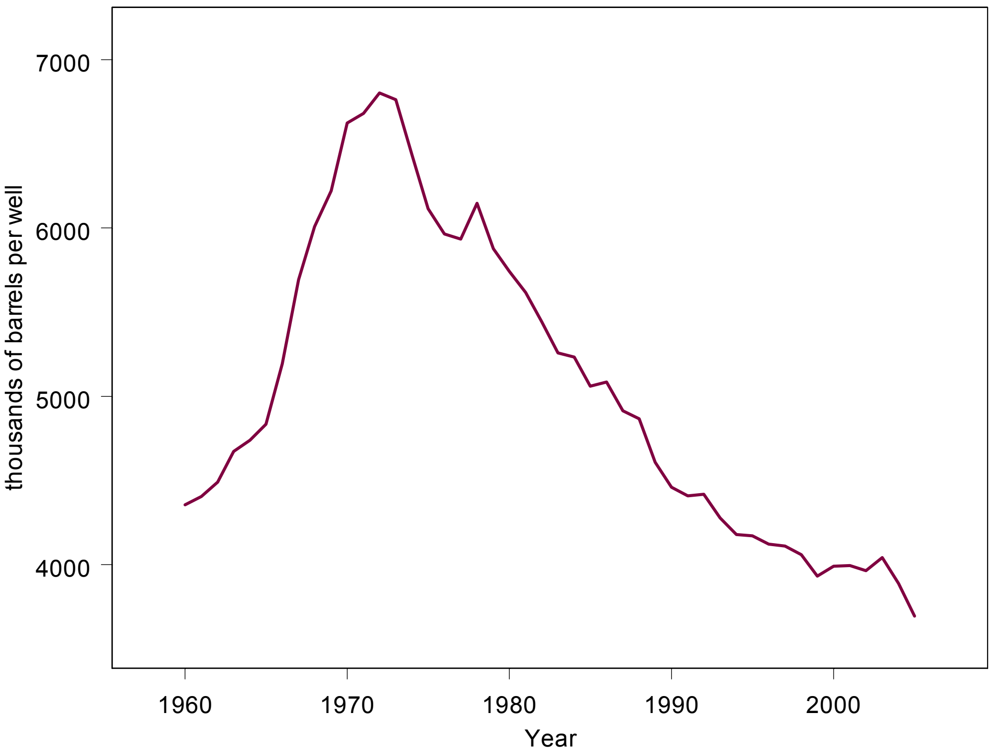

Figure 4.8. U.S. petroleum well productivity

The petroleum prices, petroleum extraction, and well productivity time paths are all parabola shaped, indicating petroleum prices are not obeying Hotelling's (1931) rule. The reason is Hotelling's (1931) rule ignores two important factors.

- Technological improvements cause marginal extraction costs to fall over time and a competitive industry passes the lower costs to the consumers as a lower price (Fishelson 1983; Solow 1974).
- Hotelling's (1931) prices depend on the petroleum reserves being known and fixed, and petroleum extraction is based on intertemporal arbitrage. However, petroleum companies do not know the location of all reserves. However, petroleum companies have a strong incentive to explore and drill

for new petroleum reserves, when petroleum prices are high (Farzin 2001; Fishelson 1983; Morrison 1987).

The empirical evidence for petroleum extraction supports Hubbert's (1959) Life Cycle Hypothesis. When the petroleum industry was young and expanding its infrastructure, petroleum companies discovered and developed new large petroleum reserves, causing the market price to decrease over time. As discoveries become rarer and smaller, and petroleum depletion caused marginal extraction costs to increase, then petroleum prices exhibit scarcity and begin to increase over time. Hubbert (1959) predicted petroleum prices, petroleum extraction, and well productivity should be parabola shaped. However, Hubbert (1959) acknowledged that technological advances could extend the time paths and he underestimated the U.S. oil production peak by 10 years.

4.6. The Petroleum Market Structure

The petroleum market is a unique market, because petroleum companies tend to be large corporations, petroleum prices influence other markets, and governments interfere or nationalize their petroleum industries. Moreover, the international market is important, because the U.S. imported approximately 69% of its petroleum needs in 2004 (Energy Information Administration 2005a), and the last imported barrel of petroleum sets the market petroleum price.

The petroleum price influences all markets in an economy, affecting an economy's growth and employment. For example, U.S. recessions occur approximately a year after dramatic petroleum price increases (Hamilton 1983, 1986). Oil price shocks contract supplies in the petroleum and chemical industries, and contract market demands for apparel, automobile, furniture household appliances, and lumber products (Lee and Ni 2002). Furthermore, real petroleum prices may influence the economy asymmetrically. If real oil price increases dramatically, then the economy grows slower. However, if real oil prices increase a little or decreases, then petroleum prices have little or no impact on the economy (Hamilton 1996; Huang, Hwang, and Peng 2005).

Petroleum companies are large conglomerate corporations. The petroleum companies extract petroleum from the ground, transport, refine, and sell petroleum products directly to consumers. Petroleum corporations merged with many natural gas companies and are merging with electric companies (Office of Energy Markets and End Use 1996). Moreover, petroleum companies form international consortiums and joint ventures with other large energy corporations. These partnerships develop new oil fields, construct pipelines, update and construct new refineries, and enter new markets, where countries are deregulating their energy industries. For example, Mobil, Chevron, Murphy Oil, Petro-Canada, and the Canadian government are developing the Hibernia field (Office of Energy Markets and End Use 1996).

Some foreign governments nationalized their petroleum industries. The well-known example is the Organization of the Petroleum Exporting Countries (OPEC). OPEC (2006) was formed in 1960, when five countries nationalized their petroleum industries and formed a cartel. OPEC (2006) tries to increase the petroleum market price by setting production quotas on member countries, thus increasing oil rent to these countries. Economists believe OPEC is not effective, because members cheat on their quotas, nullifying the production quotas (Marshalla and Nesbitt 1986). Currently OPEC (2006) has 11 members and the current membership is Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela[9].

Governments have three reasons to control their petroleum industries and Table 4.1 contains a partial listing. First, petroleum is a critical energy resource and thus, subject to national security. Second, the petroleum industry is a large source of tax revenue. For example, PEMEX (2006) is Mexico's national petroleum and natural gas company. PEMEX (2006) earned a $6.9 billion loss[10] in 2005, but paid the Mexican national government $52.8 billion in duties and taxes. Finally, petroleum companies

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[9] Venezuela's petroleum company is Petroleos de Venezuela (PDVSA), which is the fifth largest producer of crude oil, is the fourth largest refinery, and owns the largest U.S. retail gas station, Citgo (Office of Energy Markets and End Use).

[10] Used exchange rate: $1 = 11 pesos.

have strong political ties with government. The extreme case is the world's largest corporation, Gazprom, Russia's natural gas company. The Russian government owns 50.002% of the shares, thus the majority shareholder (Gazprom 2005), and Gazprom has 100% ownership in 61 companies, majority shareholder in 41 companies, and a minority shareholder in 69 companies (Gazprom). Thus, the Kremlin indirectly controls or influences 171 companies through Gazprom.

Table 4.1. Partial List of State Owned Companies

State Company	Market
China National Chemical Import and Export Corporation (Sinochem)	Imports and exports petroleum for China
China National Offshore Oil and Gas Corporation (CNOOC)	Handles China's offshore petroleum and natural gas resources
China National Petrochemical Corporation (Sinopec)	Refines petroleum into products for China
Chinese National Petroleum Corporation (CNPC)	Handles everything else for China that is not covered under the Sinochem, CNOOC, and Sinopec
Ecopetrol	Columbia's petroleum company
Gazprom	Russia's natural gas company
PEMEX	Mexico's oil and natural gas company
Petrobras	Brazil's petroleum company
Rosneft	A Russian state owned petroleum company
Statoil	Norway's oil company
Transneft	Russia's pipeline monopoly

Source: Office of Energy Markets and End Use (1996)

4.7. Price Relationship between Diesel Fuel and Gasoline

This section examines the price relationships between diesel fuel and gasoline, allowing one fossil fuel price to be specified in FASOM-GHG.

The time series plot of petroleum, gasoline, and diesel fuel prices is shown in Figure 4.9. Gasoline and diesel fuel are viewed as a markup of petroleum price. The petroleum price is substituted out to form the equation $P_{diesel,t} = \beta_0 + \beta_1 P_{gasoline,t} + \varepsilon_t$, where $P_{diesel,t}$ and $P_{gasoline,t}$ are the real prices of diesel and gasoline, while β_0 and β_1 are the parameters, and ε_t is the random noise term assumed to be $\varepsilon_t \sim iid\ N(0, \sigma_j)$. (The normality assumption allows hypothesis testing of the parameter estimates).

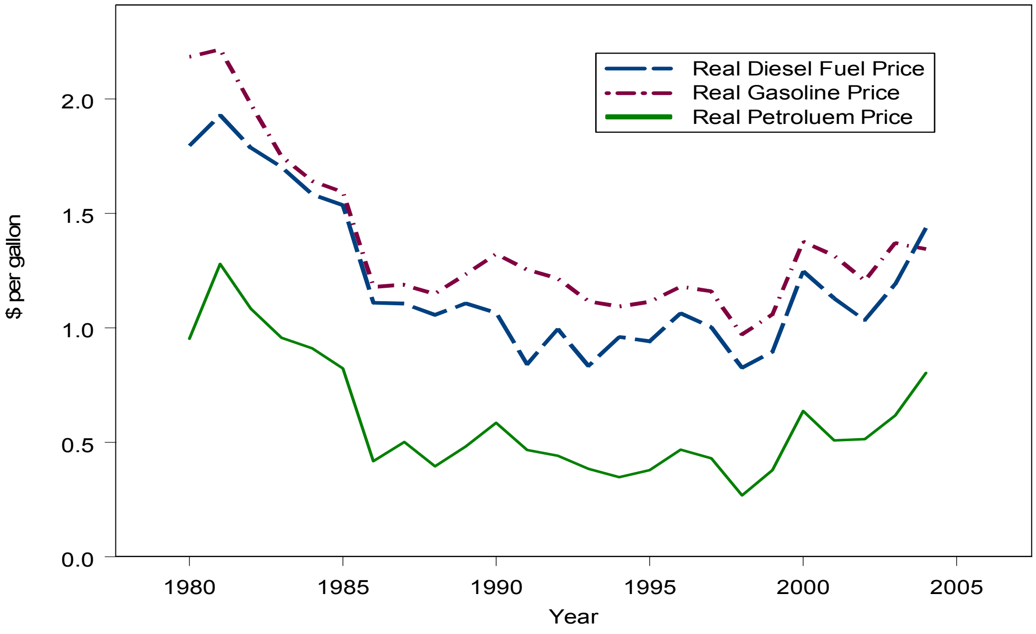

Figure 4.9. Real petroleum, gasoline, and diesel fuel prices

The petroleum price data is the U.S. average, first purchase price from the Energy Information Administration (2005a), and the gasoline and diesel fuel prices are from the Transportation Energy Data Book Edition 24 (Davis and Diegel 2006). The federal excise taxes were subtracted from the gasoline and diesel fuel prices, and are available from the Federal Highway Administration (1999). The prices were converted to real by dividing by the GDP implicit price deflator. The GDP deflator is from the Bureau of Economic Analysis, Department of Commerce with 2000 as the base year. The states' excise taxes were not subtracted, because not enough historical data is known at this point.

The first procedure is to estimate the markup equation, using ordinary least squares and data spanning between 1980 and 2004. The residuals are used to estimate the autocorrelation (ACF) and partial autocorrelation (partial ACF) functions, and are plotted in Figure 4.10. The plots provide information whether the residuals have an autoregressive and/or moving average behavior, and the number of lags is defined as ARMA(p,q), where p is the number of autoregressive lags and q is the number of moving average terms. The 95% confidence levels are shown as dashed lines. The diesel fuel as a markup of gasoline shows the residuals have an ARMA(1,1) structure and this markup equation was re-estimated with this correlation structure imposed on the residuals. The estimated parameters for ARMA(1,1) are $\hat{p}$ and $\hat{q}$ respectively. The final parameter estimates are shown in Equation 4.2. FASOM-GHG calculates the diesel price by multiplying the gasoline price by 0.8643.

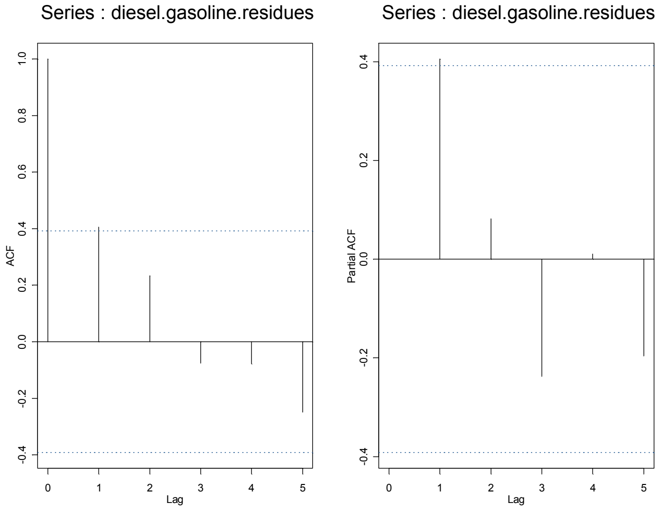

Figure 4.10. ACF and partial ACF plots of markup equation residues

Equation 4.2. Linear Regression Estimation of Markup Equation

$$P_{diesel,t} = 0.0371 + 0.8643 P_{gasoline,t} + 0.7775\hat{\varepsilon}_{t-1} \qquad \hat{p} = 0.7775 \quad \hat{q} = -0.0699$$

$$(0.2084) \quad (7.6491)$$

4.8. National Energy Modeling System (NEMS)

This section determines the bounds for gasoline fuel prices. The Energy Information Administration uses National Energy Modeling System (NEMS) for 25-year energy price forecasts. NEMS is a more comprehensive model than the other fossil price forecast models, because NEMS contains numerous assumptions such as efficiency improvements and discovery of new energy resources. NEMS is composed of 11 modules and more details are available from the Office of Integrated Analysis and Forecasting (2006):

- Macroeconomic Activity Module contains macroeconomic variables like the U.S. GDP, industrial output, and new housing starts.
- International Module decomposes the world into 16 petroleum consumption regions and 19 oil production regions.
- Residential and Commercial Demand Module contains the energy consumption for these sectors, including the impacts of appliance efficiency and energy efficient building standards.
- Industrial Demand Module contains industrial manufacturers demand for energy.
- Transportation Module includes energy consumption for road vehicles and aircraft travel.
- Electricity Market Module includes the generation, transmission, and pricing of electricity.
- Renewable Fuels Module includes hydroelectricity, biomass, geothermal, landfill gas, solar cells, and wind energy.

- Oil and Gas Supply Module contains the production of oil and natural gas.
- Natural Gas Transmission and Distribution Module contains the transmission, distribution, and pricing of natural gas to consumers.
- Petroleum Market Module contains the refining of petroleum into products. This module includes the blending of ethanol and biodiesel.
- Coal Market Module contains the mining, transportation, and pricing of coal. This module contains 40 supply functions, because each coal-producing region differs in coal grade, mine type, and sulfur content.

The Office of Integrated Analysis and Forecasting (2006) forecasted three price scenarios for all energy prices until 2030 and the fossil fuel prices are shown in Table 4.2. The base price forecast is the world crude oil price will be $50 per barrel and natural gas will be $5.92 per thousand cubic feed in 2030. The low price forecast is world oil price is $28 per barrel and natural gas is $4.96 per thousand cubic feet in 2030. Finally, the high price forecast is world crude oil price is $90 per barrel and natural gas is $7.72 per thousand cubic feet in 2030. The price forecasts include the federal excise tax of 18.4 cents per gallon on gasoline and 24.4 cents per gallon on diesel.

Table 4.2. NEMS Liquid Fuel Price Forecast

	2004	2010	2020	2030
Base Price Forecast				
Distillate Fuel ($/gal)	1.580	1.715	1.781	1.900
Motor Gasoline ($/gal)	1.720	1.843	1.892	2.004
Imported crude oil ($/barrel)	35.990	43.990	44.990	49.990
Low Price Forecast				
Distillate Fuel ($/gal)	1.580	1.540	1.382	1.398
Motor Gasoline ($/gal)	1.720	1.674	1.498	1.484
Imported crude oil ($/barrel)	35.990	37.000	27.990	27.990
High Price Forecast				
Distillate Fuel ($/gal)	1.580	2.094	2.692	2.808
Motor Gasoline ($/gal)	1.720	2.188	2.678	2.867
Imported crude oil ($/barrel)	35.990	58.990	79.980	89.880

Source: Office of Integrated Analysis and Forecasting (2006)

The high-price forecast seems low, because the nominal U.S. diesel fuel and gasoline prices fluctuated around \$3.00 per gallon in 2006. The Office of Integrated Analysis and Forecasting (2006) assumes high petroleum prices will cause petroleum companies to explore and develop new petroleum wells, causing liquid petroleum fuel prices to decrease. The NEMS forecasts define the bounds for wholesale gasoline prices in FASOM-GHG, ranging from \$1.00 to \$3.00 per gallon.

5. BIODIESEL AND ETHANOL PRODUCTION TECHNOLOGY

This section discusses the technology for biofuel production deriving feedstock-to-biofuel chemical yield coefficients. The technology is assumed to be Leontief in nature without any input substitution, because the yield coefficients are based on chemical formulas, reflecting constant economies of scale.

5.1. Biodiesel Production

Vegetable oils cannot be used directly in diesel engines, because the oil does not combust completely fouling the fuel injectors, causing carbon buildup, causing the piston rings to stick, and emitting heavy exhaust (Barnwal and Sharma 2005; Encinar et al. 2002; Gerpen et al. 2004; Graboski and McCormick 1998; Shay 1993; Srivastava and Prasad 2000). Further, vegetable oil could seep into the motor oil and thicken it, requiring frequent oil changes (Encinar et al. 2002; Shay 1993). A diesel engine could be re-engineered to utilize pure vegetable oil (Srivastava and Prasad 2000) but this has not yet happened. Until such an engine becomes widely available, biodiesel refineries convert vegetable oil into an ester, which is similar to diesel fuel and makes biodiesel usable in current diesel engines on the market.

Different methods to produce biodiesel exist, but all methods have the same underlying chemical reaction. That reaction has two inputs: vegetable oil and alcohol, and creates two outputs: ester and glycerol (Duffield et al. 1998; Gerpen et al. 2004; Zhang et al. 2003a). Biorefineries could use different alcohols in creating biodiesel, but methanol is commonly used, because it is the least expensive. If methanol is used, then the biodiesel is called methyl-ester, whereas if ethanol is used, the biodiesel is called ethyl-ester. Chemically (Equation 5.1) one triglyceride molecule and three alcohol molecules form three methylesters and one glycerol (Graboski and McCormick 1998; Fukuda, Kondo, and Noda 2001; Encinar et al. 2002; Srivastava and Prasad 2000). The molecular weights of the various compounds in the chemical formula are used herein to derive the chemical yield coefficients for producing biodiesel. The total molar weights on the left side of the equation must equal the total weight on the right side, because matter cannot be created nor destroyed.

Equation 5.1. Chemical Formula for Oil to Methylester Reaction

$$\begin{array}{cccc} 1\,oil\,(triglyceride) + 3\,methanol & \rightarrow & 3\,methylester + 1\,glycerol \\ 1{,}000\,kg \quad 107.5\,kg & & 1{,}004.5\,kg \quad 103\,kg \end{array}$$

The chemical yield coefficient for converting vegetable oil into ester is calculated via Equation 5.2. This involves calculating the oil-to-ester chemical yield coefficient by multiplying the gallon-to-liter conversion, the oil density, the ratio of ester to vegetable oil from the chemical reaction from Equation 5.1, the inverse respective methyl-ester density, and finally the liter-to-gallon conversion. Then the chemical yield coefficient is multiplied by the conversion efficiency, η_C and recovery efficiency, η_R. Research indicates the chemical yield ranges from 90 to 99% of theoretical yield, and forms the basis for the conversion efficiency (Encinar et al. 2002; Srivastava and Prasad 2000; Zhang et al. 2003a). The recovery efficiency is set at 100%, because the ester and glycerol separate into layers with glycerol settling to the bottom layer. The ester is easily separated from the mixture. Equation 5.2 reduces to the second equation under Equation 5.2 with the units being gallons of ester per gallon of vegetable oil.

Equation 5.2. Oil-to-Methylester Chemical Yield Coefficient

$$K_{ester-oil} \approx \frac{3.7854\,L}{1\,gal.\,oil} \cdot \left(\frac{Oil\,density \,{}^{kg}\!/_{L}}{Ester\,density \,{}^{kg}\!/_{L}} \right) \left(\frac{1004.5kg\,ester}{1000\,kg\,oil} \right) \cdot \frac{1\,gal.ester}{3.7854\,L} \cdot \eta_C \cdot \eta_R$$

$$K_{ester-oil} \approx 1.0045 \cdot \frac{Oil\,density}{Ester\,density} \cdot \eta_C \cdot \eta_R$$

The methylester chemical yields are shown in Table 5.1. Some vegetable oil and methylester densities were not available. The average vegetable oil density and average methylester density were used in lieu of the missing density and is indicated by italics. Moreover, some coefficients exceed one, because the chemical reaction creates a little more ester relative to vegetable oil and there is a small processing gain. The processing gain results from methyl-ester having a slightly lower density then vegetable oil, causing a larger volume.

Another important item is the amount of biodiesel that a producer could manufacture from one dry ton of feedstock. Dry feedstock does not mean devoid of water, but producers dry the feedstock to contain a certain moisture percentage that varies by feedstock. The producers harvest the feedstock, and extract the oil by crushing the seeds and use a press or solvent to remove the oil. A solvent achieves almost a 100% removal of the oil from the seeds and the soybean industry uses this method while a hot press can extract up to 95% of the oil from seeds like sunflower and rapeseed (Ortiz-Canavate 1994). The tonnage of oil that can be extracted is calculated by multiplying one ton by the percent oil content, and the oil extraction efficiency, as in Equation 5.3. The soybean calculation uses a 100% extraction efficiency, while the other oils use 95%. The extraction efficiency is denoted by η_E.

Table 5.1. Oil and Methylesters Densities, and Biodiesel Yields

Feedstock	Vegetable Oil Density (kg/liter)	Methylester Density (kg/liter)	Feedstock Oil Content (% wt)	Biodiesel Chemical Yield (gal/gal of oil)	Biodiesel Chemical Yield (gal/dry ton)
Canola	*0.915*	0.8811^{f}	40^{g}	0.939 – 1.033	93.4 – 102.8
Corn	$0.9095^{a,e}$	0.884^{b}	4.5^{h}	0.930 – 1.023	10.5 – 11.5
Cottonseed	$0.9148^{a,e}$	*0.878*	19.0^{g}	0.942 – 1.036	44.5 – 49.0
Flax seed / Linseed	$0.9236^{a,e}$	*0.878*	43.0^{a}	0.951 – 1.046	110.8 – 110.9
Lard	*0.915*	0.8762^{f}	-	0.944 – 1.038	-
Mustard	*0.915*	*0.878*	40^{g}	0.942 – 1.036	93.7 – 103.1
Peanuts	$0.9026^{a,e}$	$0.883^{a,b,e}$	25^{g}	0.924 – 1.017	58.3 – 64.1
Rapeseed	$0.9115^{a,e}$ - 0.916^{d}	0.88^{d} - 0.882^{b}	33^{a} – 40^{g}	0.934 – 1.035	77.0 – 103.4
Safflower	$0.9144^{a,e}$	*0.878*	25^{g}	0.941 – 1.035	58.6 – 64.4
Sesame	$0.9133^{a,e}$	*0.878*	50^{c}	0.940 – 1.035	117.2 – 128.9
Soybean	$0.9138^{a,e}$	0.880^{b} – $0.885^{a,b,e}$	18^{g}	0.933 – 1.033	44.1 – 48.7
Sunflower	$0.9161^{a,e}$ - 0.924^{d}	$0.860^{a,b,e}$ - 0.88^{d}	35^{a} – 40^{g}	0.941 – 1.068	81.9 – 106.2
Tallow	*0.915*	0.8708^{f}	-	0.950 – 1.045	-

Sources:

a. Barnwal and Sharma 2005
b. Fukuda, Kondo, and Noda 2001
c. Oplinger et al. 1990
d. Ortiz-Canavate 1994
e. Srivastava and Prasad 2000
f. Tat and Gerpen 2001
g. Tyson et al. 2004
h. Wallace et al. 2005

Equation 5.3. Quantity of Oil Extracted from One Dry Ton of Feedstock

$$oil\ \ quantity\, tons = 1\, dry\, ton\ \ feedstock \cdot oil\ \ content \cdot \eta_E$$

The feedstock-to-ester chemical yield is computed via Equation 5.4. There one converts the oil to kilograms, multiplies by the inverse oil density, a gallons-to-liters conversion, and a vegetable oil-to-ester chemical yield using the data in Table 5.1. The feedstock-to-ester chemical yields are in gallons of biodiesel per ton of feedstock. The chemical yield coefficients were used to add corn oil, soybean oil, tallow and yellow grease biodiesel processing possibilities into FASOM-GHG.

Equation 5.4. Feedstock-to-Methylester Chemical Yield Coefficient

$$K_{ester-feedstock} \approx \left(\frac{907.1847 kg}{1 ton\ feedstock} \right) \left(\frac{1}{oil\ density \, {}^{kg}\!/_{L}} \right) \cdot \frac{1 gal.\ oil}{3.7854 L} \cdot K_{ester-oil}$$

$$K_{ester-feedstock} \approx 239.654 \cdot \frac{K_{ester-oil}}{oil\ density}$$

The biodiesel yield can also be calculated in gallons per acre of land. The first step is to calculate the crop yield by dividing total crops harvested in tons by total acres harvested. Most crop yield data are available from National Agricultural Statistics Service (2005) and converted to tons by using the conversions in Appendix 2. The second step is to calculate the biodiesel yield per acre by multiplying the crop yield from Table 5.2 by the respective feedstock-to-ester chemical yield coefficients from Table 5.1. The highest biodiesel yield per acre is peanuts, while the lowest is cottonseed.

Several byproducts arise from biodiesel production. The first is glycerol. The glycerol yield is computed in a similar manner to the vegetable oil-to-biodiesel chemical yields (Equation 5.5). After producers separate glycerol from ester, the glycerol contains impurities. The impurities cause the glycerol recovery efficiency to be 92% and is denoted by η_R (Zhang et al. 2003a). Table 5.3 contains the amount of glycerol produced in pounds from each feedstock and on average, one gallon of biodiesel production produces approximately 0.76 pounds of glycerol. The second equation under Equation 5.5 has been reduced with the units being pounds of glycerol per gallon of biodiesel.

Table 5.2. Oil Crop and Biodiesel Yields

Crop	Year	Acres Harvested (1,000 acres)	Production (1,000 tons)	Crop Yield (tons/acre)	Biodiesel Yield (gallons/acre)
Canola	2003	1,512[b]		0.69[b]	64.2 – 70.6
Corn	2004	73,632.0[a]	330,602.1[a]	4.49	47.0 – 51.7
Cottonseed	2004	13,057.0[a]	8,411.0[a]	0.64	28.7 – 31.6
Flax seed/ Linseed	2004	516.0[a]	293.2[a]	0.57	57.3 – 63.0
Mustard	2001	44.2[d]	20.6	0.47[d]	43.6 – 47.9
Peanuts	2004	1,394.0[a]	2,130.9[a]	1.53	89.1 – 98.0
Rapeseed	2001	3.1[d]	2.0	0.65[d]	50.3 – 67.5
Safflower	2001	177.0[d]	120.8	0.68[d]	40.0 – 44.0
Sesame				0.50[c] – 0.75[c]	58.6 – 64.4
Soybean	2004	73,958.0[a]	94,229.9[a]	1.27	56.1 – 62.1
Sunflower	2004	1,711[a]	1,023.8[a]	0.60	49.0 – 63.6

Sources:

a. National Agricultural Statistics Service 2005
b. Ash and Dohlman 2005
c. Oplinger et al. 1990
d. Tyson et al. 2004

Equation 5.5. Quantity of Glycerol Produced from Biodiesel

$$K_{glycerol-ester} \approx \frac{3.7854\,L}{1\,gal.ester} \cdot ester\,density\,{}^{kg}\!/_{L} \cdot \left(\frac{103\,kg\,glycerol}{1004.5\,kg\,ester}\right)\left(\frac{2.2\,lbs}{1\,kg}\right) \cdot \eta_R$$

$$K_{glycerol-ester} \approx 0.8539\eta_R\left(ester\,density\right)$$

The second byproduct is protein meal that is used for animal feed (Table 5.3). The protein meal calculation has three steps (Equation 5.6). The first step is to determine the amount of protein meal produced after oil removal. The seed residue is the percentage of feed after deducting the percent oil content, $\left(1-\%\,oil\,content\right)$. The second step is to calculate the ratio between protein meal and oil content, converting the percentages into kilograms. This is the first term in Equation 5.6. Then one converts the feed from kilograms to pounds by the pound-kilogram conversion, the oil into methyl-ester by the oil density, liter-to-gallon conversion, and the inverse of the oil-to-ester conversion coefficients. The second equation under Equation 5.6 is reduced to lowest terms, and the units are pounds of feed per gallon of biodiesel. The highest protein meal yield per acre is soybeans while the smallest is sesame seeds.

Table 5.3. Biodiesel Byproducts

Feedstock	Glycerol Yield (lbs/1 gal ester)	Protein Meal (% protein content)	Animal Feed (tons/acre)	Protein Meal Yield (lbs/gal biodiesel)
Canola seeds	0.738 – 0.811	0.38[a]	0.412	11.07 - 12.17
Corn seeds	0.731 – 0.804	-	-	-
Cottonseed seeds	0.740 – 0.814	0.41[a]	0.522	31.35 - 34.49
Flax seed/ Linseed	0.747 – 0.822	0.33[a]	0.371	13.81 - 15.19
Mustard seeds	0.740 – 0.814	-	-	-
Peanuts	0.726 – 0.799	0.48[a]	1.146	22.06 – 24.27
Rapeseed	0.734 – 0.813	0.36[a]	0.392 - 0.438	11.00 – 16.58
Safflower seeds	0.739 – 0.813	0.42[a]	0.512	22.06 – 24.27
Sesame seeds	0.739 – 0.812	0.42[a]	0.250	7.35 – 8.09
Soybeans	0.733 – 0.811	0.44[a]	1.045	33.57 – 37.13
Sunflower seeds	0.739 – 0.839	0.42[a]	0.359 - 0.389	10.71 – 15.18
Tallow	0.746 – 0.821	-	-	-

Source:

a. Tyson et al. 2004

Equation 5.6. Quantity of Protein Meal Produced from Biodiesel Production

$$K_{meal-ester} \approx \frac{(100 - oil\,content\%)}{oil\,content\%} \cdot \frac{2.2\,lbs}{1\,kg} \cdot \left(oil\,density\, {}^{kg}\!/\!_{L} \right) \cdot \frac{3.7854\,L}{1\,gal.} \cdot \left(\frac{1}{K_{ester-oil}} \right)$$

$$K_{meal-ester} \approx 8.3279 \frac{(100 - oil\,content\%)}{oil\,content\%} \cdot \left(\frac{oil\,density}{K_{ester-oil}} \right)$$

Two protein meals are omitted from Table 5.3. The first arises from corn, because corn is a complex feedstock and producers convert corn into numerous byproducts. Corn is the only crop in this dissertation that a producer could use to produce both biodiesel and ethanol. The second is mustard seed residues. Livestock producers do not use mustard seeds for animal feed, because they contain high levels of glucosinolate, making the animal feed poisonous. If mustard seed becomes an important feedstock source, producers could market mustard seed residue as an organic insecticide

(Tyson et al. 2004). Another potential problem arises with rapeseed, because it contains high levels of erucic acid, which reduces the value of this animal feed (Duffield et al. 1998).

5.2. Ethanol Production

Different technologies exist to produce ethanol. The main differences involve the way sugar is separated from the feedstock. Once separated, the sugar is dissolved in a solution, which allows microorganisms to ferment the sugar into ethanol. Producers separate the ethanol from the solution by distillation. Ethanol is distilled in two stages. The first stage distills ethanol to a 95.6% concentration with the remaining being water (Committee on Animal Nutrition et al. 1981, p. 11; Gerpen et al. 2004), while the second stage uses denaturants to remove the remaining water. Then the denaturants are distilled from ethanol (Hewlett et al. 1983).

Ethanol production has three main variants, which represent how sugar is removed or created from the feedstock.

5.2.1. Sugar Fermentation

Sugar crops are the easiest to ferment, because of the presence of simple sugars. The three U.S. sugar crops considered are sugar beets, sugarcane, and sweet sorghum. The first step in computing the ethanol chemical yield involves the amount of sugar that a producer could recover from a dry ton of feedstock. The chemical yield is found by multiplying the feedstock tonnage by the crop's percent sugar content and the sugar extraction efficiency (Equation 5.7). If the percentage of sugar recovered is not available, such as the case with sugarcane, then one multiplies the feedstock tonnage by the percentage of sugar that a producer could extract, given the current technology.

Equation 5.7. Quantity of Sugar Extracted from Sugar Crops

$$tons\,sugar = 1\,dry\,ton\,feedstock \cdot sugar\,content \cdot \eta_E$$

The fermentation process converts glucose into ethanol and is shown in Equation 5.8. One calculates the ethanol yield by multiplying the tons-to-kilograms conversion, the reaction that one kilogram of sugar yields 0.51 kilograms of ethanol, the inverse ethanol density, and liters-to-gallons conversion. The chemical yield is not 100%. Research indicates the chemical yield ranges from 92 to 92.5% (Hamelinck, Hooijdonk, and Faaij 2005; Stenzel et al. 1980), forming the basis for the conversion efficiency, η_C. Moreover, ethanol is recovered from the mixture, using the two-stage distillation process, setting the recovery efficiency, η_R, to 100%. The chemical yield coefficient has been simplified as the second equation in Equation 5.8 and the units reduce to ethanol gallons per 1 ton of sugar.

Equation 5.8. Quantity of Ethanol Produced from Sugar

$$K_{ethanol\text{-}sugar} \approx \left(\frac{907.18474\,kg}{1\,ton}\right)\left(\frac{0.51\,kg\ ethanol}{1\,kg\ sugar}\right)\left(\frac{1\,L}{0.789\,kg}\right)\left(\frac{1\,gal}{3.7854\,L}\right)\cdot\eta_C\cdot\eta_R$$

$$K_{ethanol\text{-}sugar} \approx 154.913\cdot\eta_C\cdot\eta_R$$

The ethanol chemical yield in gallons per ton of dry feedstock is given in Table 5.4. Ethanol chemical yield falls in a range, because the variation in sugar content, extraction and conversion efficiencies. These chemical yields were used to update the production budgets in FASOM-GHG. The highest yielding feedstock is sugar beets while the lowest are sugarcane and sweet sorghum.

Table 5.4. Sugar Content, Extraction Efficiency, and Ethanol Yield

Feedstock	Sugar Extracted (%)	Sugar Content (%)	Extraction Efficiency (%)	Ethanol Chemical Yield (gal/ton of feedstock)
Pure sugar	-	100	100	142.5 - 143.3
Sugar beet	-	16[c]- 17.34[b]	87.9[b]	20.0 - 21.8
Sugarcane	11.17[b] -11.64[b]	-	-	15.9 - 16.7
Sweet Sorghum	11.3[a]	13.0[a]	86.9[a]	16.1 - 16.2

Sources:

a. Gnansounou, Dauriat, and Wyman 2005
b. Haley, Kelch, and Jerardo 2006
c. Stenzel et al. 1980

The ethanol yield can be calculated per acre of land and the results are shown in Table 5.5. One calculates this measure by multiplying the crop yield in tons per acre by the feedstock to ethanol conversion from Table 5.4. The crop yield data are from National Agricultural Statistics Service (2005). All units are converted into tons using the conversion coefficients in the Appendix 2. National Agricultural Statistics Service (2005) combines sweet and grain sorghum, thus a composite crop yield was used. Sugarcane is the highest yielding ethanol crop per acre while sweet sorghum is the lowest.

Table 5.5. Sugar Crop Yields and Ethanol Yields

Crop	Year	Acres Harvested (1,000 acres)	Production (1,000 tons)	Crop Yield (tons/acre)	Ethanol Yield (gal/acre)
Sugar beet	2004	1,306.7	29,932.0	22.9	459.1 - 500.3
Sugarcane	2004	952.1	29,295.0	30.8	489.8 - 513.2
Sweet Sorghum	2004	6517.0	12,737.2	2.0	31.5 – 31.6

Source: Area harvested and total production are from National Agricultural Statistics Service 2005

5.2.2. Starch Fermentation

Starch fermentation is similar to sugar fermentation. Starch is a polymer denoted by the chemical formula $(C_6H_{10}O_5)_N$; inside the parenthesis is a molecule that is similar to glucose. The N denotes how many molecules are linked together. The molecules can link in two ways. The first is a linear polymer called amylase while the second is a branched polymer called amylopectin. For this dissertation, both amylase and amylopectin are summed collectively as starch. A hydrolysis process breaks down the starch, causing it to react with water. Hydrolysis results in a solution of glucose and uses an enzyme or acid to facilitate the reaction (Carver Research Foundation 1985; Hewlett et al. 1983).

The ethanol industry uses two broad technologies to convert starch crops into ethanol: Wet mill and dry grind. Wet mill is more complex. It processes the feedstock into germ, starch, fiber, and possibly more components (Gallagher et al. 2003). Dry grind processes and converts the whole feedstock into ethanol with dried distiller's grains with solubles (DDGS) as a byproduct (Committee on Animal Nutrition et al. 1981, pp. 8-11, p. 20; Gallagher et al. 2005; Hammerschlag 2006). The two technologies differ in the percentage of starch that a biorefinery can recover from the crop. If the technology is not specified in Table 5.6, then the technology is dry grind. In addition, some researchers confuse dry grind with dry mill. Dry mill produces little ethanol and is used to produce products for humans and animals. For example, corn is dry milled into flaking grits, brewer's grits, cornmeal, and hominy feed (Rausch and Belyea 2006).

The first step calculates the quantity of starch extracted from the feedstock (Equation 5.9). One calculates the tonnage of starch extracted by multiplying one dry ton of feedstock with the percent starch content and extraction efficiency. If the extraction efficiency is not available, then the tonnage of starch is found by multiplying 1 ton of feedstock by the percent of starch extracted. For some crops the starch content was known, but the extraction efficiency was not available for barley, oats, potatoes, rice grain, and sweet potatoes. The average extraction efficiency was calculated from corn, grain sorghum, and wheat, which is 85.4%. Grain sorghum has a range of extraction efficiencies, so the mid-value, 0.842, was used to compute the average.

Equation 5.9. Quantity of Starch Extracted from the Starch Crops

$$tons\, starch = 1 ton\ feedstock \cdot starch\, content \cdot \eta_E$$

One calculates the ethanol chemical yield in Equation 5.10 by multiplying by the tons-to-kilograms conversion, the starch theoretical chemical reaction of 1.11 kg of glucose equals 1 kg of starch[11] (Koutinas et al.; Stenzel et al. 1980), the ethanol chemical conversion of 1 kg of sugar equals 0.51 kilograms of ethanol, and the conversion and recovery efficiencies. The conversion efficiency, η_C, ranges from 92-92.5% (Hamelinck, Hooijdonk, and Faaij. 2005; Stenzel et al. 1980), while the recovery efficiency is set at 100%. Finally, the result is converted to gallons by dividing by the ethanol density and multiplying by the liter-to-gallon conversion. The conversion coefficient is reduced to the second equation under Equation 5.10 with the units in ethanol gallons per ton of starch. Table 5.6 contains the ethanol chemical yields from various feedstocks. The chemical yields are added to potatoes-to-ethanol production budget, and to update the other ethanol production budgets in FASOM-GHG .

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

Equation 5.10. Quantity of Ethanol Produced from Starch

$$K_{ethanol\text{-}starch} \approx \left(\frac{907.1847\,kg}{1\,ton}\right)\left(\frac{1.11\,kg\,sugar}{1\,kg\,starch}\right)\left(\frac{0.51\,kg\,ethanol}{1\,kg\,sugar}\right)\left(\frac{1\,L}{0.789\,kg}\right)\left(\frac{1\,gal}{3.7854\,L}\right)\eta_C\eta_R$$

$$K_{ethanol\text{-}starch} \approx 171.954\,\eta_C \cdot \eta_R$$

Table 5.6. Starch Content, Extraction Efficiency, and Ethanol Yield

Feedstock	Starch Extracted (%)	Starch Content (%)	Extraction Efficiency (%)	Ethanol Chemical Yield (gal/ton dry feed stock)
Barley		50-55[a]		67.6 – 74.8
Corn (wet milled)	56.3[e]	72[g]	78.1	89.0 – 89.4
Corn (dry grind)	60.8[e]	72[g]	84.4	96.1 – 96.7
Grain sorghum	52.3 – 66.7[h]	67-73.8[h]	78.0 – 90.4[h]	82.7 – 106.1
Oats		64.0[d]		86.5 – 87.0
Potato		15.0[c, f]		20.3 – 20.4
Rice grain		74.5[b]		100.7 – 101.2
Sweet potato		26.7[b]		36.1 – 36.3
Wheat		57.9[f]	95.0[f]	87.0 – 87.4

Sources:

a. Agricultural Research Center 2005
b. Committee on Animal Nutrition et al. 1981, p.16
c. Hewlett et al. 1983
d. Pardee 1998
e. Rausch and Belyea 2006
f. Stenzel et al. 1980
g. Wallace et al. 2005
h. Xie et al. 2002

Note: The total carbohydrates were used for oats, rice grain, and sweet potato, which include trace amounts of simple sugars.

The ethanol yield figures per ton of feedstock are approximate. The starch crops contain trace amounts of simple sugars, which are not included in the ethanol calculations. For example, winter wheat contains approximately 3.15% sugar (Stenzel et al. 1980) while corn contains approximately 2% sugar (Wallace et al. 2005). The highest yield of ethanol per dry ton is rice grain while the lowest is potatoes. Potatoes and sweet potatoes have a low ethanol yield, because they both contain large amounts of water.

The ethanol yield can also be calculated in gallons per acre of land (Table 5.7). The recent U.S. yields are available from National Agricultural Statistics Service (2005). All crop yields were converted to tons by using the conversions in Appendix 2. One obtains the ethanol gallons per acre by multiplying the crop yield and feedstock-to-ethanol chemical yields from Table 5.6. The highest ethanol yield per acre is both the corn wet-mill and corn dry grind, which are used by the U.S. ethanol industry. The lowest ethanol yield per acre is oats.

Table 5.7. Starch Crop Yields and Ethanol Yields

Crop	Year	Acres Harvested (1,000 acres)	Production (1,000 tons)	Crop Yield (tons/acre)	Ethanol Yield (gal/acre)
Barley	2004	4,021.0	6,702.1	1.7	112.7 – 124.6
Grain Corn (wet milled)	2004	73,632.0	330,602.1	4.5	399.4 – 401.6
Grain Corn (dry grind)	2004	73,632.0	330,602.1	4.5	431.6 – 434.0
Grain sorghum	2004	6,517.0	12,737.2	2.0	161.7 – 207.3
Oats	2004	1,792.0	1,855.0	1.0	89.5 – 90.0
Potato	2004	1,168.1	22,818.1	19.5	396.0 – 398.1
Rice grain	2004	3,325.0	11,541.1	3.5	349.4 – 351.3
Sweet potato	2004	93.3	820.0	8.8	317.3 – 318.8
Wheat	2004	49,999	64,747.4	1.3	112.6 – 113.2

Source: Total harvested and total production are from National Agricultural Statistics Service 2005

The ethanol refinery could produce three types of animal feeds: Wet distiller's grains (WDG), modified distiller's grains (MDG), and dried distiller's grains with solubles (DDGS). The WGS is the fermentation residues that contain 65% moisture; MDG is WGS mixed with grains and contains 50% moisture; while DDGS is dried to 10% or less moisture. Both WGS and MDG have a 3 to 4 day shelf life, which restricts their use near the ethanol plant. Moreover, WGS and MDG spoil quicker in the summer, and they both freeze in the winter (Shapouri et al. 2002).

The alternative is DDGS, because it has a longer shelf life, and can be transported longer distances (Committee on Animal Nutrition et al. 1981, pp. 20-2; Shapouri et al. 2002). However, the ethanol refinery has to use more energy to remove the moisture (Committee on Animal Nutrition et al. 1981, p. 2). One problem with the penetration of distiller's grains is the nutritional content depends on the feedstock used. Fermentation only removes the starch and sugars from the feedstock, concentrating the protein, oil, and minerals in the mixture. The rule of thumb is fermentation causes an approximately three-fold increase in protein, fats, fiber, vitamins, and minerals in the DDGS (Committee on Animal Nutrition et al. 1981, p. 1, p. 15; Hewlett et al. 1983). As the industry matures, DDGS from different sources could be blended together or DDGS could be mixed with other grains and gluten feeds to achieve a uniform nutritional content. The quantity of DDGS produced in pounds per gallon of ethanol is shown in Table 5.8. The DDGS value for sweet sorghum was unknown and grain sorghum is used in its place.

Table 5.8. Dried Distiller's Grain with Solubles (DDGS) Production Coefficients

Feedstock	DDGS (lbs/ethanol gallon)	DDGS Moisture Content (%)
Barley		
Corn (dry grind)	5.9[c] – 6.4[e]	9[e]
Grain sorghum	7.9[b]	6.0[a]
Oats	9.9[b]	
Potato	6.7[d]	4.3[a]
Rice grain	5.3[b]	
Sugar beet	*14.2*	9
Sugarcane	*14.9*	4.5[a]
Sweet Sorghum	7.9	9
Sweet potato	*6.7*	9
Wheat	7.3[d] – 9.2[b]	7.5[a]

Sources:

a. Committee on Animal Nutrition et al. 1981, p. 17
b. Kim and Dale 2004
c. Rausch and Belyea 2006
d. Stenzel et al. 1980
e. Wallace et al. 2005

The DDGS coefficients for sugar beets, sugarcane, sweet sorghum, and sweet potatoes are not known. Consequently, one could impute the DDGS from the chemical composition of the crops. Crop compositions are shown in Table 5.9. The assumption is the fermentation process does not destroy the protein, fat, fiber, and minerals of the feedstock, and the biorefinery removes and ferments all starch and sugar into ethanol. One expects the imputed numbers to be conservative, because some starch and sugar will remain and the yeast residues contain proteins and vitamins. The biorefinery dries the DDGS to a moisture content specified in Table 5.8 and the DDGS imputed values are shown in Table 5.10. Moreover, four of the DDGS values are known and compared to the imputed DDGS values, determining accuracy. Imputed feedstocks for potatoes, corn, rice, and wheat are 5.9, 4.7, 3.8, and 5.1, and are lower than reported DDGS values in Table 5.8. The potato, sugarcane, and sugar beet DDGS coefficients added to FASOM-GHG, while the other DDGS values are updated for the other feedstocks, using the larger coefficients.

Table 5.9. Composition of Several Starch/Sugar Crops

Crop	Water (% wt)	Protein (% wt)	Fat (% wt)	Fiber (% wt)	Carbohydrates N-free Extract (% wt)	Minerals (% wt)	Total (% wt)
Sugar beets	83.6	1.6	0.1	1	12.6	1.1	100
Potatoes, tubers	78.8	2.2	0.1	0.4	17.4	1.1	100
Sugarcane	76.8	1	0.8	6.8	13.4	1.2	100
Sweet Potatoes	68.2	1.6	0.4	1.9	26.7	1.2	100
Corn, dent no. 3	16.5	8.9	3.8	2	67.5	1.3	100
Rice	12.2	9.1	2	1.1	74.5	1.1	100
Wheat, hard winter,southerplains	10.6	13.5	1.8	2.8	69.2	2.1	100

Source: Committee on Animal Nutrition et al. 1981 p. 16.

Table 5.10. Imputed Dried Distiller's Grain with Solubles (DDGS) Values

Feedstock	Ethanol Yield (gal/kg of feedstock)	DDGS Yield (kg/kg of feedstock)	Imputed DDGS Yield (lbs/gal of ethanol)
Sugar beets	0.020	0.128	14.2
Potatoes, tubers	0.030	0.081	5.9
Sugarcane	0.021	0.143	14.9
Sweet Potatoes	0.047	0.141	6.7
Corn, dent no. 3	0.118	0.250	4.7
Rice	0.130	0.223	3.8
Wheat, hard winter, southern plains	0.121	0.277	5.1

The last byproduct of ethanol production is CO2 (Hammerschlag 2006; Kaylen et al. 2000; Stenzel et al. 1980). As yeast ferment the glucose into ethanol, each gallon of ethanol creates approximately 6.285 pounds of CO2 (Hamelinck, Hooijdonk, and Faaij 2005; Hewlett et al. 1983). The biorefinery could collect and sell the CO2 to other industries or could pump the CO2 into the feedstock and byproduct storage tanks, preserving the feedstocks and byproducts.

5.2.3. Lignocellulostic Fermentation

Lignocellulostic fermentation can use any plant feedstock, because all plants contain cellulose and hemicellulose. Cellulose is the largest component in crops and crop residues, and composed of glucan, which is a polymer of glucose. Hemicellulose is composed of arabinan, galactan, mannan, and xylan. Galactan and mannan are decomposed into galactose and mannose, which are C6[12] sugars while arabinan and xylan are decomposed into arabinose and xylose, which are C5 sugars. Microorganisms can ferment all sugars into ethanol (Kadam 2000). Furthermore, the feedstock also

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[12] C6 means the sugar molecule contains 6 carbon atoms like glucose while C5 contains only five carbon atoms.

contains lignin, which is a fiber. Lignin has to be removed, because it interferes with the fermentation process (Hamelinck, Hooijdonk, and Faaij 2005).

Lignocellulostic fermentation has two hydrolysis processes, which is either an acid or an enzyme process. The first hydrolysis converts hemicellulose into four sugars, while the second hydrolysis converts cellulose into glucose. The fermentation occurs in two stages. For instance, C5 sugars are fermented first, and then C6 sugars. Then the ethanol is distilled and purified (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 5.11 with the percentage of C6 and C5 polymers. One calculates the theoretical ethanol yield from Equation 5.11, which is similar to the starch yield calculation. One converts the C6 polymers by converting the percentage into decimal, by multiplying the conversion of C6 polymer into sugar, by multiplying the sugar-to-ethanol conversion, by dividing by the ethanol density in English units, and by multiplying by the pounds-to-tons conversion (Energy Efficiency and Renewable Energy 2006b). The second equation under Equation 5.11 has been reduced and the units are gallons of ethanol per percentage of C6 polymer.

One calculates the practical yield from the theoretical ethanol yield by multiplying by the respective extraction, conversion, and recovery efficiencies for each sugar type. Extraction efficiency ranges from 50-90% for glucose, 89% for mannose, and 82% for galatose, the conversion efficiency ranges 92-92.5% for glucose, and 90% for galactose and mannose (Hamelinck, Hooijdonk, and Faaij 2005), while the recovery efficiency is set at 100%.

Equation 5.11. Theoretical Ethanol Yield from C6 Polymers

$$K_{ethanol\text{-}C6\ polymer} \approx \left(\frac{1}{100}\right)\left(\frac{1.11\, sugar\, lbs}{1\, lb\ polymer}\right)\left(\frac{0.51\, lbs\, ethanol}{1\, lb\, sugar}\right)\left(\frac{1\, gal.}{6.55\, lbs}\right)\left(\frac{2{,}000\, lbs}{1\, ton}\right)$$

$$K_{ethanol\text{-}C6\ polymer} \approx 1.7285$$

One computes the theoretical ethanol yields from C5 sugars via Equation 5.12. This calculation is similar to that Equation 5.10. The only difference is the conversion of C5 polymers into C5 sugars, where one pound of galactan or mannan produces 1.136 lbs of C5 sugar (Energy Efficiency and Renewable Energy 2006b). The second equation under Equation 5.12 has been reduced with the units being gallons of ethanol per percent of C5 polymer content. One calculates the practical ethanol yield by multiplying by the extraction, conversion, and recovery efficiencies. The extraction efficiency ranges from 75-90% for xylose (Hamelinck, Hooijdonk, and Faaij 2005). The extraction efficiency is unknown for arabinose, thus the xylose efficiency is used. The conversion efficiency ranges 59-92% for xylose and 59% for arabinose (Hamelinck, Hooijdonk, and Faaij 2005), while the recovery efficiency is set at 100%.

Equation 5.12. Theoretical Ethanol Yield from C5 Polymers

$$K_{ethanol\text{-}C5\ polymer} \approx \left(\frac{1}{100}\right)\left(\frac{1.136\,sugar\ lbs}{1lb\ polymer}\right)\left(\frac{0.51\,lbs\ ethanol}{1lb\ sugar}\right)\left(\frac{1\,gal.}{6.55\,lbs}\right)\left(\frac{2{,}000\,lbs}{1\,ton}\right)$$

$$K_{ethanol\text{-}C5\ polymer} \approx 1.7690$$

The total ethanol chemical yield in gallons per dry ton for each feedstock is the sum of all ethanol produced from all sugars and is shown in Table 5.11. The ethanol industry does not currently use lignocellulostic fermentation and researchers determined the extraction and conversion efficiencies under laboratory conditions. In this case, one is wise to use the lowest extraction and conversion efficiencies. Moreover, the composition of barley straw and oat straw are not known. Barley, oats, and wheat are in the grass family, thus the ethanol yields for barley and oat straw use the wheat ethanol chemical yield. The ethanol chemical yields are used to update the crop residue production budgets in FASOM-GHG.

Table 5.11. Feedstock Composition of C5 and C6 Polymers and Ethanol Yield

Feedstock	Glucan Content (% wt)	Galactan Content (% wt)	Mannan Content (% wt)	Arabinan Content (% wt)	Xylan Content (% wt)	Total Ethanol Chemical Yield (gal/dry ton)
Barley straw						*50.20*
Corn Stover[d]	40.9	1	0	1.8	21.5	52.04
Hawaiian Bagasse[b]	40.6	0.8	0.2	1.7	20	50.54
Oat straw						*50.20*
Rice Straw[c]	34.2	0	0	0	24.5	46.37
Sorghum straw[a]	34.01	0.52	0.2	1.65	14.1	40.29
Wheat Straw[c]	38.2	0.7	0.3	2.5	21.2	50.20

Sources:

a. Energy Efficiency and Renewable Energy 2006a
b. Kadam 2000
c. Kim 2004, p. 33
d. Tshiteya and Tshiteya 1998

Producers are limited in the amount of crop residues that could be removed from the field, because plant residues provide two benefits. First, plant residues provide surface cover that prevents soil erosion (Gallagher et al. 1999; Kadam and McMillan 2003; Kim and Dale 2004; Kim and Dale 2005; Sheehan et al. 2004; Wallace et al. 2005). Second, the plant residues and wastes provide nutrients and organic matter for the soil, which boost future crop yields. USDA recommends producers could remove 100% of rice and 70% for the other crop residues (Kadam and McMillan 2003; Kim and Dale 2004; Wallace et al. 2005).

The ethanol yield for crop residues is shown in Table 5.12 and is measured in gallons per acre. One calculates the ethanol yield by multiplying the crop yield from Tables 5.5 and 5.7, field crop residue, residue-to-crop ratio, and the ethanol yield from Table 5.11. The residue-to-crop ratio relates the total amount of residue available per ton of crop harvested. Bagasse yields the highest ethanol gallons per acre while oat straw yields the smallest.

Table 5.12. Crop Residue Yields and Ethanol Yields

Feedstock	Year	Crop Residue Yield (tons/acre)	Crop Residue Removed (%)	Residue-to-crop Ratio (ton/crop ton)	Ethanol Yield (gal/acre)
Bagasse	2004	22.9	70	0.6[c]	486.28
Barley straw	2004	1.7	70	1.2[c]	70.29
Corn Stover	2004	4.5	70	1[b,c,d, e]	163.55
Oat straw	2004	1.0	70	1.3[b]	47.29
Rice Straw	2004	3.5	100	1.35[a] - 1.40[c]	217.29
Sorghum Straw	2004	2.0	70	1.3[c]	71.66
Wheat Straw	2004	1.3	70	1.3[c]	59.16

Source:

a. Kadam, Forrest, and Jacobson 2000
b. Kadam and McMillan 2003
c. Kim and Dale 2004
d. Sheehan et al. 2004
e. Wallace et al. 2005

Lignocellulostic fermentation produces lignin and residues as a byproduct. A biorefinery could sell the lignin and residues as an animal feed. Unfortunately, lignocellulosic feedstocks contain little protein, making the residues and lignin a poor animal feed (Kadam and McMillan 2003; Wallace et al. 2005). More likely, this type of feed would be restricted locally around the biorefinery.

The other option is to burn the lignin and residuals for electricity and heat (Gallagher et al. 1999; Gnansounou, Dauriat, and Wyman 2005; Hammerschlag 2006; Kadam and McMillan 2003; Kadam 2000; Kaylen et al. 2000; Kim and Dale 2005; Sheehan et al. 2004; Wallace et al. 2005). 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. Hamelinck, Hooijdonk, and Faaij (2005), and White (1987) cited the HHV of lignin lying between 20 – 22 mBTUs per dry ton. One calculates the quantity of energy from one dry ton of feedstock by multiplying the one ton of feedstock by the lignin percentage, and then by the energy conversion coefficient, which ranges between 20 and 22 mBTUs per dry ton. The lignin higher heating values are shown in Table 5.13, and the coefficients were updated in FASOM-GHG.

Table 5.13. Lignin Higher Heating Values (HHV) for Crop Residues

Feedstock	Lignin Content (% wt)	HHV (mBTU/ton) min	HHV (mBTU/ton) max
Barley straw		*4.7*	*5.1*
Corn Stover[d]	16.7	3.3	3.7
Hawaiian Bagasse[b]	25.5	5.1	5.6
Oat straw		*4.7*	*5.1*
Rice Straw[c]	11.9	2.4	2.6
Sorghum straw[a]	16.1	3.2	3.5
Wheat Straw[c]	23.4	4.7	5.1

Sources:

a. Energy Efficiency and Renewable Energy 2006a
b. Kadam 2000
c. Kim 2004, p. 33
d. Tshiteya and Tshiteya 1998

Lignocellulostic fermentation also produces CO2, furfural, and methane gas as byproducts. Each gallon of ethanol produces 6.285 pounds of CO2 (Hamelinck, Hooijdonk, and Faaij 2005). Ironically, the fermentation of five different sugars emits the same quantity of CO2 gas as traditional fermentation. The CO2 could be stored in pressurized tanks and sold to other industries. Furfural is another valuable byproduct and is created from the breakdown of hemicellulose (Kadam and McMillan 2003; Kaylen et al. 2000; Zerbe 1992). Manufacturers could use furfural to make carpet fibers, creating a strong demand (Kaylen et al. 2000). Finally, the last byproduct is methane gas. Anaerobic fermentation occurs in the biorefinery's wastewater and produces biogas with 75% methane. A biorefinery could collect and burn this gas to provide heat and electricity to the ethanol plant (Gnansounou, Dauriat, and Wyman 2005; Kaylen et al. 2000; Ortiz-Canavate 1994; Wallace et al. 2005).

5.3. Technological Improvement

This dissertation handles technological improvement as five exogenous factors, which are the genetic makeup of crop, extraction efficiency, conversion efficiency, crop yield improvements, and decreasing production costs. All factors have an impact on the biofuel production possibilities.

The first technological improvement is the genetic makeup of the crop. There is no way to predict how researchers could change a crop's composition. However, as new crop breeds become available, researchers can improve feedstock-to-biofuel chemical yields. For example, researchers at the University of Illinois created two separate genetic corn lines. They bred the first corn line to maximize corn kernel oil with an oil content of 20% while the other line contained almost zero oil (Hill 2005). These two corn lines create significant differences for biodiesel production from corn oil.

The source of technological improvement is improvement in extraction and conversion efficiencies. Biodiesel is technologically efficient, because the extraction and conversion efficiencies exceed 90%. Consequently, this dissertation assumes the feedstock-to-biodiesel chemical yields do not change for biodiesel.

The ethanol conversion efficiencies for traditional fermentation are likely to see improvement. Assume the industry can achieve a total efficiency of 90% of theoretical in 20 years. The 90% efficiency assumes the conversion efficiency remains at 92.5% and extraction efficiency increases to 97%. The conversion efficiency is not likely to increase, because the yeast consumes some of the sugar to create offspring. Furthermore, this extraction efficiency serves as an upper bound for ethanol yield.

One calculates the growth rate of technological improvement by using Equation 5.13, where η_0 is the current feedstock-to-biofuel chemical yield, while η_{20} is the chemical yield for 90% of theoretical yield in the 20th year. The technological improvement for the sugar and starch feedstocks is shown in Figure 5.14. Wet-milled corn is not included, and is discussed in Section 7.2.2. The technological improvement updates the ethanol chemical yield by dividing the input on the production budget in

FASOM-GHG by $e^{\delta t}$ for each time period t. These technological growth rates are used for all scenarios in Section 8.

Equation 5.13. Technological Improvement in Total Efficiency

$$\begin{Bmatrix} \eta_t = \eta_0 e^{\delta t} & 0 \le t \le 20 \\ \eta_t = \eta_0 e^{20\delta} & t > 20 \end{Bmatrix}$$

Table 5.14. Technological Improvement for Sugar and Starch Crops

Feedstock	Annual Technological Growth Rate
Barley	0.678
Corn (dried grind)	0.738
Grain sorghum	0.750
Oats	0.678
Potato	0.678
Rice grain	0.678
Sugar beets	0.535
Sweet potato	0.678
Sweet sorghum	0.592
Wheat	0.147

Technology for lignocellulostic fermentation could allow higher ethanol yields in both extraction and conversion efficiencies for all sugars. The main hindrance to a high ethanol yield is the amount of glucan that a biorefinery can extract from the cellulose and cellulose tends to be the largest component in crop residues. Researchers differ on the total efficiency, ranging from 60 to 90% of the theoretical efficiency (Gnansounou, Dauriat, and Wyman 2005; Michaels et al. 1981; Sheehan et al. 2004; Wallace et al. 2005). The upper bound on the aggregate extraction and conversion efficiencies are calculated in the same manner and the annual technological growth rates are in Table 5.15. Barley straw and oat straw are unknown, so wheat straw data were used for those cases. These technological growth rates are used to dynamically reduce the input feedstocks for each crop residue production budget in FASOM-GHG.

Table 5.15. Technological Improvement for Crop Residues

Feedstock	Annual Technological Growth Rate
Bagasse	2.98
Barley straw	*2.95*
Corn Stover	2.97
Oat straw	*2.95*
Rice Straw	2.96
Sorghum straw	3.02
Sweet Sorghum	2.96
Wheat Straw	2.95

Another source of technological improvement is increases in crop yields. Over time, producers become more efficient growing and cultivating crops, thus, crop yields improve over time. The crop yield improvement is defined as a constant, annual growth in crop yields and is defined as Equation 5.14, where F_t is crop yield at time t, F_0 is the initial crop yield in time period 0, δ is the exogenous increase in yield over time, and t is time.

Equation 5.14. Exogenous Crop Yield Improvements

$$F_t = F_0 e^{\delta t}$$

Many random events affect agricultural producers and crop yields, and researchers control for this randomness using econometrics. Taking the natural logarithm and reparameterizing Equation 5.14 results in Equation 5.15. The error term is assumed to be $\varepsilon_t \sim iid\left(0,\sigma^2\right)$ and Equation 5.15 is estimated by Ordinary Least Squares (OLS).

Equation 5.15. Crop Yield Improvement as a Linear Function in Parameters

$$\ln F_t = \alpha + \delta t + \varepsilon_t$$

The estimated parameters, $\hat{\delta}$ and $\hat{\alpha}$, are in Table 5.16 and estimated from the annual, average U.S. crop yields data, spanning from 1990 to 2004 from National Agricultural Statistics Service (1997, 2005). The t-statistics are in parenthesis and goodness of fit measure is R^2. The crop yield improvements were updated in FASOM-GHG. The negative growth rates for sugarcane and sorghum were included, indicating "negative" technological improvement.

The last source of technological improvement is decreasing production cost. Two rates are examined as a separate scenario in Section 8.4. The first rate is a 0.5% annual decrease for 20 years for all biofuel production budgets in FASOM-GHG, while the second rate is 1% decrease.

Table 5.16. Estimated Exogenous Crop Improvement and Cultivation

Crop	Intercept Parameter Estimate $\hat{\alpha}$	Crop Yield Improvement Parameter Estimate $\hat{\delta}$	Goodness of Fit R^2
Barley	4.0317	0.0055	0.180
	(136.25)	(1.69)	
Canola	-	-	-
Corn	4.7059	0.0188	0.525
	(104.29)	(3.79)	
Cottonseed	6.9158	0.0046	0.046
	(132.69)	(0.79)	
Flaxseed	2.8170	0.0104	0.182
	(50.79)	(1.70)	
Mustard	-	-	-
Oats	4.0149	0.0084	0.251
	(110.38)	(2.09)	
Peanuts	7.6662	0.0226	0.568
	(154.06)	(4.13)	
Potatoes	5.7060	0.0166	0.859
	(337.29)	(8.90)	
Rapeseed	-	-	-
Rice grain	8.5891	0.0143	0.756
	(418.32)	(6.34)	
Safflower	-	-	-
Sesame	-	-	-
Sorghum	4.1971	-0.0068	0.069
	(67.17)	(-0.98)	
Soybeans	3.5537	0.0078	0.206
	(92.41)	(1.84)	
Sugar beets	2.9772	0.0091	0.373
	(100.46)	(2.78)	
Sugarcane	3.5259	-0.0003	0.001
	(146.67)	(-0.12)	
Sunflower	7.1588	0.0007	0.000
	(122.48)	(0.10)	
Sweet potato	4.9485	0.0104	0.435
	(164.81)	(3.16)	
Wheat	3.5955	0.0094	0.265
	(91.13)	(2.17)	

Note: Numbers in parenthesis are t-statistics.

6. THE COSTS OF PRODUCING BIODIESEL AND ETHANOL

Market data for biodiesel and ethanol are scarce, but one way around the lack of data is to assume the biofuels industry is competitive. Thus, the biofuel prices equal the biofuel producing firm's marginal cost, and the marginal cost is decomposed into five marginal cost categories, which are operating costs, capital cost, hauling cost, transportation costs, and feedstock costs.

6.1. Operating Costs

This section determines the operating costs of producing biofuels and views operating costs as being constant.

6.1.1. Biodiesel Production

The operating costs of converting vegetable oil into biodiesel involve three different technologies. Each technology is briefly reviewed and then operating costs are cited from the literature.

- The first method of producing biodiesel is the transesterification of oil with a catalyst. The chemical reaction occurs around or slightly above room temperature (Gerpen et al. 2004; Graboski and McCormick 1998; Encinar et al. 2002; Srivastava and Prasad 2000; Zhang et al. 2003a). However, this method has two problems. First, the catalyst has to be recovered by washing the biodiesel with water (Barnwal and Sharma 2005; Zhang et al. 2003a) or neutralized with an acid (Zhang et al. 2003a). The catalyst has to be removed, because small traces of the catalyst are corrosive to diesel engines. Second, if an alkaline catalyst is used, then the free fatty acids create soapy compounds that contaminant the biodiesel (Encinar et al. 2002; Gerpen et al. 2004; Shay 1993; Zhang et al. 2003a).
- The second method to produce biodiesel is the supercritical methanol transesterification method. The oil and methanol mixture are heated to 240^0

C and subjected to high pressure with no catalyst (Barnwal and Sharma 2005; Fukuda, Kondo, and Noda 2001; Gerpen et al. 2004; Tyson et al. 2004; Zhang et al. 2003a). This method has three benefits. First, no caustic catalyst is used. Second, the free fatty acids are converted to methylesters (Fukuda, Kondo, and Noda 2001). Finally, the reaction time is much quicker and is approximately 2-4 minutes for full conversion (Barnwal and Sharma 2005), but the drawback is the higher energy and capital costs needed to heat the mixture under high pressure (Zhang et al. 2003a).

- The third and final method is using enzymatic transesterification by lipase. A lipase is an enzyme that breaks down fat and is used as the catalyst in the chemical reaction (Fukuda, Kondo, and Noda 2001; Zhang et al. 2003a). Like the previous method, the free fatty acids from used oil can be converted to methylester and glycerol is easily recovered from the reaction. However, the lipase is expensive to manufacture and this method is not used to produce biodiesel commercially (Fukuda, Kondo, and Noda 2001; Gerpen et al. 2004).

U.S. biorefineries use the catalyst method of producing biodiesel. The U.S. biorefineries use alkaline catalysts for vegetable oils that contain trace amounts of free fatty acids and acid catalysts for yellow grease and recycled oils that contain high levels of free fatty acids. For instance, yellow grease contains up to 15% free fatty acids[13], especially in the summer when temperatures are high and moisture is present (Canakci 2007; Tyson et al. 2004). Acid catalyst cause slow chemical reactions, but has high conversion rates (Encinar et al. 2002; Fukuda, Kondo, and Noda 2001; Gerpen et al. 2004; Tyson et al. 2004; Zhang et al. 2003a).

The operating costs from four sources are shown in Table 6.1. The operating costs are in dollars per gallon, and include costs for labor, overhead, methanol, catalyst,

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[13] When the free fatty acids exceed 15%, then this recycled grease is referred to as brown grease and sold at a discount (Canakci 2007).

electricity, natural gas, steam, water, waste disposal, local taxes and insurance, and maintenance. The itemized cost data were summed and converted to real 2000$ by dividing by the GDP deflator. The operating cost for biodiesel production using virgin oil is the average of the three virgin oils from Graboski and McCormick (1998); Haas et al. 2006; and Zhang et al. 2003b, which is $0.641 per gallon. These operating costs were added to the corn and soybean biodiesel production budgets in FASOM-GHG, and the tallow biodiesel production budget was updated. The operating cost for yellow grease is $1.146 per gallon and is from Zhang et al. (2003b). This cost was used to update the yellow grease biodiesel budget in FASOM-GHG. The operating costs are higher, because yellow grease uses an acid catalyst.

Table 6.1. Estimated Biodiesel Operating Costs

Item	Units	Cost Estimates from Graboski and McCormick (1998)	Cost Estimates from Haas et al. (2006)	Cost Estimates from Zhang et al. (2003)	Cost Estimates from Zhang et al. (2003)
Oil source		Virgin oil	Virgin oil	Virgin oil	Waste oil
Capacity	gal	10,000,000	10,000,000	2,400,000	2,400,000
Capital	$	20,000,000	11,348,000	1,340,000	2,550,000
Labor	$/gal	0.500	0.052	0.201	0.294
Overhead	$/gal	0.025	0.010	0.561	0.573
Methanol	$/gal	0.088	0.097	0.051	0.093
Catalyst	$/gal	0.001	0.055	0.096	0.021
Electricity	$/gal	0.006	0.005	0.006	0.009
Natural gas	$/gal		0.032	0.000	0.000
Steam	$/gal	0.001		0.027	0.069
Water	$/gal	0.005	0.000	0.002	0.006
Waste disposal	$/gal		0.005	0.004	0.102
Taxes and insurance	$/gal	0.040	0.007	0.008	0.012
Maintenance	$/gal	0.070	0.011	0.021	0.039
Nominal total cost	$/gal	0.735	0.273	0.976	1.218
GDP deflator	base 2000	96.472	112.113	106.305	106.305
Real total cost	$/gal	0.762	0.243	0.918	1.146

The biodiesel industry could produce and sell glycerol. Companies use glycerol to make soap, foods, cosmetics, and pharmaceutical products (Duffield et al. 1998; Tyson et al. 2004). The current U.S. glycerol production is around 249.2 million pounds (Tyson et al. 2004) and seven biodiesel biorefineries with production capacities of 50 million gallons could supply this market. If any other factor does not change in the glycerol market, then a large biodiesel industry would quickly saturate the glycerol supply, causing the market price to decrease (Bender 1999; Ortiz-Canavate 1994). Moreover, the biorefinery has higher marginal cost to collect and purify the glycerol and glycerol is difficult to recover and purify from yellow grease, because the presence of impurities (Fukuda, Kondo, and Noda 2001). As a result, glycerol is not included in the operating costs as an offset.

6.1.2. Ethanol Production

The traditional and lignocellulostic fermentations use different technologies, therefore, the operating costs are different. Traditional fermentation operating costs are discussed first and then lignocellulostic.

6.1.2.1. Traditional Fermentation

The operating cost for an ethanol biorefinery is from a 2002 USDA survey of 21 dry grind plants. The survey represented a variety of dry-grind ethanol plants that were farm cooperatives, limited liability companies, investor owned, and partnerships with capacities ranging from nine to 90 million gallons of ethanol. The smaller companies fermented only corn while the large ones fermented corn, sorghum, and other grains (Shapouri et al. 2002).

The operating costs are in dollars per ethanol gallon and are shown in Table 6.2. The operating costs are classified into five categories. The first category is labor, supplies, and overhead; the second category is the denaturant, which is used to remove the water from ethanol; the third category is utilities; the fourth category is waste disposal; and the last is water. All costs are aggregated and converted to real by dividing by the GDP deflator. The 21 dry grind ethanol plants have a real operating cost of 39.58

cents per gallon and the dry-grind operating budgets in FASOM-GHG were updated with the production costs.

Wallace et al. (2005) estimated the operating costs for a corn fermentation biorefinery and their estimates are included in Table 6.2 as a comparison. The reason is to assess the accuracy of Wallace et al. (2005), because this dissertation uses their operating costs for a lignocellulostic corn stover ethanol facility. Wallace et al. (2005) under estimated several cost, but only differs from Shapouri et al. (2002) approximately 8 cents per gallon when operating costs are converted into real.

Table 6.2. Estimated Traditional Ethanol Operating Costs

Item	Units	Cost Estimates from Shapouri et al. (2002)	Cost Estimates from Wallace et al. (2002)
Labor, supplies, and overhead	$/gal	0.1958	0.1370
Denaturant	$/gal	0.0348	0.0260
Utilities	$/gal	0.1729	0.1670
Waste disposal	$/gal	0.0059	
Water	$/gal	0.0030	
Nominal total cost	$/gal	0.4124	0.3300
GDP deflator	base 2000	104.1870	104.1870
Real total cost	$/gal	0.3958	0.3167

The ethanol industry produces CO2 as a byproduct and could sell the CO2 to the food industry. The food industry liquefies the CO2, using it to freeze, chill, and preserve food, or use the CO2 to carbonate beverages. The CO2 market was 5.6 million tons in 1995 and the market growth rate ranges from 3 to 4 percent per year (Chemical Marketing Reporter 1995). An ethanol industry with 36 ethanol refineries with production capacity of 50 million gallons per year could supply this market. For biorefineries to sell CO2, they have to invest in capital to capture the CO2 from fermentation tanks and store it pressurized tanks. A large ethanol industry could easily saturate the CO2 market, causing the market price to drop significantly. Hence, no offsets are provided in the operating costs for the CO2 byproduct.

6.1.2.2. Lignocellulostic Fermentation

Ethanol from lignocellulostic fermentation is not produced on an industrial scale. This dissertation uses the operating cost estimates from Wallace et al. (2005) and decomposes the costs into the same cost categories as traditional fermentation. The lignocellulostic fermentation operating costs are shown in Table 6.3 and are based on a 50 million gallon facility. The production costs are approximately twice the costs as the traditional fermentation. The crop residues production budgets in FASOM-GHG were updated to reflect these costs.

Table 6.3. Estimated Lignocellulostic Ethanol Operating Costs

Item	Units	Cost Estimates from Wallace et al. (2002)
Labor, supplies, and overhead	$/gal	0.3980
Denaturant	$/gal	0.0240
Utilities	$/gal	0.1670
Waste disposal	$/gal	0.0360
Nominal total cost	$/gal	0.6250
GDP deflator	base 2000	104.1870
Real total cost	$/gal	0.5999

The lignocellulostic byproducts are CO2, furfural, lignin, and methane. A large ethanol industry could saturate the CO2 market, causing a low market price. Therefore, the low market price provides a weak incentive to invest in capital to collect and to store the CO2. No offset is included in the budget. Second, not much is known about furfural and its market price. Hence, no offset is included in the operating costs for this byproduct. Third, the lignin could be burned to produce electricity. FASOM-GHG allows biorefineries to burn the lignin and to sell electricity if the marginal revenue is greater than or equal to marginal costs. Finally, the operating and capital costs of collecting and burning methane gas are not known, and thus, not included as an offset in the operating budget.

6.2. Capital Requirements and Costs

The production of biofuels and byproducts are assumed to be Leontief technology, but the refinery's production capacity and capital are not. Biorefineries have large capital costs, which include an assortment of buildings, storage tanks, bins, machines and equipment. A biorefinery needs tanks and bins to store feedstocks, byproducts, biofuels, chemicals, and enzymes, and needs separate tanks for the chemical reactions and processing. Economies of scale result from how the tanks surface area increases relative to an increase in a tank's volume. For example, the material costs to construct a tank are proportional to the tank's surface area while the tank's volume is proportional to the tank's production capacity. Consequently, doubling a tank's costs, more than doubles the tank's volume (Gallagher et al. 1999, 2005).

6.2.1. The Economics of a Biorefinery's Size

A biofuel refinery has large capital costs and could produce a variety of products to hedge against fluctuating commodity prices, ensuring the biorefinery earns a return on its investment. Refer to the examples below:

- Brazil uses two types of ethanol distilleries: Annexed and autonomous. An annexed distillery produces both ethanol and sugar, while an autonomous distillery only produces ethanol. The annexed distillery can hedge against fluctuating prices and earn higher profits by switching sugar and ethanol production into the more valuable commodity (Rask 1995).
- U.S. corn wet mills produce a host of products and are similar to Brazil's annexed distilleries. The wet mills can alter the production possibilities among cornstarch, dextrose, high fructose corn syrup, and ethanol, creating corn oil and various animal feeds as byproducts.

- As the biodiesel industry expands, the biodiesel refineries could be annexed to a crushing facility, feed mill, grain handling facility, or rendering plant (Bender 1999; Van Dyne, Weber, and Braschler 1996). The annexed refinery has the flexibility to sell either vegetable oil and tallow, or biodiesel, depending on market prices and production costs.

Biorefineries are classified into three sizes. The smallest and simplest is on-farm processing. The next size is medium-scale processing, and the largest biorefineries are large-scale processing.

The smallest biorefinery size is on-farm processing, where the farmer harvests the energy crop and converts it to biofuel. Farmers could produce ethanol on a small scale, but would have more difficulty in producing biodiesel. For the farmer to produce biodiesel, farmers need large machines and equipment to crush, press, and purify the oils. On-farm processing is not likely to be a large segment of the biofuels market. Farmers may also have trouble providing a standardized product with minimal impurities (Ortiz-Canavate 1994).

The medium-scale production facilities can be in two forms, which are co-operative processing or producer owned. A cooperative (co-op) pools member resources together and invests in large machines and equipment. The quantity and quality of the biofuels are higher than on-farm processing (Ortiz-Canavate 1994). For example, the cooperative Ag-Processing produces soy-diesel and has a membership of 300,000 (Bender 1999). The other form of medium size production facilities are producer owned, such as U.S. dry-grind facilities. Dry grind facilities range in annual production between 5 and 30 million gallons, and currently dry mills are being constructed with capacities ranging from 40 to100 million gallons (Gallagher et al., 2005; Rausch and Belyea 2006).

Large-scale processing plants tend to be corporate owned, capital intensive, use more complex technology, and produce a spectrum of outputs (Ortiz-Canavate 1994; Rausch and Belyea 2006). For example, U.S. corn wet-milling facilities are capital intensive that process large quantities of corn and generate a large array of products

(Rausch and Belyea 2006). Corn wet mills range between 50 to 330 million gallons (Gallagher et al. 2005).

Regulations and taxes have an impact on biorefinery size. For example, not only does the U.S. federal law provide credits for ethanol and biodiesel, but also grants a tax credit to small producers. Federal law provides a \$0.10 per gallon tax credit to small producers with production capacities below 60 million gallons. The credit applies to both ethanol and biodiesel producers and the credit cannot be applied to more than 30 million gallons per year (U.S. Government Printing Office 2002, 2004, 2005). Any firm constructing a biofuel refinery around a 60 million gallon capacity has a financial incentive to keep the capacity below 60 million gallons in order to receive this tax break.

The last and an important factor that determines biorefinery scale are hauling costs. The larger the biorefinery size, the more feedstock the biorefinery processes, and thus, biorefineries haul the feedstocks over longer distances, exponentially increasing hauling costs (French 1960; Tembo, Epplin, and Huhnke 2003).

6.2.2. Mathematical Derivation of Capital

The annual capital depreciation cost is calculated from the discount rate, life of capital, and the relationship between a biorefinery's capacity and capital costs. The annual capital depreciation cost is defined as M and the market return rate is assumed to be 8%. Investors invest in capital in time period 0. The firm either receives a loan and makes payments equal to M each year, or the payment could be considered the opportunity cost of capital. Most researchers assume a biorefinery's capital has a life of either 10 or 15 years (Graboski and McCormick 1998; Kaylen et al. 2000; Tembo, Epplin, and Huhnke 2003; Wallace et al. 2005). Thus, the capital is assumed to have a life of 10 years, because investors replace aging biorefineries quicker, using the most recent technology. The continuous present value formula is Formula 6.1 and is used to calculate the annual depreciation costs.

Equation 6.1. Relating Capital Costs to Annual Capital Depreciation Expense

$$K = \int_{0}^{10} Me^{0.08t} dt \quad \Rightarrow \quad M = 0.06528K$$

The estimated capital costs are from a 2002 survey of 19 dry grind facilities, where Gallagher et al. (2005) estimated the relationship as $K = 2.337S^{0.8356}$. Capital is measured in millions of real dollars and S is in millions of ethanol gallons. Using a 50 million gallon capacity yields a capital cost of $61.4 million. Using Equation 6.1 yields a capital depreciation cost of $0.08 per gallon. The amortized capital costs are added to the production costs in the FASOM-GHG production budgets.

The capital costs for lignocellulostic fermentation is from Wallace et al. (2005). They estimated a 50 million gallon facility would cost $193.7 million. Converting the capital costs into 2000 dollars by dividing by the GDP deflator (1.04187) and using Equation 6.1 yields an annual capital depreciation costs of $0.243 per gallon. The amortized capital costs are added to the production costs in the FASOM-GHG production budgets.

The capital costs for biodiesel biorefinery is from Haas et al. 2006. They estimated a 50 million gallon facility would cost $56.4 million. Converting the capital costs into 2000 dollars by dividing by the GDP deflator (1.12113) and using Equation 6.1 yields an annual capital depreciation cost of $0.066 per gallon. The glycerol refining capital was deducted from capital costs. The capital costs are added to the capital costs in the FASOM-GHG production budgets for corn and soybean biodiesel, and added to the production costs for yellow grease and tallow biodiesel production budgets.

6.3. Hauling Costs

The hauling cost includes the handling, processing, and transportation of the feedstock to the processing plant. This dissertation uses French's (1960) approximation of hauling costs and assumes the biorefinery is in the center of a square and a grid layout of the roads surround the biorefinery as depicted in Figure 6.1.

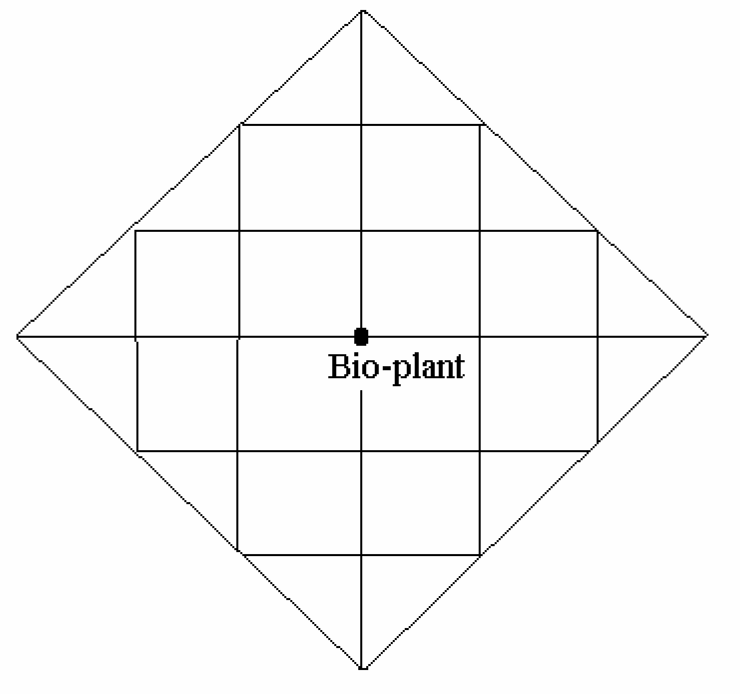

Figure 6.1. Hauling costs for biofuel feedstocks

McCarl et al. (2000) changed French's (1960) hauling equation to Equation 6.2, where $\overline{D}$ is the average distance the feedstock is hauled in miles, S is the amount of feedstock input for a biorefinery to produce 50 million gallons of biofuel, Y is the crop density in tons per acre, and 640 is acres-per-square-mile conversion. The per-unit hauling costs is $b_0 + b_1\overline{D}$, where b_0 is the fixed loading charge and b_1 is the rate charge. The rate charge includes gas, labor, and maintenance costs. The total hauling cost, H, is the per-unit hauling costs multiplied by the biorefinery's capacity. McCarl et al. (2000) defined the hauling cost parameters as $b_0 = 38$ and $b_1 = 1$.

Equation 6.2. Average Hauling Cost and Distance Given Capacity and Crop Yield

$$H = \left(b_0 + b_1\overline{D}\right)S \quad \text{and} \quad \overline{D} = 0.4714\sqrt{\frac{S}{640Y}}$$

FASOM-GHG calculates the hauling cost for all feedstocks. Even though the biorefinery capacity is fixed, FASOM-GHG allows crop yields to change over time and differ by region. Hauling costs are updated when crop yield changes. The hauling costs are calculated for the oil crops in Table 6.4 using Equation 6.2, and the biorefinery size is set to 50 million gallon capacities. The input feedstock is added to the corn and soybean biodiesel production budgets in FASOM-GHG. Peanuts have the smallest average hauling distance while sesame has the lowest hauling costs. Cottonseed has the highest average hauling distance while corn has the highest hauling costs.

Table 6.4. Average Hauling Distance and Cost for Oil Crops

Crop	Feedstock Input (tons)	Average Distance (miles)	Hauling Cost ($)
Canola	486,455	15.7	26,112,832
Corn	4,338,275	18.3	244,315,742
Cottonseed	1,020,813	23.5	62,735,964
Flax seed/ Linseed	451,057	16.6	24,628,556
Mustard	484,886	19.0	27,652,071
Peanuts	780,006	13.3	40,022,600
Rapeseed	483,461	16.0	26,122,990
Safflower	775,818	19.9	44,894,081
Sesame	387,909	16.4	21,107,153
Soybean	1,025,678	16.7	56,123,805
Sunflower	470,746	16.5	25,668,662

The hauling costs are calculated for the sugar crops in Table 6.5 using Equation 6.2 and biorefinery size is 50 million gallon capacity. The input feedstocks were used to update the production budgets in FASOM-GHG. Sugarcane has the smallest average hauling distance while sugar beets have the lowest hauling costs. Sweet sorghum has both the highest average hauling distance and costs.

Table 6.5. **Average Hauling Distance and Cost for Sugar Crops**

Crop	Feedstock Input (tons)	Average Distance (miles)	Hauling Cost ($)
Sugar beet	2,289,355.2	5.9	100,481,691
Sugarcane	2,997,769.0	5.8	131,351,000
Sweet sorghum	3,088,787.4	23.4	189,728,909

The hauling costs are calculated for the starch crops in Table 6.6 using Equation 6.2 and the biorefinery size is 50 million gallon capacity. The input feedstocks were used to update the production budgets in FASOM-GHG. Dry grind corn has the smallest average hauling distance, but rice grain has the smallest hauling costs. Oats have the highest average hauling distance, but potatoes have the highest hauling costs.

Table 6.6. **Average Hauling Distance and Cost for Starch Crops**

Crop	Feedstock Input (tons)	Average Distance (miles)	Hauling Cost ($)
Barley	669,083.8	11.8	33,324,361
corn (wet milled)	559,042.2	6.6	24,919,365
corn (dried grind)	517,312.8	6.3	22,929,861
grain sorghum	471,305.3	9.2	22,222,209
Oats	574,993.9	13.9	29,835,070
Potato	2,453,307.1	6.6	109,426,144
rice grain	493,954.4	7.0	22,242,449
sweet potato	1,378,262.4	7.4	62,544,525
Wheat	571,809.1	12.4	28,808,949

The hauling costs are calculated for crop residues in Table 6.7 using Equation 6.2 and the biorefinery size is 50 million gallon capacity. The crop residue yields are calculated by multiplying the crop yield, the crop residue-to- crop ratio, and the percentage of residue that can be removed from the land from Table 6.7. The feedstock input is used to update the production budgets in FASOM-GHG. Bagasse has the smallest average hauling distance and rice straw has the lowest hauling costs, while oat straw has the largest distance and sweet sorghum has the highest hauling costs.

Table 6.7. Average Hauling Distance and Cost for Crop Residues

Crop Residue	Crop Residue Yield (ton/acre)	Feedstock Input (tons)	Average Distance (miles)	Hauling Cost ($)
Bagasse	9.6	1,240,037.8	6.7	55,417,028
Barley straw	1.4	1,085,651.9	16.4	59,068,605
Corn Stover	3.1	865,335.6	9.8	41,343,485
Oat straw	0.9	898,294.6	18.2	50,480,918
Rice Straw	4.7	673,826.8	7.1	30,366,737
Sorghum straw	1.8	1,078,233.9	14.5	56,616,436
Sweet Sorghum	1.8	1,241,001.5	15.6	66,474,370
Wheat Straw	1.2	919,504.6	16.5	50,076,065

6.4. Transportation Costs

This section provides an overview how ethanol and biodiesel are shipped from the biorefineries to the retail markets. Then the transportation cost is estimated.

Biorefineries currently produce ethanol in the Midwest and ship it to the petroleum products terminals via truck, barge, or rail. At these terminals, the ethanol is stored separately. When ethanol is ready to ship to retail outlets, the ethanol is mixed with gasoline (Reynolds 2000). Trucks transport ethanol, if the distance is less than 300 miles, and tanker truck capacity ranges from 7,800 to 8,200 gallons (Reynolds 2000). Trains also transport ethanol to any U.S. destination, and the tank capacity is 29,000 gallons per car with 3 to 25 cars transported at the same time (Reynolds 2000). If ethanol is shipped to the east or west coasts of the U.S., then ethanol could be transported by barges. River barges carry the ethanol to New Orleans, then ocean barges transport ethanol to the east or west coasts. River barges have a 420,000 gallon capacity, while ocean barges have a capacity ranging from 1 to 12 million gallons (Reynolds 2000).

Reynolds (2000) gives transportation costs from Illinois to several U.S. cities. For example, ethanol transported from Illinois to Indianapolis by truck costs 5 cents per gallon, from Illinois to Dallas by rail costs 8.5 cents per gallon, from Illinois to Los Angeles by rail or barge costs 14-15 cents per gallon, and from Illinois to New York by rail or barge costs 11 to 12 cents per gallon.

This dissertation makes two assumptions. First, biodiesel is relatively a new industry and transportation costs are unknown. Thus, biodiesel is assumed to be transported to its markets similar to ethanol. Second, biorefineries are assumed to be constructed near their feedstocks, but also be constructed within 300 miles of the biofuel's retail market. The reason is biorefineries range in size from 10 to 100 million gallon capacities, and when compared to their respective liquid fuels, the market quantities for diesel fuel and gasoline are measured in billions of gallons per year. Therefore, biorefineries are small and could be constructed uniformly across the U.S. near their retail outlets. Consequently, this dissertation uses 5 cents per gallon of biofuel to ship the biofuel to the retail market and this transportation cost is added to all the production cost budgets in FASOM-GHG for biodiesel and ethanol.

The industry could build dedicated pipelines specifically for ethanol and biodiesel, but the biofuels industry needs to produce sufficient quantities to justify the pipeline infrastructure costs (American Petroleum Institute 2006; Reynolds 2000).

6.5. Feedstock Costs

One could use feedstock market price data to calculate the equivalent fossil fuel price for ethanol and biodiesel. The feedstock price is converted to a biofuel price, using the conversion coefficients from Sections 5.1 and 5.2. Then hauling, capital, operating, and transportation costs are added, and then adjusted for energy content. The common sugar/starch crops are examined first, and then the common vegetable oils. The lignocellulostic ethanol feedstock prices are not included, because the absence of market price data.

The sugar and starch prices are available from the National Agricultural Statistics Service (2005, 1997), and from the Sugar and Sweeteners Outlook 2006 (Haley, Kelch, and Jerardo 2006). Several feedstock prices are converted to equivalent gasoline price, reflecting all costs and energy content. Only the crops with high crop densities are plotted. The reason is high density crops also have lower hauling costs. Two corn prices are included, which are grain corn and yellow dent corn. Grain corn is dry grind while yellow dent corn is wet milled. The ethanol equivalent prices are plotted in Figure 6.2 along with gasoline price. The gasoline price is the average, annual, nominal price for gasoline, excluding the federal excise tax. For all feedstocks and all years, the feedstock equivalent gasoline price exceeds the gasoline price.

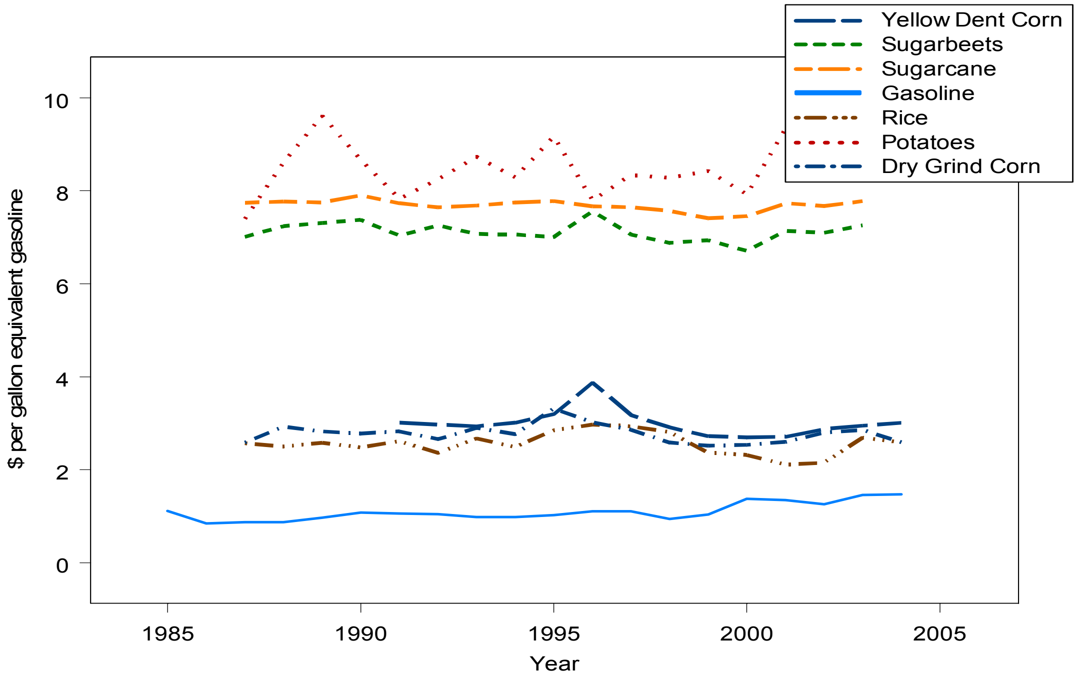

Figure 6.2. Equivalent gasoline prices derived from all costs

The vegetable and tallow prices are available from the Oil Crops Situation and Outlook Yearbook (Ash and Dohlman 2005) and all prices are converted to equivalent diesel price, reflecting all costs and energy content. The biodiesel prices are shown in Figure 6.3 and include the diesel fuel price. The diesel fuel price is the average, annual, nominal, retail price in the U.S., excluding the federal excise tax. For all years, the diesel fuel prices are lower than the equivalent biodiesel prices.

This simple analysis assumed biorefineries produce only biodiesel or ethanol. Consequently, for the market to supply biodiesel or ethanol, biorefineries will either be subsidized or produce valuable byproducts that offset some of the costs.

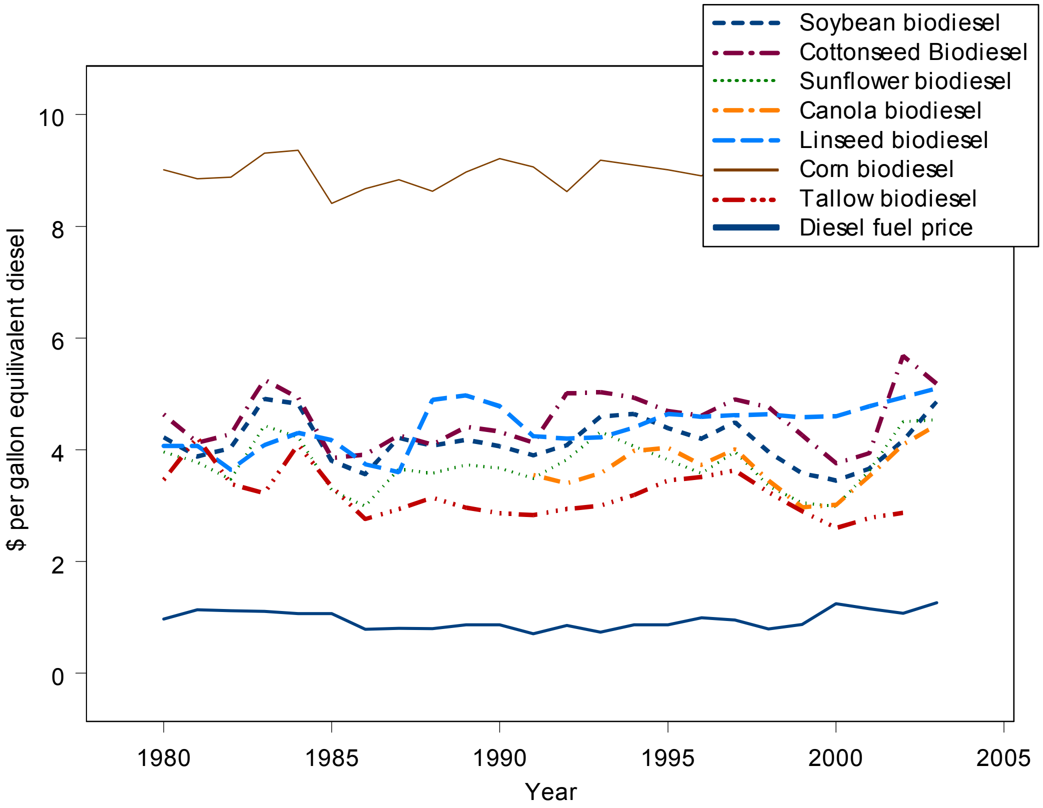

Figure 6.3. Equivalent diesel prices derived from all costs

7. MODELING OF MARKET PENETRATION

The Forest and Agricultural Sector Optimization Model-GHG (FASOM-GHG) is used to predict ethanol and biodiesel penetration, capturing market interactions among biofuel feedstocks, byproducts, and opportunity costs. This section provides an overview of FASOM-GHG, and which markets it includes. Moreover, this section explains how ethanol and biodiesel production coefficients, costs, and emissions are incorporated and how the author modified FASOM-GHG for this dissertation.

7.1. FASOM-GHG Overview

The Forest and Agricultural Sector Optimization Model-Greenhouse Gas (FASOM-GHG) is used to model the U.S. agricultural and forestry markets. FASOM-GHG is a large programming, price endogenous model, and consists of approximately 120,000 variables, 800 nonlinear variables, and 9,500 constraints. FASOM-GHG 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. The optimal price is a potential Pareto optimum and a welfare measure. FASOM-GHG uses the Law of One Price, where any price differences between markets originate from transportation costs. With a large number of markets, FASOM-GHG accounts for the opportunity costs and byproducts of biofuel production (McCarl et al. 2000).

The U.S. is decomposed into 63 agricultural production regions in FASOM-GHG. 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. Furthermore, the producers can process the primary commodities into 39 secondary products. The primary and secondary activities are aggregated into 11 regions and shown in Table 7.1 (Adams et al. 2006; McCarl et al. 2000).

Table 7.1. Forest and Agricultural Sector Optimization Model-Greenhouse Gas Regions

FASOM-GHG Region	States
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia
Lake States	Michigan, Minnesota, and Wisconsin
Corn Belt	Illinois, Indiana, Iowa, Missouri, and Ohio
Great Plains	Kansas, Nebraska, North Dakota, and South Dakota
Southeast	Florida, Georgia, North Carolina, South Carolina, and Virginia
South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Eastern Oklahoma, Tennessee, and Eastern Texas
Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming
Pacific Northwest-Eastside	Oregon, and Washington, East of the Cascade Mountains
Pacific Northwest-Westside	Oregon, and Washington, West of the Cascade Mountains
Pacific Southwest	California
Southwest	Western and central Oklahoma and all regions in Texas except eastern.

Source: Adams et al. (2006) and McCarl et al. (2000)

FASOM-GHG allows producers to switch land use to the most productive activities and producers could switch land use among agricultural land, forests, or pastures. FASOM-GHG constrains some land transfer, because land is not a homogenous resource. For example, some land may be suitable for a forest, but not for crop production. FASOM-GHG also constrains the cultivation of some crops. For instance, sugarcane is a warm climate crop, so producers can only grow sugarcane in the south (Adams et al. 2006; McCarl et al. 2000).

Allocation of land to crops, forests, livestock and pasture involves economic decisions. If a producer switches land into forest, then the producer has planting, labor, and fertilizer costs and receives revenue for selling timber. Producers grow forests in long-time frames, requiring boundary conditions for FASOM-GHG. FASOM-GHG starts with an inventory of forest in the first time period and requires a terminal value of forests in the last time period. Without a terminal value, the value of forests is zero in the last period, and producers would harvest all forest and produce timber (McCarl et al. 2000).

An agricultural producer can switch land into crop or livestock production and again this production requires many economic decisions. The producer hires workers, which include family or outside help, has limited access to water, and has to buy supplies. If the producer grows crops, he can grow a bundle of crops, choose different tillage techniques, and chose application levels of nitrogen fertilizer. If the producer raises livestock, then the producer sets aside land for pastures, raise a variety of cattle, and choose from 20 animal feeds. The producers choose feeds to minimize cost and contain minimum protein requirements for each particular livestock type. Table 7.2 contains the primary products used in FASOM-GHG and the primary products are defined in four categories. The primary crops are used for food, animal feeds, and many are the feedstocks for biofuels. The energy crops are only used for energy and are not valuable as feeds. The livestock lists the different types and each type contains different cattle weights and categories. Finally, producers can raise chickens to yield eggs.

Table 7.2. Forest and Agricultural Sector Optimization Model-Greenhouse Gas Primary Products

Category	Primary Products
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. (2006)

The producers in each region can process the crops and livestock into a variety of secondary products, which are listed in Table 7.3. The producers process the livestock into beef, pork, chicken, and turkey, and create edible tallow, non-edible tallow, and sheep wool as byproducts. Producers can convert the energy crops into biodiesel and ethanol or burn the energy crops to generate electricity. Corn could be wet-milled into high fructose corn syrup, gluten feed, cornstarch, corn oil, corn syrup, and dextrose. The milk from dairy cattle is processed into milk, butter, cream, ice cream, and a variety of cheeses. Producers process potatoes into frozen potatoes, dried potatoes, and potato chips while other producers process citrus crops into juices. Moreover, producers could refine sugar beets and sugarcane into sugar and/or crush soybeans into soybean meal and oil. Finally, producers use sugar and high fructose corn syrup as sweeteners in products like beverages, confection, baking, and canning products.

Table 7.3. Forest and Agricultural Sector Optimization Model-Greenhouse Gas Secondary Products

Category	Seconday Product
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 juice
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. (2006)

FASOM-GHG includes an international sector, because the U.S. exports and imports many agricultural commodities and products. FASOM-GHG decomposes the world into 27 trade regions and U.S. trade depends on the commodity and region of the world. Biodiesel and ethanol are currently not traded and no international markets are included for these biofuels.

FASOM-GHG accounts for GHGs. A producer chooses an activity, and the activity either releases or sequesters GHGs. For example, when the producer tills the soil by turning it over, the exposed carbon reacts with the oxygen in the air, and carbon sublimes into the atmosphere as carbon dioxide. Similarly, the nitrogen from the fertilizer reacts with the air and forms nitrous oxide. If the producer raises livestock, then some livestock like cows emit methane and nitrous oxide gases from enteric fermentation and decaying of manure. However, as producers grow crops, the plants remove carbon dioxide from the atmosphere.

FASOM-GHG includes a GHG price and the Global Warming Potential (GWP) is used as an exchange rate among all GHGs using the GWPs from the Intergovernmental Panel on Climatic Change (Cole et al. 1996, pp. 726-71). For example, one ton of carbon dioxide traps a specific amount of heat in the atmosphere. CO2 is defined with a GWP of 1 while the other gases are priced relative to CO2, rendering the GHG price in the model to be a CO2 equivalent price. One ton of methane in the atmosphere traps 21 times the amount of heat relative to CO2, causing one to 21 to be the exchange rate between CO2 and methane. Nitrous oxide traps 310 times the heat, sulfur hexafluoride traps 23,900 times the heat, and HFCs, and PFCs refer to broad category of gases with varying GWPs (Adams et al. p. 114; Beer et al. 2002; Kadam 2000). The agricultural and forestry sectors influence the CO2, methane, and nitrous oxide emissions while specialized industries influence the sulfur hexafluoride, HFCs, and PFCs.

The CO2 equivalent price acts like a tax for net emitters of GHGs or a subsidy for producers who are GHG sinks. For example, a producer can switch his land into forest and the trees sequester carbon from the air. The tree stores carbon in the roots, truck, limbs, and leaves and the producers receives the carbon dioxide equivalent subsidy. Even if the producer cuts the tree down and processes it into lumber, the lumber and tree roots still sequester carbon (Adams et al. 2006). Moreover, no distinction between taxes and tradeable permits are made in FASOM-GHG. Both place a price on emissions. The atmosphere becomes a scarce resource and producers choose the optimal amount of carbon to abate, emit, or sequester.

7.2. Biodiesel and Ethanol Production Budgets

This section describes the production budgets for biodiesel and ethanol production, and the budgets that were added to or modified in FASOM-GHG for the purposes of this dissertation.

7.2.1. Biodiesel Production Budgets

FASOM-GHG contains the major crops and livestock of the U.S. The major feedstocks for biodiesel are soybean oil, corn oil, edible tallow, non-edible tallow, and yellow grease. The other oil crops have a small presence in the U.S. and are not included. Processing budgets for each of these possibilities were added to FASOM-GHG in the process of completing this study,

Tallow is a byproduct of the beef cattle industry and comes in edible and non-edible forms. Each hundred pounds of meat yield 5.38474 pounds of edible tallow and 10.96508 pounds of non-edible tallow (Swisher 2004). Yellow grease is waste cooking oil from restaurants. The estimated amount of yellow grease created is the ratio between yellow grease and the total amount of soybean and corn oils. Soybean and corn oils are the two largest sources of vegetable oil in the U.S. and each pound of soybean or corn oil yields 0.1547 pounds of yellow grease (Duffield et al. 1998). If oil is produced from the corn wet mill or soybean crushing facility, then 15.47% of the oil returns as yellow grease.

The possibilities for biodiesel production from soybean oil and associated markets are shown in Figure 7.1. Soybeans could be exported, used directly in feeds, or sent to a crushing facility. The soybean crushing facility crushes the soybeans, producing soybean meal and soybean oil. The soybean meal is sent to the feed or export markets, while soybean oil is either used by the biodiesel industry, or sent to other markets. The production budgets are regional and could be located in any of the 10 FASOM-GHG crop-producing regions. FASOM-GHG only produces products from a production or processing budget, if the activity enhances producer plus consumer welfare.

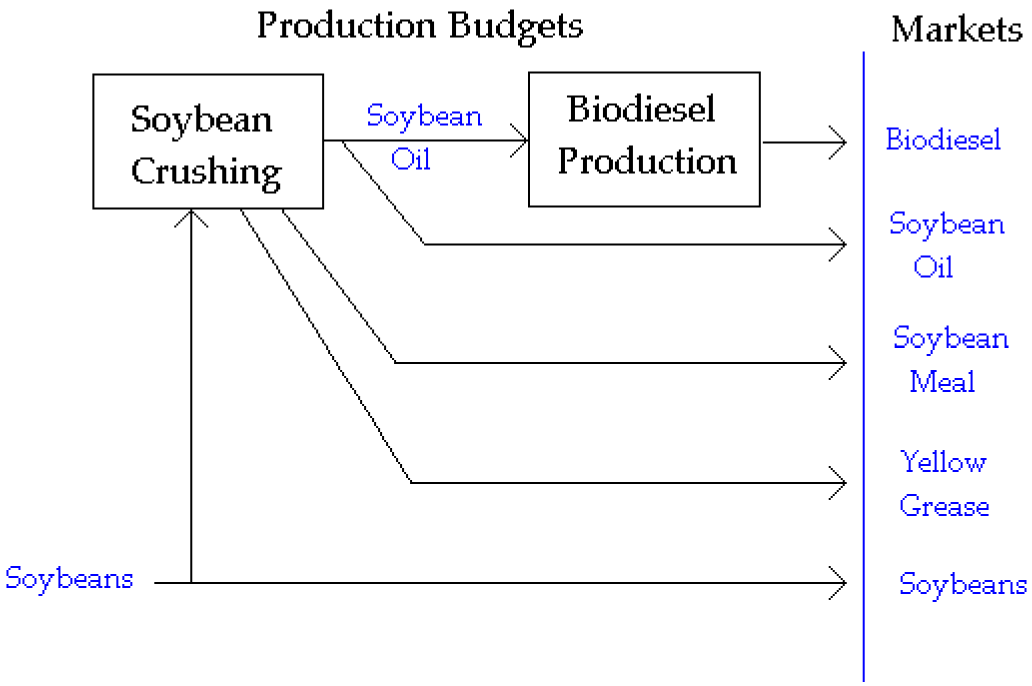

Figure 7.1. Flow chart for soybean biodiesel production

The biodiesel processing budget links the input and output markets in FASOM-GHG and is shown in Table 7.4. A constant price, small producer assumption is made, and demand functions for biodiesel are not defined. The region defines the area, where producers manufacture biodiesel. The item, Soybean Oil, is the amount of soybean oil to produce biodiesel, whereas Biodiesel specifies the production output for biodiesel. The Capital Replacement and Process Cost are the capital replacement and production costs. Finally, the items, Carbon, Methane, and Nitrous Oxide are the GHG gas offset emissions for biodiesel.

Table 7.4. Soybean Oil Biodiesel Production Budget for 1,000 Gallons

Item	Coefficient
Carbon in tons	-6.97083
Nitrous oxide in tons	-0.00032
Methane in tons	-0.01064
Capital Replacement in $1,000	1,128.00
Process cost in $1,000	646.00
Use of soybean oil in 1,000 lbs	7.3783
Yield of biodiesel in 1,000 gallons	1.0000

The soy-biodiesel life-cycle emissions were drawn from Sheehan et al. (1998). They reported all emissions as grams per break horsepower-hour and each emission is an offset of fossil fuel. For example, the CO2 emission for biodiesel is found by aggregating emissions from transporting the soybean oil to the biorefinery, converting the soybean oil into biodiesel, transporting the biodiesel to the retail market, and consuming the biodiesel. Since each power unit of biodiesel offsets diesel fuel, then the life-cycle emissions of diesel fuel is deducted from biodiesel. The break horsepower-hour compensates for the different energy content of biodiesel and diesel. The coefficients shown in Table 7.4 are negative, indicating biodiesel lowers CO2, methane, and nitrous oxide emissions.

The emission conversion coefficient is derived using Equation 7.1 and converts emission data from grams per break horsepower-hour into tons per gallon of biodiesel. The first fraction is the emission data in grams per horsepower-hour, the second fraction converts the horsepower-hour into British Thermal Units (BTUs), the third fraction is the energy content of one gallon of biodiesel, the fourth is the grams into kilograms, the fifth converts kilograms into pounds, and finally, the last fraction convert pounds into tons.

Equation 7.1. Emissions Conversion for Biodiesel

$$K_{emissions} = \frac{g}{hp-h} \cdot \frac{39.30 \times 10^{-5}\, hp-h}{BTU} \cdot \frac{117{,}093\, BTU}{1\, gal} \cdot \frac{1\, kg}{1{,}000\, g} \cdot \frac{2.2\, lbs}{1\, kg} \cdot \frac{1\, ton}{2000\, lbs}$$

A corn oil to biodiesel production possibility was also developed and is similar to soy biodiesel production. The life-cycle emissions for corn biodiesel are not known, and the soy biodiesel emission offsets were used in lieu.

7.2.2. Corn Processing Budgets

FASOM-GHG contains three types of processing budgets for corn in the 10 agricultural regions. This dissertation did not alter the coefficients for those budgets as they were recently updated during summer 2006 for an EPA renewable fuel standard study (National Archives and Records Administration 2006), except to scale the ethanol production capacity to 50 million gallons and update the corn ethanol dry grind.

The first type produces ethanol from the corn wet mill. The wet mill separates the corn into starch, and the starch is fermented into ethanol. One bushel of corn initially yields 2.5 gallons of ethanol and assumes there is no technological progress, because the corn wet mill is a specialized industry. Moreover, the corn wet mill also produces 1.5 lbs of corn oil, 3.0 lbs corn gluten meal, and 12.4 lbs corn gluten feed as byproducts (Rausch and Belyea 2006). The flow chart for corn wet mill ethanol is shown in Figure 7.2.

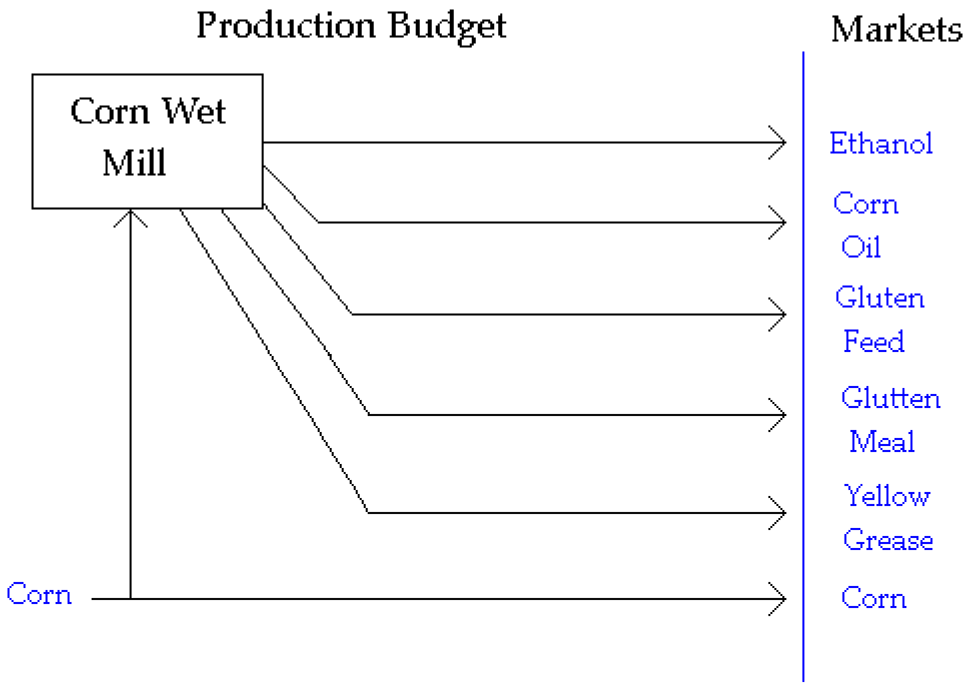

Figure 7.2. Flow chart for ethanol production from a corn wet mill

The second type produces starch from a corn wet mill, whereas one bushel of corn yields 31.5 lbs of starch. The corn wet mill could sell the starch directly to the markets, or further process starch into either dextrose or high fructose corn syrup (HFCS). One pound of starch yields 1.19 pounds of dextrose monohydrate (Light 2006), and the corn wet mill produces three types of HFCS, which are HFCS-42, HFCS-55, and HFCS-90[14]. The number denotes the percent concentration of fructose sugar and correlates how sweet the syrup tastes. The beverage industry uses HFCS-55 as a sweetener, while the canned, confections, and baking industry use HFCS-42 (Lurgi Life Science). One pound of dry cornstarch produces 1.54 lbs of HFCS-42 or 1.41 lbs of HFCS-55 (Light 2006).

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[14] HFCS-90 is an intermediary product to help produce HFCS-55 from HFCS-42 (Lurgi Life Science).

The corn wet mill for starch production is shown in Figure 7.3. The regional production budgets are represented by black boxes, while national production budget are represented by red ones. FASOM-GHG contains one budget to produce one type of high fructose corn syrup. The high fructose corn syrup could be used as inputs to the beverages, canned products, confections, or baked products production budgets. The budget adjusts the amount of high fructose corn syrup needed for each product. Moreover, the corn well mill still produces gluten meal, gluten feed, and corn oil as byproducts.

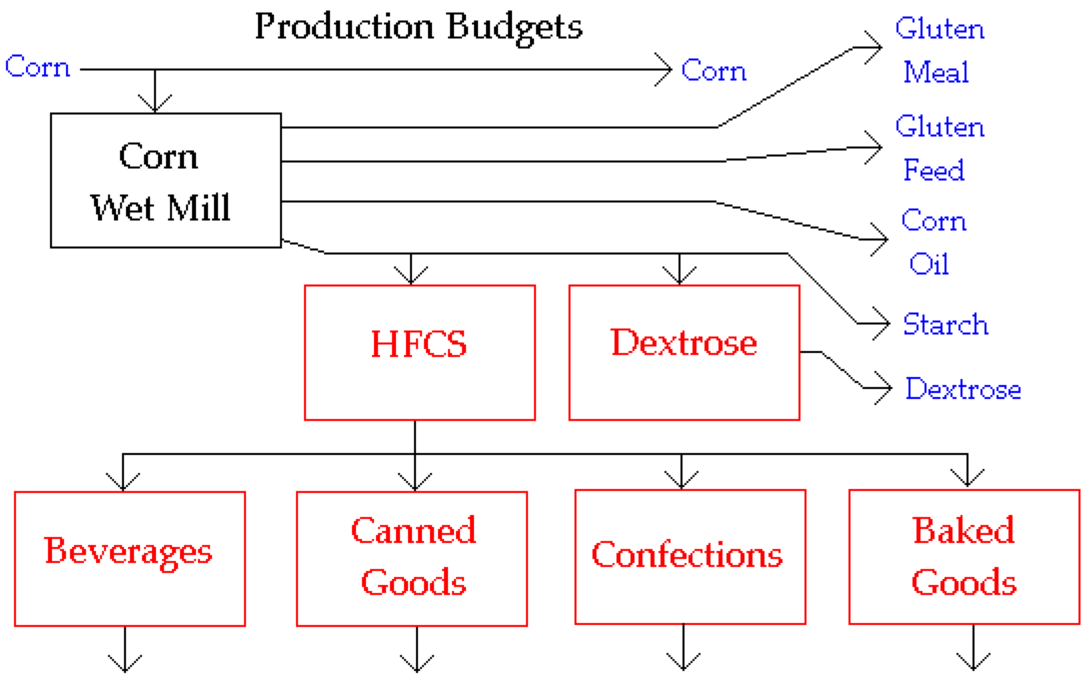


Figure 7.3. Flow chart for corn wet mill production

The third type produces ethanol from the corn dry grind. The production flow chart is shown as Figure 7.4, whereas one bushel of corn yields 2.71 gallons of ethanol and 17.33 lbs of distiller's dry grinds with solubles.

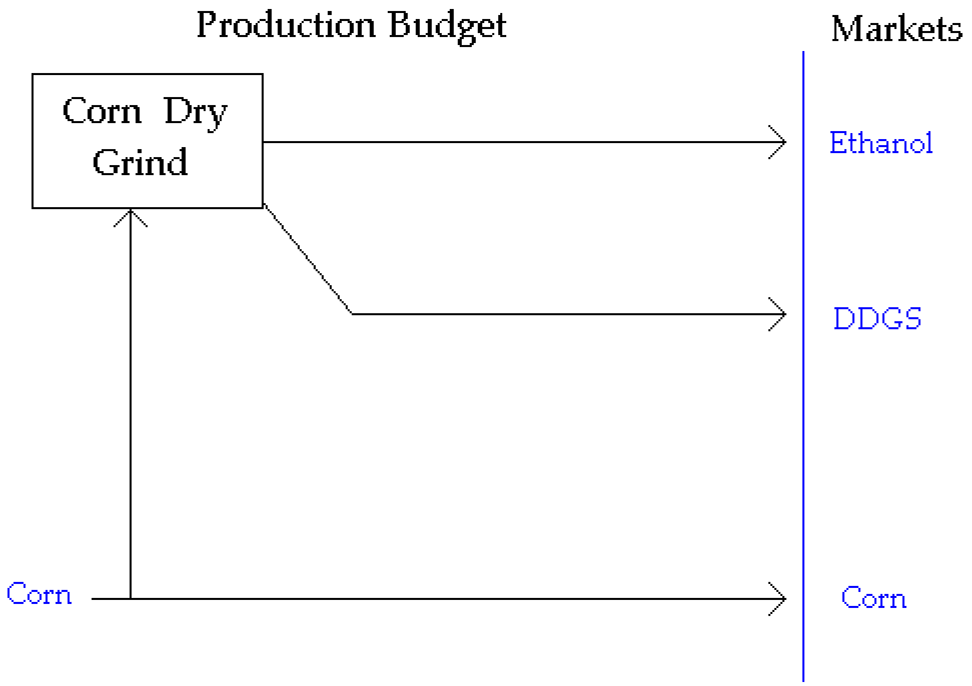


Figure 7.4. Flow chart for corn dry grind

7.2.3. Other Ethanol Production Budgets

Biorefineries could produce ethanol from barley, sorghum, oats, potatoes, rice, sugar beats, sugarcane, and wheat, using the dry grind, and ethanol from bagasse, barley straw, corn stover, oat straw, rice straw, sorghum straw, and wheat straw, using lignocellulostic fermentation.

The potato-to-ethanol production budget using the dry grind is shown in Table 7.5. The tableau items are similar to the ethanol dry grind corn production and no flow chart is provided. Potato ethanol could be produced in all regions except the Pacific Northwest-Westside. The item, Potatoes, is the amount of potatoes to produce ethanol, the Crop ethanol specifies the production output for ethanol in 50 million gallons, while the DDGS is the amount of distiller's dried grains produced as a byproduct. The State

Subsidy and Process Cost are the state subsidies and production costs. Process Cost includes production, transportation, and amortized capital costs. Finally, the items, Carbon, Methane, and Nitrous Oxide are the GHG gas offset emissions for ethanol.

Table 7.5. Potato-to-Ethanol Production Budget for 50 Million Gallons

Item	Coefficient
State subsidy in dollars	0.0
Carbon in tons	-70777.38257
Methane in tons	-36.16755234
Nitrous oxide in tons	-36.01925751
Potatoes in cwt	49,019,607.84
Process cost in dollars	26,290,000
DDGS in tons	295,000
Crop ethanol for 1,000 gallons	50,000

The ethanol production budgets for other feedstocks including crop residues are similar. The author appended the potatoes-to-ethanol production budget to FASOM-GHG, and updated the other ethanol production budgets for crop and crop residues. Moreover, the author added the byproduct, distiller's dry grains, to ethanol dry grind production from sugar beets and sugarcane.

7.3. Technological Improvement

The production technology is assumed to be additive. For example, if FASOM-GHG determines that soy-biodiesel is optimal to produce, then the soy-diesel production is added to a soybean crushing facility. FASOM-GHG currently does not solve for the optimal size biorefinery. There is no tradeoff between economies of scale and hauling cost. The ethanol and biodiesel capital costs are based on 50-million-gallon biorefineries.

Technological improvement is introduced by three methods. The first method is to allow crop yields to increase over time. As producers grow more crops, then more crops are provided to the markets. The second method is to allow the production cost to decrease over time, because the biorefinery becomes more efficient at producing biofuel. The production cost coefficients are decreased at a constant annual rate. Finally, the last method is to allow the input feedstock to decrease over time by reducing the feedstock input coefficient by a constant annual rate. Furthermore, the hauling costs could decline over time, because the hauling cost is calculated from the feedstock inputs of the dry-grind ethanol and lignocellulostic ethanol biorefineries. Furthermore, technological change does not alter the GHG emission offsets. The emission offsets are determined by the aggregate amount of biodiesel or ethanol produced.

8. BIODIESEL AND ETHANOL POTENTIAL MARKET PENETRATION

Attention is now turned to a study of market penetration using the data developed earlier and the FASOM-GHG model. In particular, the author studies market penetration under

- Alternative wholesale gasoline prices
- Alternative GHG offset prices on a CO2 equivalent basis
- Alternative rates of technical progress in crop yields
- Alternative rates of technical progress in production costs
- Alternative subsidy levels

To examine these issues, FASOM-GHG is used to predict biofuel market penetration for four scenarios.

- The first scenario is the base scenario with varying wholesale gasoline and GHG offset prices.
- The second scenario assumes U.S. crop yields increase an additional 0.5%.
- The third scenario considers decreasing production costs as biorefineries become more efficient at producing biofuels over time.
- The last scenario simulates the impact of eliminating the ethanol and biodiesel federal subsidies.

Two important assumptions are implied in this section. First, any references to ethanol or biodiesel refer to market blends, but only the ethanol or biodiesel quantity is specified. The petroleum-based fuel markets remain the same size. Thus, increases in biodiesel or ethanol production increases market penetration. Second, no problems are encountered, when the biofuels are blended with petroleum-based fuels. The problems were discussed in Section 3.2, such as using biodiesel during winter months, or ethanol and gasoline blends exceeding E15.

8.1. Base Conditions with Varying Energy and GHG Offset Prices

The first scenario contains the base set of assumptions without extra technological improvements in feedstock-to-biofuel production or crop yields, and also includes federal ethanol and biodiesel subsidies. The production period ranges from 2000 to 2015 with five-year increments. Schneider and McCarl (2003) indicated carbon dioxide taxes up to $100 per carbon dioxide equivalent ton are effective in reducing carbon dioxide equivalent emissions. Thus, a range of carbon prices between $0 and $100 per carbon equivalent ton is used. Moreover, the 25-year energy price forecasts from NEMS indicate the gasoline price is bounded by $1.00 and $3.00 per gallon. Therefore, this gasoline price range is used. The ethanol subsidy is $0.51 per gallon, while the biodiesel subsidy is $1.00 per gallon for corn oil, soybean oil, and tallow biodiesel, and $0.50 per gallon for yellow grease biodiesel.

8.1.1. Ethanol Production

The predicted total production / market penetration of ethanol is shown in Figure 8.1. When the gasoline price is $1.00 per gallon and the CO2 equivalent price is zero, ethanol biorefineries produce a peak of 2.8 billion gallons of ethanol in 2005, and then gradually declines. When gasoline prices are $1.50 per gallon or higher, the ethanol production time paths are identical. Furthermore, FASOM-GHG predicts an ethanol production level of 3.643 billion gallons in 2005, agreeing with the Renewable Fuels Association (2005) estimates of 3.6 billion gallons. Moreover, ethanol production rises monotonically over time, approaching 13.6 billion gallons in 2015. Appendix 1 contains more detailed FASOM-GHG output.

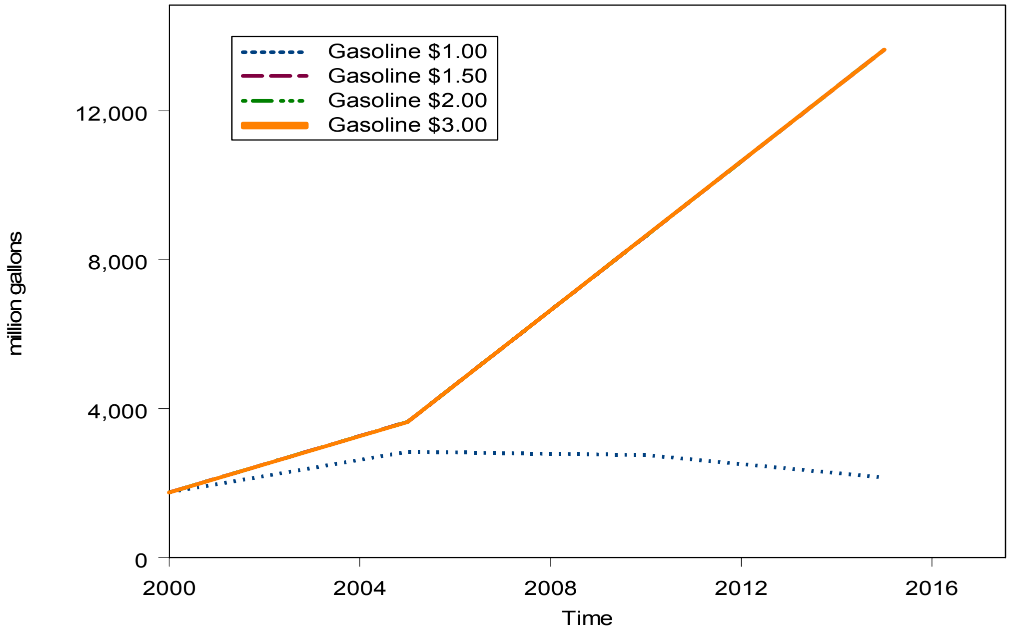


Figure 8.1. Market penetration of ethanol-base scenario

Gasoline prices of $1.50 per gallon and higher cause ethanol production to bind at an aggregate production constraint. Ethanol production is restricted to 1.750 billion gallons in 2000, 3.643 billion gallons in 2005, and the constraint increases by 1 billion gallons per year after that. The constraint results from the limited number of contractors that can construct ethanol refineries. For example, the ethanol industry comprised approximately 113 refineries in 2005 (Renewable Fuels Association 2005a) and Fagen Engineering LLC (2005) designed and constructed 22 of them and is currently constructing seven more.

The breakdown of the feedstock sources for ethanol production is shown in Figure 8.2 for a gasoline price of $2.00 per gallon and a CO2 equivalent price of zero. Only the major feedstocks are shown. In the 2005 simulation, ethanol production arises from corn wet milling, sorghum, wheat, and oats. This prediction deviates from current events, because most of the recent ethanol expansion is from the corn dry grind.

However, the corn wet mill creates more valuable byproducts, such as gluten feed, gluten meal, and corn oil, while the dry-grind only produces distiller's dried grains. Ethanol from the corn wet milling gradually increases to 2.7 billion gallons in 2015.

The U.S. ethanol industry currently does not use lignocellulostic fermentation and the interesting feature is lignocellulostic fermentation rapidly expands from corn stover. Corn stover ethanol increases rapidly to 9.6 billion gallons per year in 2015. The ethanol industry also produces ethanol from bagasse, sorghum residue, and wheat residues, but at much lower levels.

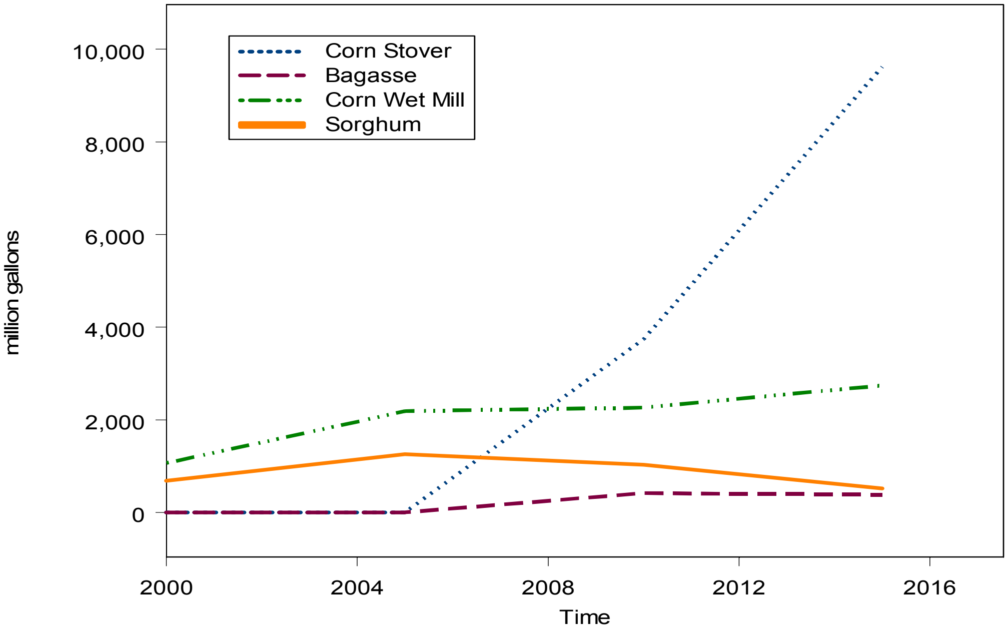


Figure 8.2. Sources of ethanol-base scenario

8.1.2. Biodiesel Production

The predicted market penetration of biodiesel is shown in Figure 8.3. When the gasoline price is \$1.00 per gallon and the CO2 equivalent price is zero, biodiesel biorefineries produce only tallow biodiesel. Furthermore, biodiesel production gradually expands to 116 million gallons of biodiesel in 2015. When gasoline price is $2.00 per gallon, FASOM-GHG predicts a production level at 755 million gallons in 2005, a 10-fold increase from the National Biodiesel Board (2006) estimates of 75 million gallons. FASOM-GHG over produces biodiesel, because FASOM-GHG contains no uncertainty in gasoline price (and hence the diesel fuel price), because the gasoline price is constant over time. As gasoline prices increase, the biodiesel production time paths shift upward. Furthermore, biodiesel production rises monotonically over time, approaching 1.8 billion gallons in 2015 with a gasoline price of $3.00 per gallon. Moreover, three time paths show a dip between 2005 and 2015, and this dip is explained later in the exports section. Appendix 1 contains more detailed FASOM-GHG output.

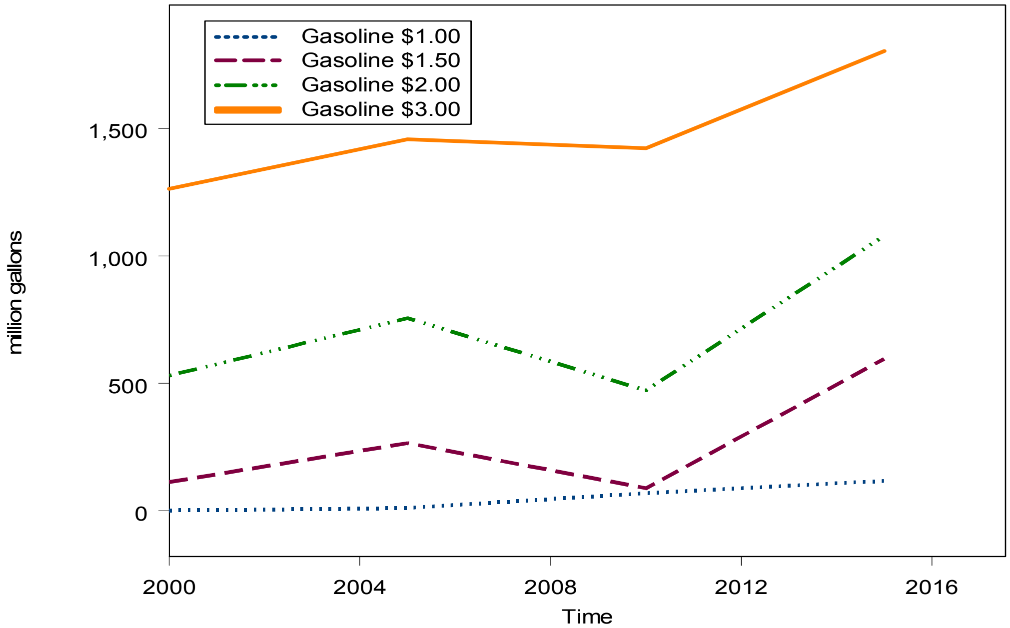


Figure 8.3. Market penetration of biodiesel-base scenario

The breakdown of the feedstock sources for biodiesel production is shown in Figure 8.4 for a gasoline price of $2.00 per gallon and a CO2 equivalent price of zero. Moreover, FASOM-GHG depicts edible and non-edible tallow as separate feedstocks, but the results are aggregated as tallow biodiesel. The largest feedstock source is soy diesel and is the source of the dip between 2005 and 2015. Furthermore, yellow grease also exhibits a small dip, because less yellow grease is created from soybean oil. Soybean biodiesel production reaches 800 million gallons in 2015.

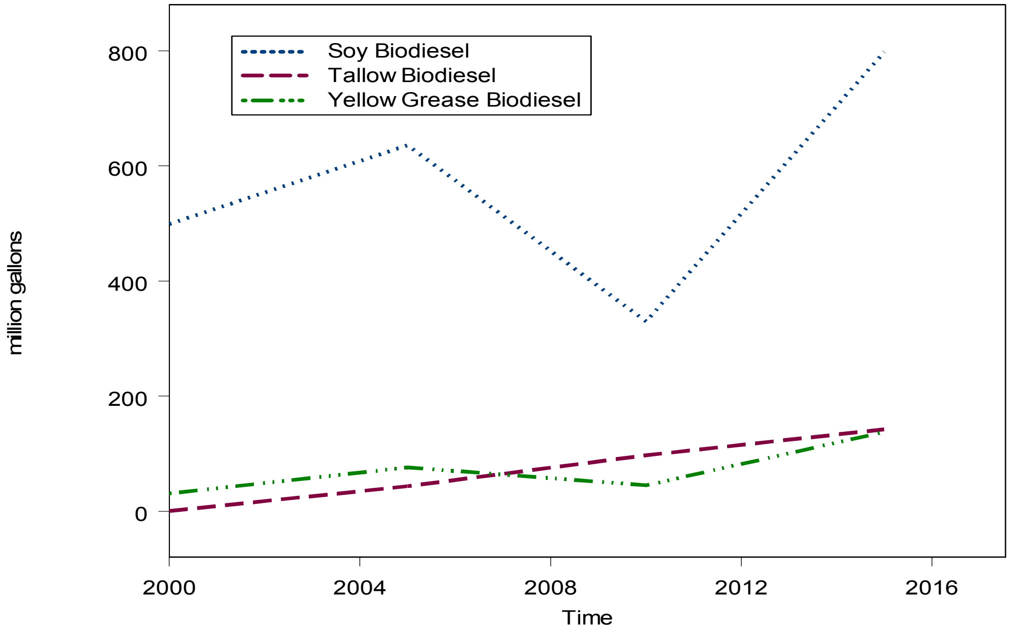


Figure 8.4. Sources of biodiesel-base scenario

8.1.3. Impact on the Agricultural Markets

The biofuel industries and gasoline price affect many markets, but this section only examines the impact on the beef, corn, soybean, DDGS, and soybean meal markets.

The slaughtered beef market is shown in Figure 8.5, because the ethanol and biodiesel industries produce cattle feeds as byproducts. The National Agricultural Statistics Service (2005) reported a beef price of $79.70 per hundred weight in 2003, while the quantity was 388 million hundred weight. These statistics agree with the price and quantity forecasts from FASOM-GHG. As gasoline prices increase, the quantity of slaughtered beef quantity increases slightly. In order for the cattle industry to supply more beef, they need to raise more cattle and use more feed. Demand for cattle feeds should increase, when gasoline prices increase.

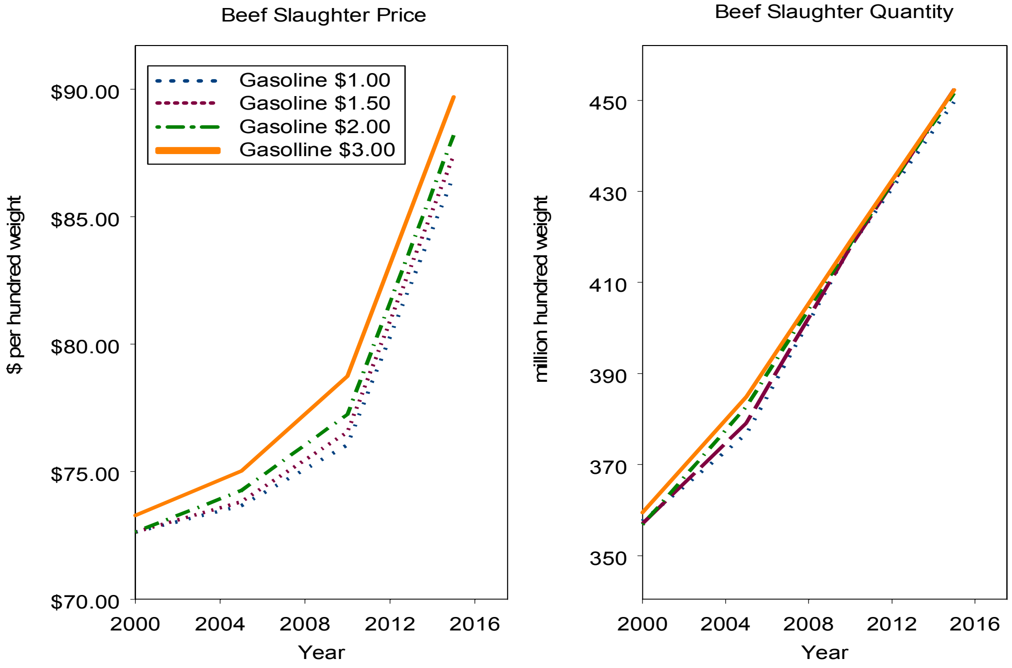


Figure 8.5. Impact on the beef market-base scenario

The impact of gasoline price on the corn market is shown in Figure 8.6. National Agricultural Statistics Service (2005) reported that corn production ranged between 8.0 and 11.8 billion bushels for the last five years, while the price ranged between $1.85 and

$2.42 per bushel. The statistics agree with the FASOM-GHG corn price and quantity predictions. As the gasoline price increases, the corn price paths shift upward. Moreover, three price paths rise to a peak in 2005 and decline, indicating corn producers are increasing production faster than the increasing demand for corn.

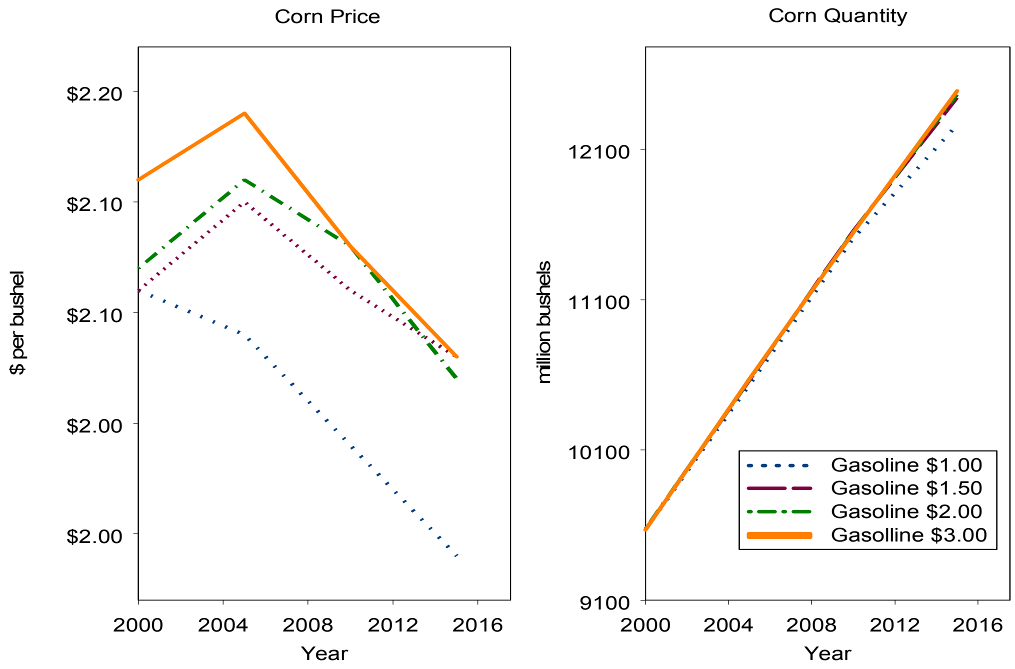


Figure 8.6. Impact on the corn market-base scenario

The impact of gasoline prices on the soybean market are shown in Figure 8.7. The left panel is the price and the right is quantity produced. Ash and Dohlman (2005) reported that soybean production ranged between 2.4 and 3.1 billion bushels, while soybean price varied between $4.38 and $7.34 per bushel for the last five years. The statistics agree with the FASOM-GHG soybean price and quantity predictions. As the gasoline price increases, biodiesel producers expand biodiesel production, using soybean oil. The demand from the biodiesel industry increases greater than quantity supplied, causing soybean market prices to increase. The higher soybean price provides an incentive for producers to expand soybean production.

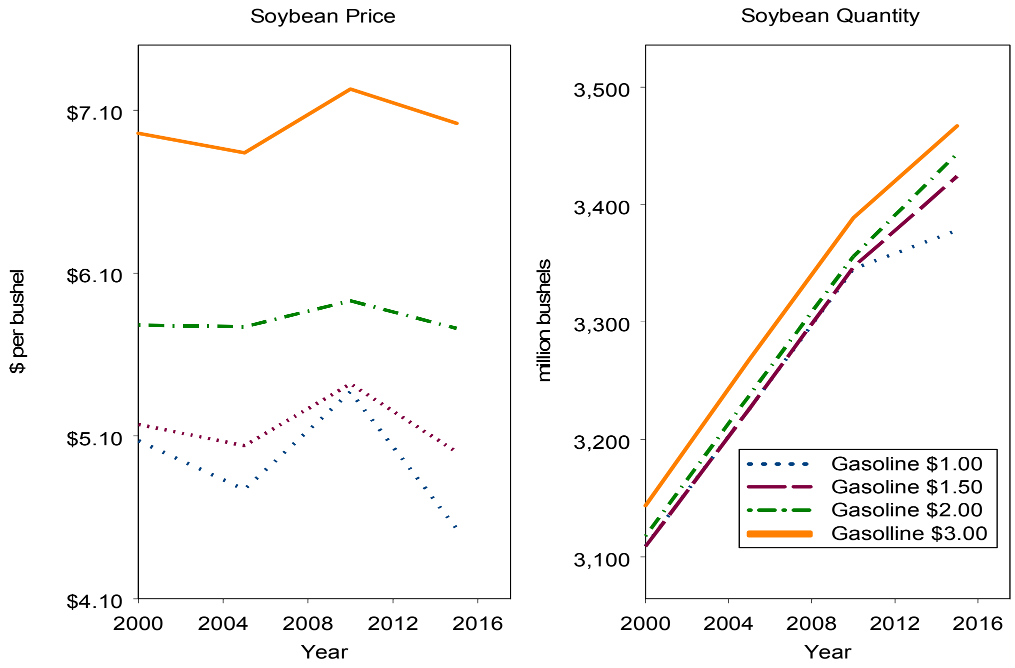


Figure 8.7. Impact on the soybean market-base scenario

Ethanol biorefineries produce DDGS from the dry grind, using sorghum, oats, and wheat, and shown in Figure 8.8. Dry grind ethanol production increases until 2005 and goes into decline, because the competition of crop residues. The DDGS market reflects this pattern. The DDGS production peaks at 2005 and then production falls while the DDGS price declines over time with a spike in 2010. The price spike results from the decrease of soybean meal production, and cattle producers bidding upward all the feed prices. When the gasoline price is $1.00 per gallon, ethanol production from the dry grind has the lowest production, producing low amounts of DDGS. When the gasoline prices rises to $1.50, ethanol production from the dry grind reaches a peak. As the gasoline price rises to $2.00 per gallon, ethanol producers use crop residues to make ethanol, decreasing their use of the dry grind. DDGS further declines when the gasoline price $3.00 per gallon.

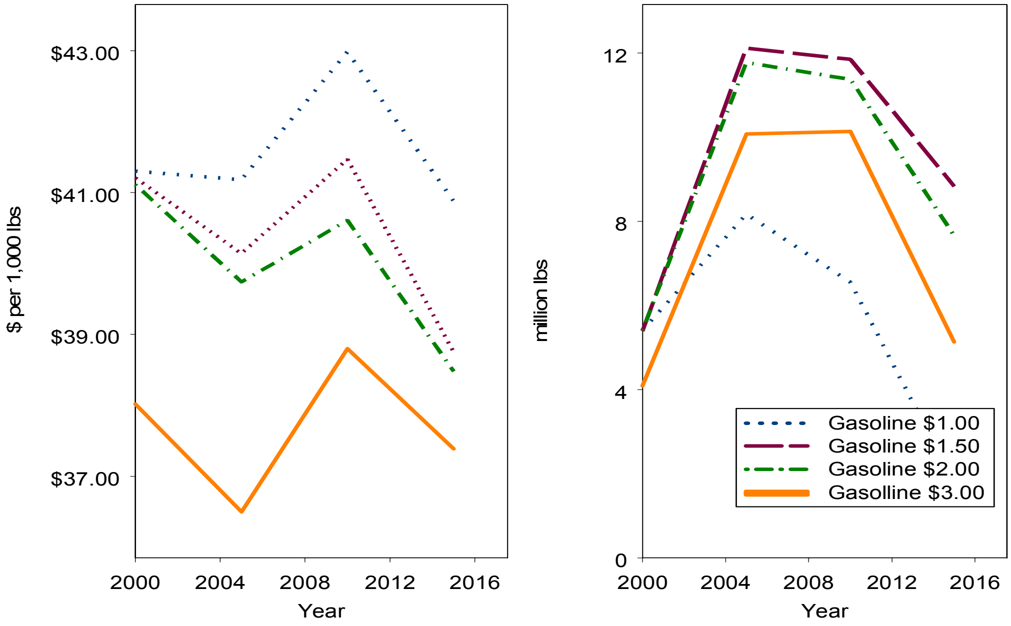


Figure 8.8. Impact on the DDGS market-base scenario

The impact on the soybean meal market is shown in Figure 8.9. The right panel is soybean meal price and the left panel is soybean meal quantity. Ash and Dohlman (2005) reported in 2003 a soybean meal price as $256.05 per ton and soybean meal production of 36.3 tons. FASOM-GHG predicts a lower price and higher quantity, because the large demand from biodiesel producers cause more soybeans to be crushed, supplying more soybean meal. As gasoline prices increase, the soy biodiesel industry expands, producing more soybean protein meal, shifting the quantity time path upward.

The meal price spikes for all gasoline prices. During the spike, less soybeans are crushed, because the soybeans are diverted to another industry.

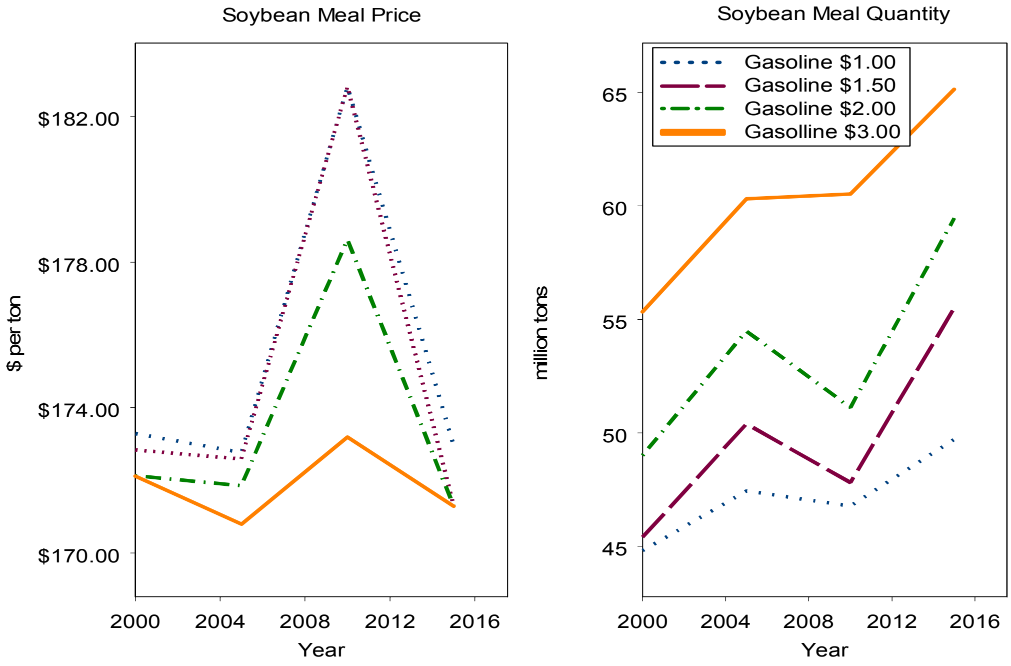


Figure 8.9. Impact on the soybean meal market-base scenario

8.1.4. U.S. Exports

The impact of gasoline prices on U.S. corn and soybean exports are shown in Figure 8.10. The left panel is corn exports, while the right panel is soybeans. National Agricultural Statistics Service (2005) reported U.S. corn exports as 1.9 billion bushels, while soybean exports were 833 million bushels in 2003/2004, agreeing with the FASOM-GHG forecasts. Moreover, FASOM-GHG predicts corn exports will grow over time. The reason is corn producers increase production over time and the increase is enough to satisfy corn demand for the corn wet mill and export sector, and even causing corn prices to decrease. As gasoline prices increase, more corn is used in the ethanol corn wet mill and diverted away from exports.

Soybean exports show the opposite pattern and decrease over time. Soybean producers are also increasing production, but the soy biodiesel industry grows rapidly enough to consume the soybean supply and divert soybeans away from exports. As gasoline prices increase, the soy biodiesel industry diverts more soybeans away from exports. Consequently, the biofuels industries have an ambiguous impact on U.S. trade balance, because a biofuels industry allows less petroleum to be imported, but soybean exports decrease.

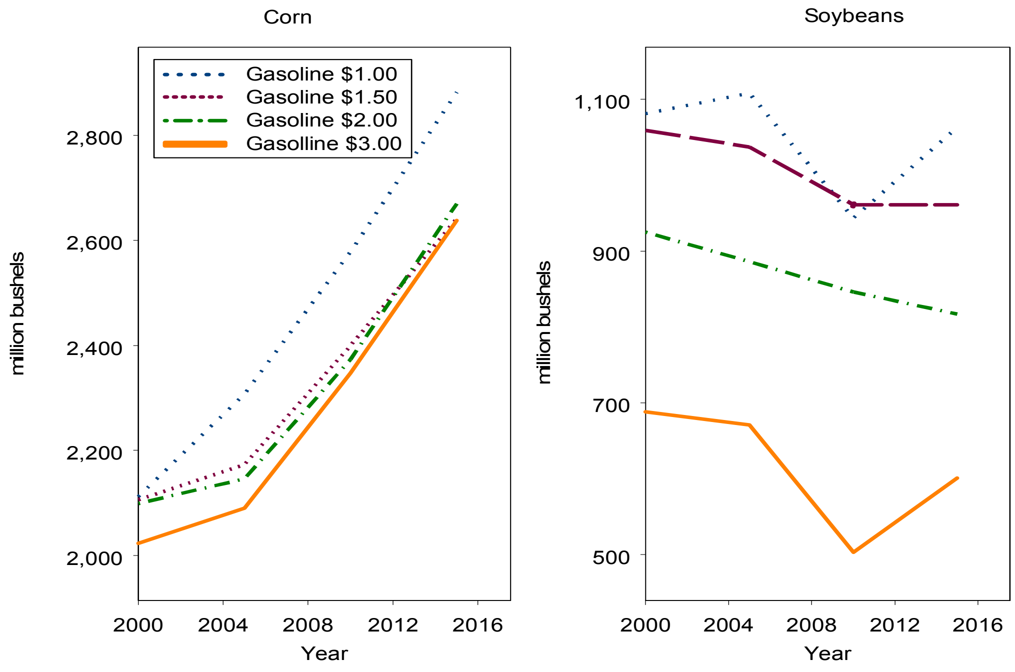


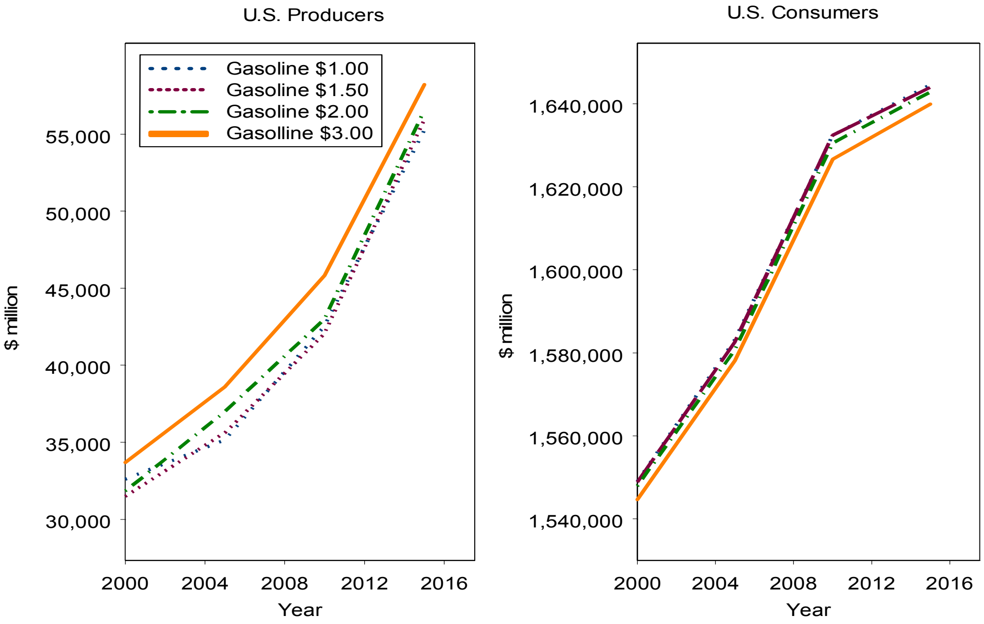
Figure 8.10. Corn and soybean exports-base scenario

The "kink" in the time paths for soy biodiesel production results from the cattle industry. Between 2005 and 2015, producers crush and export fewer soybeans.

However, soybean and cattle production are increasing over time. An expanding cattle industry requires more feeds, diverting soybeans, grains, and feeds from the other industries.

8.1.5. U.S. Welfare

The U.S. producer and consumer welfare are shown in Figure 8.11. The welfare is only for the agricultural markets. As gasoline prices increase, the U.S. agriculture producers gain. Even though high gasoline prices increase cultivation costs, some producers gain by expanding biofuel production. On the other hand, U.S. consumers lose welfare as gasoline prices increase. Even though U.S. consumers consume more biofuels, the prices of many agricultural commodities also increase, causing a net loss to consumers. This analysis is limited, because the exclusion of other non-agricultural markets. Moreover, this analysis does not determine how the producer surplus is distributed and in which industries.


U.S. Producers

U.S. Consumers

Figure 8.11. U.S. welfare change over time-base scenario

8.2. Carbon Dioxide Equivalent Prices

This section examines the impact of CO2 equivalent prices on the ethanol and biodiesel industries.

The impact of CO2 equivalent prices on the ethanol market is shown in Figure 8.12. The CO2 equivalent price varies between \$0 and \$100 per equivalent ton while the gasoline price is fixed at \$2.00 per gallon. All ethanol production time paths are identical; CO2 equivalent prices do not have an impact on ethanol aggregate production levels, because of the ethanol aggregate production constraint. Appendix 1 contains the detailed output from FASOM-GHG.

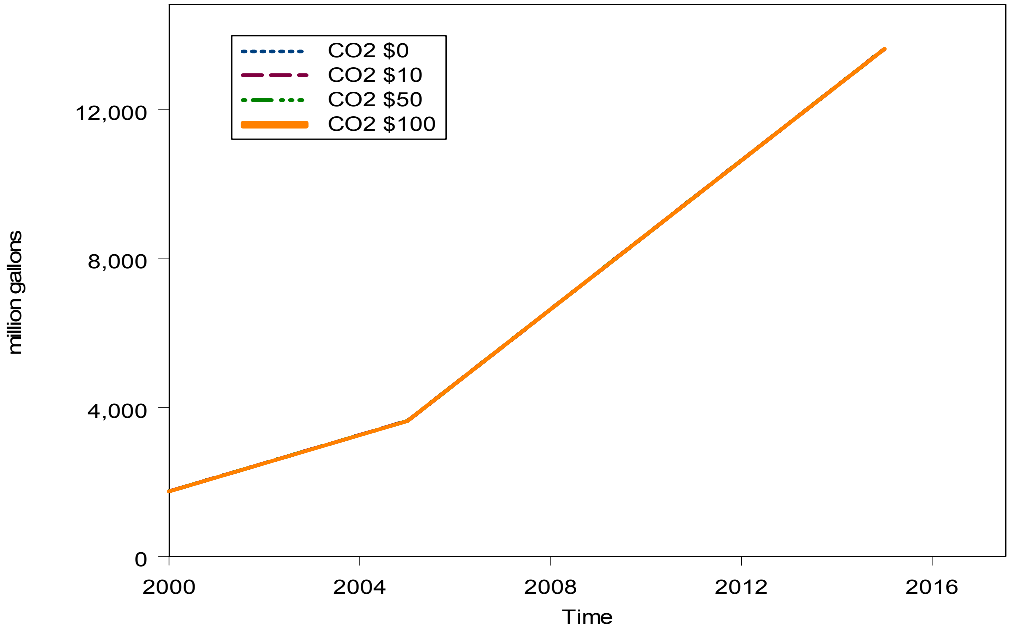


Figure 8.12. Market penetration of ethanol given CO2 prices

CO2 equivalent prices influence the choice of ethanol feedstocks, and the gasoline price is \$2.00 per gallon. The ethanol production from a corn wet mill is shown in Figure 8.13. As carbon equivalent prices increase, ethanol producers move production away from the corn wet mill, and use more crop residues, because corn wet mills have higher life-cycle GHG emissions. Moreover, producers start producing ethanol from corn stover and wheat residues as early as 2000. Appendix 1 contains the detailed output from FASOM-GHG.

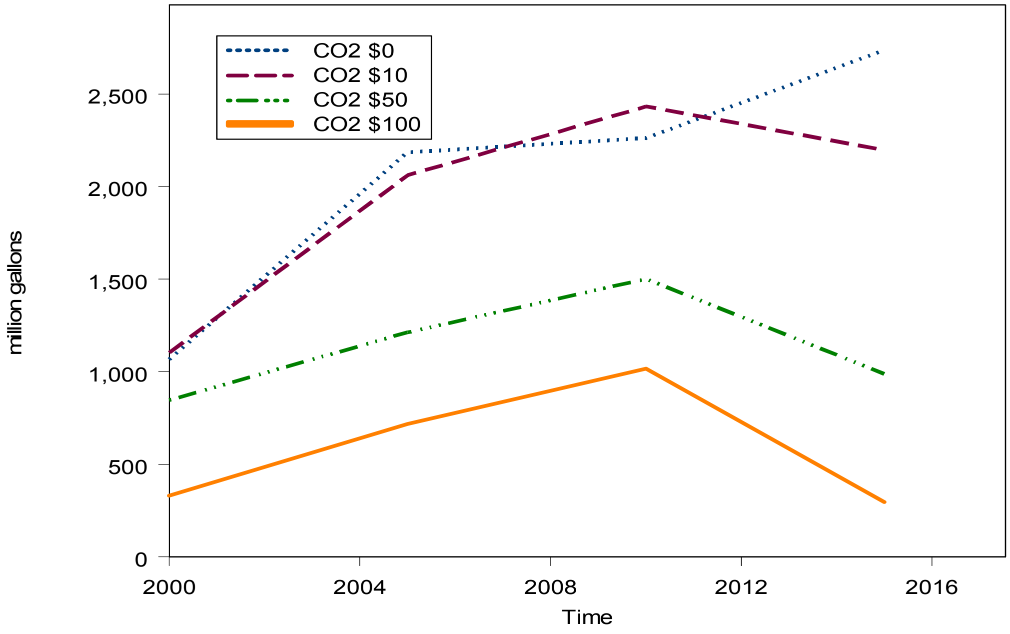


Figure 8.13. Impact of CO2 prices on corn wet mill

The impact of CO2 equivalent prices on the biodiesel industry is shown in Figure 8.14. The gasoline price is fixed at $2.00 per gallon. When CO2 equivalent prices increase, the prices expand biodiesel production. A higher GHG price encourage society to use more biodiesel, because each gallon consumed decreases methane, CO2, and nitrous oxide emissions and has a higher GHG efficiency. Most of the biodiesel expansion results from soy biodiesel. Appendix 1 contains the detailed output from FASOM-GHG.

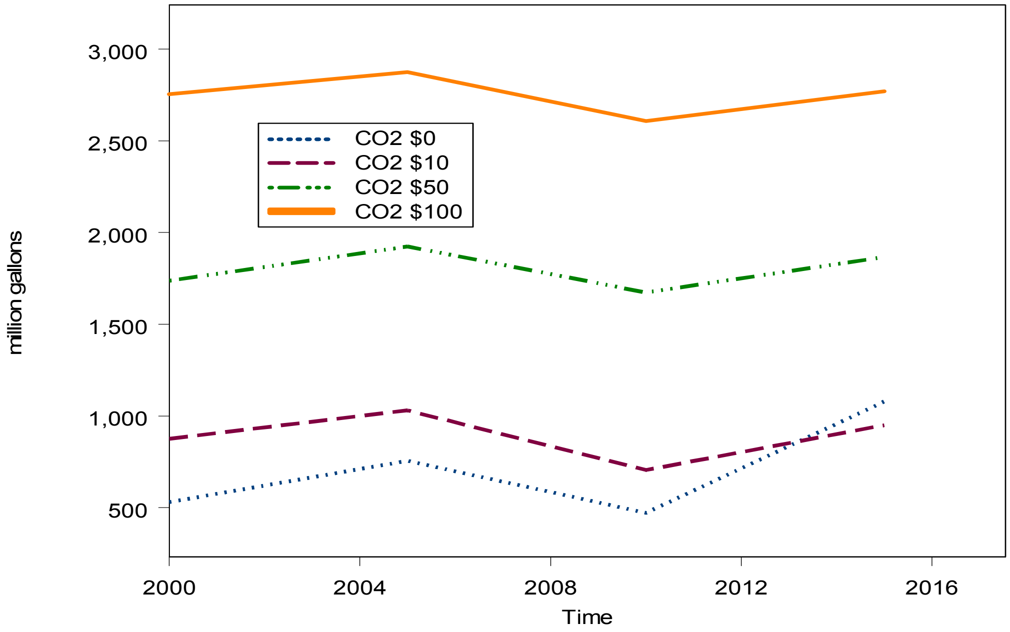


Figure 8.14. Market penetration of biodiesel given CO2 prices

The impact of carbon dioxide equivalent prices has a predictable impact on U.S. welfare. As carbon equivalent prices increases, U.S. agricultural producer welfare increases while U.S. consumer welfare decreases for all time periods. The carbon equivalent prices cause producers to abate and sequester GHG emissions. Sequestering GHG is a subsidy, but higher carbon dioxide equivalent prices cause higher agricultural prices.

8.3. Crop Yield Improvements

Now we turn attention to a study of the effects of increases in the rate to yield technical progress. To do this we simulate the effects of having the oil, starch, and sugar crops exhibit a yield increase of an additional 0.5% per year. The assumption is a growing biofuels industry encourages producers to improve cultivation techniques and introduce better crop cultivars.

The impact of the crop yield improvement on the ethanol industry is shown in Figure 8.15. When the gasoline price is \$1.00 per gallon, crop yield improvement expands ethanol production. However, crop yield improvement has no impact on the ethanol industry, when the gasoline price is \$3.00 per gallon. The main reason for this lies in a FASOM-GHG assumption. Namely, the ethanol industry is constrained to be able to build no mere than 1 billion gallons of capacity a year due to availability of contractors and at higher energy prices this becomes binding. In turn, more abundant crops have no impact because expansion is proceeding at maximum capacity and cannot expand further. Appendix 1 contains the detailed output from FASOM-GHG.

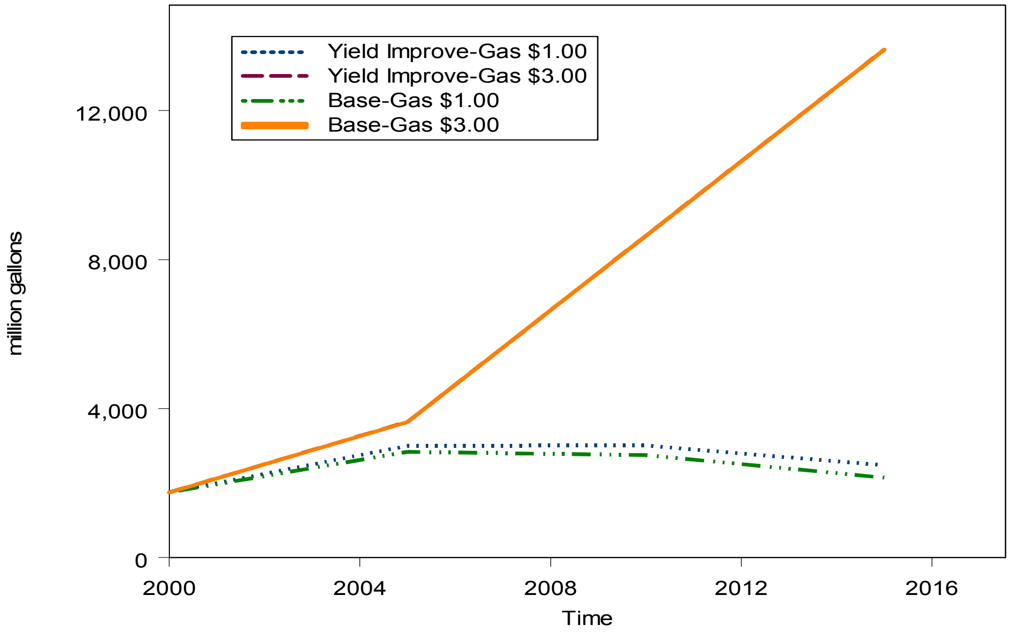


Figure 8.15. Market penetration of ethanol with yield improvement

The impact of crop yield improvements on the biodiesel industry is shown in Figure 8.16. Crop yield improvement expands the biodiesel production for all gasoline prices. The higher the gasoline price, the greater the impact of crop yields. Appendix 1 contains the detailed output from FASOM-GHG.

Figure 8.16. Market penetration of biodiesel with yield improvement

The increase in crop yield has an interesting impact on U.S. producer and consumer welfare. Crop yield improvements increase U.S. producers' welfare for all time periods and gasoline prices. However, U.S. consumer welfare is lower in 2000 for all gasoline prices, but becomes higher for all gasoline prices for year 2005 and higher. The reason is the higher crop yields increase U.S. agricultural exports, causing less commodities to be provided to U.S. consumers in year 2000 than the base scenario.

8.4. Processing Technological Improvement

This scenario allows the cost of producing biofuels from feedstocks to decrease over time. Gains on the chemical yields are not likely, because the base scenario already allows biorefineries to achieve up to 90% of theoretical chemical yield in 20 years. Consequently, two rates for production cost decreases were tested. The first is a uniform 0.5% decrease in production costs while the second is a 1% decrease. No graphs are given, because decreasing production costs had minimal impact on the markets again being influenced by the constraint on ethanol industry expansion. Refer to Appendix 1 for detailed FASOM-GHG output.

8.5. Federal Subsidies

Some question whether the ethanol and biodiesel industries could produce any biofuels without government subsidies. This section helps to answer this question by removing the U.S. federal government's subsidies on ethanol and biodiesel. The impact of no federal government subsidies on the ethanol industry is shown in Figure 8.17 under a CO2 equivalent price of zero. When gasoline price is $1.00 per gallon, the ethanol industry produces 296 million gallons with all ethanol originating from the corn wet mill. When gasoline price is $1.50 or higher, the ethanol production paths are identical to the base scenario. Ethanol aggregate production is bounded at the constraint. The main difference is the ethanol industry produces ethanol from bagasse, corn stover, and wheat residues as early as 2000.

The impact of no U.S. government subsidies on the biodiesel industry is shown as Figure 8.18. The CO2 equivalent price is zero. When the gasoline price is $1.00 per gallon, biorefineries do not produce biodiesel. Furthermore, biorefineries do not produce soy biodiesel when the gasoline price is $2.00 or lower. When the gasoline price is $2.00 per gallon, biodiesel production reaches a paltry 124 million gallons in 2015. If the gasoline price is $3.00, the biodiesel industry produces 892 million gallons in 2015, with the majority being soy biodiesel. Federal government subsidies have a large expansionary impact on the biodiesel industry.

The removal of federal government subsidies causes predictable changes in U.S. welfare. U.S agricultural producer surplus is lower and U.S. consumer surplus is higher, because the absence of subsidies causes lower biodiesel and ethanol prices. Biorefineries produce less biofuel, lowering their demand for feedstocks and causing feedstock prices to be lower.

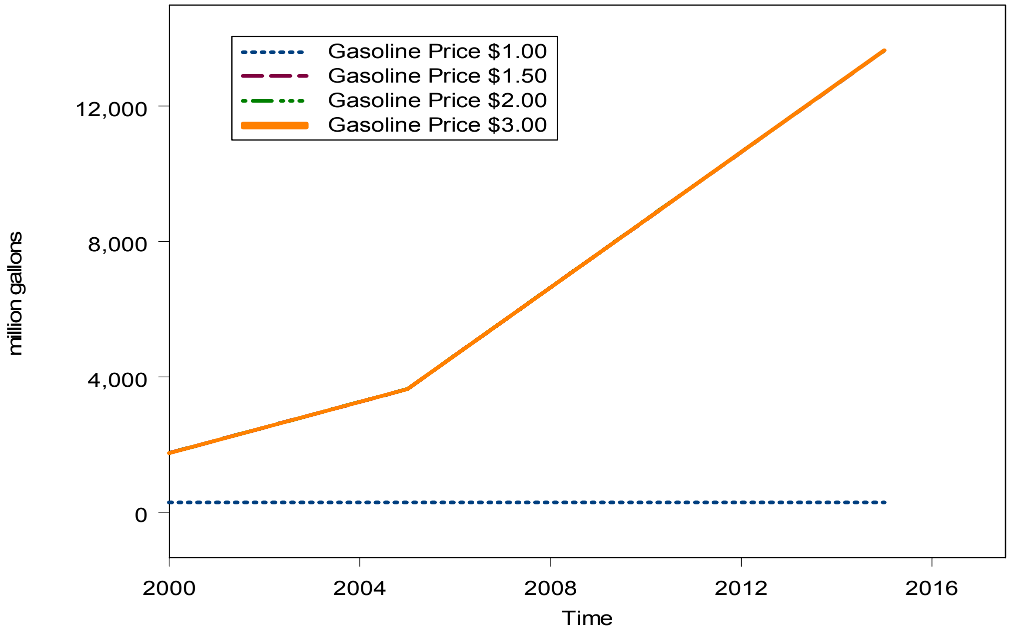


Figure 8.17. Market penetration of ethanol with no subsidies

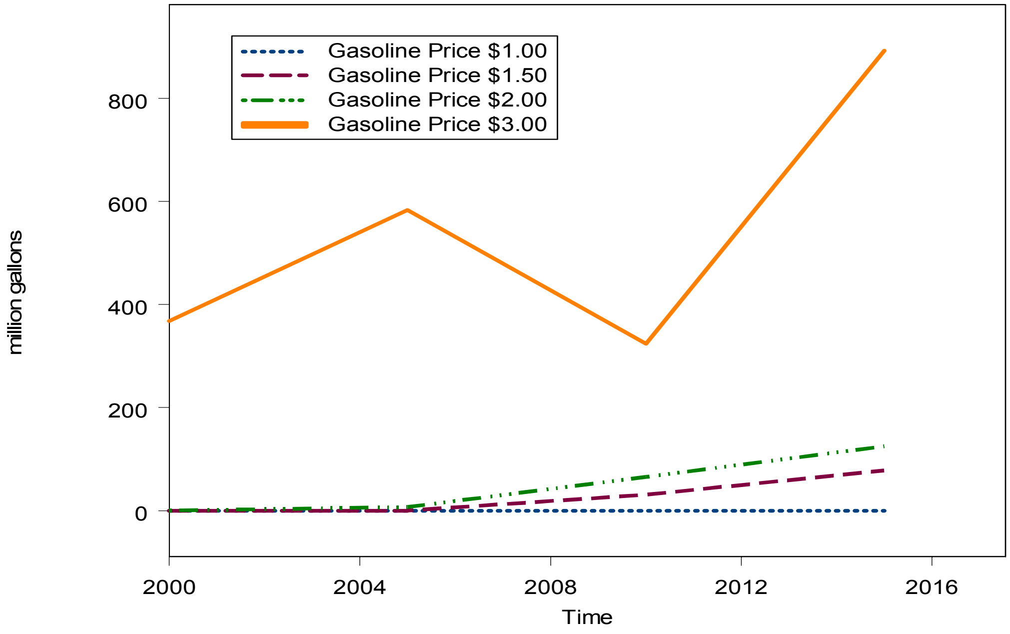


Figure 8.18. Market penetration of biodiesel with no subsidies

9. SUMMARY AND CONCLUSIONS

This dissertation examines the influence that economic and technological factors have on the penetration of biodiesel and ethanol into the transportation fuels market.

Biodiesel and ethanol have six benefits for society. First, biofuels are renewable. If society needs more biofuels, then producers expand their production of energy crops. Second, a large biofuel industry increases the demand for agricultural commodities, boosting agricultural prices and income. Third, biorefineries produce biofuels domestically in the U.S., improving national energy security. Fourth, biofuels are a potential backstop technology and may constrain the growth in petroleum prices. Fifth, biofuels recycle carbon from the atmosphere and have cleaner tail pipe emissions. Finally, biofuels are easily blended with fossil fuels without costly engine upgrades or replacements.

Biodiesel and ethanol have several disadvantages that could prevent market penetration. First, both biodiesel and ethanol contain less energy than their respective fuels. Second, both biodiesel and ethanol are difficult to store and transport. For instance, moisture causes ethanol to separate from gasoline, while biodiesel can oxidize and degrade over time. Finally, both biofuels have their own unique problem. Ethanol could potentially contaminate soil around gas service stations while consumers could not use biodiesel in the northern U.S. during the winter.

All biodiesel and ethanol industries have opportunity costs and byproducts. The biodiesel industry diverts vegetable oil from human consumption and seed grains for animal feed. However, the biodiesel industry creates biodiesel, high-protein animal feeds, and glycerol. The traditional ethanol industry diverts starch and sugar feedstocks from human food and animal feeds, but creates ethanol, vegetable oil, and a variety of high protein animal feeds. The byproducts depend on which process and feedstocks the ethanol industry uses. Finally, the lignocellulostic ethanol industry uses crop residues as a feedstock, but this industry is limited in the amount of crop residues that can be removed. Crop residues prevent soil erosion and provide nutrients to the soil. However, the lignocellulostic ethanol produces lignin as a byproduct that could be burned for heat and electricity.

Several factors encourage the market penetration of biofuels. This dissertation focuses on four aspects. The first involves the influence of fossil fuel prices, because biofuels are substitutes and have to compete in price. The second involves biofuel manufacturing technology principally the feedstock-to-biofuel conversion rates, and the biofuel manufacturing costs. The third involves prices for greenhouse gas offsets. The fourth involves the agricultural commodity markets for feedstocks, and biofuel byproducts. This dissertation uses the Forest and Agricultural Sector Optimization Model-GHG (FASOM-GHG) to quantitatively examine these issues calculating equilibrium prices and quantities, given market interactions, fossil fuel prices, carbon dioxide equivalent prices, government biofuel subsidies, technological improvement, and crop yield gains.

Specifically FASOM-GHG was used to analyze four scenarios with the first being the base scenario. The base scenario allows the gasoline price to vary between $1 and $3 per gallon, and the carbon equivalent price to vary between $0 and $100 per carbon equivalent ton. When the gasoline price is $1.00 per gallon, ethanol production peaks at 2.8 billion gallons in 2005, and then declines. For gasoline prices between $1.50 and $3.00 per gallon, the ethanol production time paths are identical, producing 13.6 billion gallons in 2015, because ethanol production binds at the aggregate ethanol production constraint. The aggregate ethanol production constraint occurs from the limited number of contractors that construct biorefineries and the production constraint grows 1.0 billion gallons per year in new capacity after 2005. Moreover, corn stover ethanol rapidly expands to 9.6 billion gallons per year in 2015.

Biodiesel production is more sensitive to gasoline prices. When the gasoline price is $1.00 per gallon, the biodiesel industry attains 116 million gallons in 2015, using tallow as a feedstock. When the gasoline price is $3.00 per gallon, the biodiesel industry produces 1.8 billion gallons in 2015, primarily from soybean oil.

The primary feedstocks in ethanol and biodiesel are corn and soybeans. Producers cultivate more corn and soybeans, expanding their production of these crops as gasoline price increases. However, the price and export time paths show a different pattern. For all gasoline prices, corn prices fall over time, corn exports increase, and the corn wet mill gradually expands ethanol production. On the other hand, soybean prices remain relatively flat, soybean exports decrease, and more soybeans are diverted to the biodiesel industry.

FASOM-GHG was used to examine the impact of CO2 equivalent prices on the biofuels markets. The gasoline price is fixed at $2.00 per gallon and all ethanol production time paths are identical, because the aggregate ethanol production constraint. Consequently, a CO2 equivalent price does not have an impact on aggregate ethanol production. However, CO2 prices impact which feedstocks are used. As carbon dioxide equivalent price increases, producers move production away from the corn wet mill, and use more crop residues, because corn wet mill have higher life-cycle GHG emissions. Moreover, producers start producing ethanol from corn stover and wheat residues as early as 2000. Carbon dioxide equivalent price affects biodiesel production. A higher carbon equivalent price encourages society to use more biodiesel, because each gallon consumed decreases GHG emissions. Most of the biodiesel expansion results from soy biodiesel.

The second scenario examined involved crop yield improvement. Crop yield improvement expands ethanol production, when gasoline price is $1.00 per gallon. However, crop yield improvement has no impact on the ethanol industry for higher gasoline prices, because of the aggregate ethanol production constraint. On the other hand, crop yield improvement expands the biodiesel production for all gasoline prices. Further, the higher the gasoline price, the greater the impact of crop yields.

The third scenario is technological improvement, which allows production cost to decrease over time. Two production cost rates were tested, which were 0.5% and 1% annual decreases. Decreasing production costs had minimal impact on the markets.

The fourth scenario eliminates the U.S. government biofuel subsidies. When gasoline price is $1.00 per gallon, the ethanol industry produces 296 million gallons with all ethanol originating from the corn wet mill. For higher gasoline prices, the ethanol production paths are similar to the base scenario. The main difference is the feedstocks. The ethanol industry produces ethanol from bagasse, corn stover, and wheat residues as early as 2000. When the gasoline price is $1.00 per gallon, biorefineries do not produce biodiesel. When the gasoline price is $2.00 per gallon, biodiesel production reaches a paltry 124 million gallons in 2015. If the gasoline price is $3.00, the biodiesel industry produces 892 million gallons in 2015, mainly from soy biodiesel. Hence, federal government subsidies have a large expansionary impact on the biodiesel industry and only on the ethanol industry for low gasoline prices.

FASOM-GHG helps address which factors expand biofuel market penetration. Gasoline price, carbon dioxide equivalent price, crop yield improvements, and federal government subsidies correlate to the size of the biodiesel industry. Increasing gasoline price expands the ethanol industry when gasoline prices are low, but has no impact for high gasoline prices because of the aggregate ethanol production constraint. Crop yield improvement and government subsidies also expand the ethanol industry but are capped by the capacity expansion assumption.

FASOM-GHG helps address which factors influence U.S. welfare. High carbon dioxide equivalent and gasoline prices increase U.S. producer welfare and decrease U.S. consumer welfare. Crop yield improvement increases producers’ and consumers’ welfare, except in the year 2000. Crop yield improvements cause higher U.S. exports, temporarily lowering U.S. consumer welfare in 2000. Finally, federal government subsidies benefit U.S. producers and decrease U.S. consumer welfare. The primary mechanism for welfare changes is market prices. Gasoline and carbon dioxide equivalent prices, and government subsidies increase market price, benefiting the U.S. producers and penalizing the U.S. consumers

What is the market penetration of biodiesel and ethanol? If the U.S. refineries produce the same quantity of gasoline and diesel fuel in 2004, which they may because of the petroleum refinery production constraint, U.S. refineries produce 126.6 billion gallons of gasoline and 58.6 billion gallons of diesel fuel (Energy Information Administration 2005a, Table 5.8). If the gasoline price remains at $2.00 per gallon and the assumptions remain true for the base scenario, then aggregate ethanol production rises to approximately 11% market penetration in 2015, while biodiesel production rises approximately to 2%. Consequently, biodiesel and ethanol remain a small part of the transportation fuels market.

FASOM-GHG contains many assumptions that limit biofuel market penetration forecasts. Correcting these limitations could improve forecasts and provide future research endeavors.

- Expand FASOM-GHG to include other feedstocks. For example, some feedstocks such as Canola have a small presence in U.S. agriculture, but a rapidly growing biofuel industry could rapidly expand the production of these feedstocks.
- Modify FASOM-GHG to solve for the optimal biorefinery's size, which includes the tradeoff between biorefinery size and hauling costs.
- Allow producers to substitute methanol for ethanol biodiesel production, and allow methanol price to be endogenous.
- Provide more accurate life-cycle emissions for biodiesel and ethanol production.
- Append an import/export for biodiesel and ethanol. As the biofuel industry increases in size, the international markets will play a stronger role on biofuel prices.
- Expand this study to include regional distribution impacts.
- Either append a petroleum market system or allow dynamic behavior for gasoline prices.
- Examine the realism and expansion of the aggregate ethanol facility construction constraint.

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APPENDIX 1

FASOM-GHG Results-Base Scenario

	2000	2005	2010	2015
Lignocellulostic Ethanol				
Bagasse Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	1.0	427.0	385.0
Gas $2.00, CO2 $0	0.0	1.0	417.0	382.0
Gas $3.00, CO2 $0	0.0	1.0	398.0	377.0
Corn Stover Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	0.0	3,729.0	9,617.0
Gas $2.00, CO2 $0	0.0	0.0	3,741.0	9,618.0
Gas $3.00, CO2 $0	0.0	0.0	4,449.0	9,623.0
Wheat Residue Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	0.0	843.0	0.0
Gas $2.00, CO2 $0	0.0	0.0	842.0	0.0
Gas $3.00, CO2 $0	0.0	0.0	155.0	0.0
Sorghum Residue Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	0.0	1.0	0.0
Gas $2.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $3.00, CO2 $0	0.0	0.0	0.0	0.0
Traditional Ethanol				
Corn Wet Mill Ethanol (million gallons)				
Gas $1.00, CO2 $0	1,067.0	1,803.0	1,917.0	1,917.0
Gas $1.50, CO2 $0	1,069.0	2,148.0	2,208.0	2,608.0
Gas $2.00, CO2 $0	1,066.0	2,184.0	2,261.0	2,737.0
Gas $3.00, CO2 $0	1,232.0	2,370.0	2,397.0	3,012.0

Continued

	2000	2005	2010	2015
Sorghum (Ethanol million gallons)				
Gas $1.00, CO2 $0	684.0	1,027.0	826.0	226.0
Gas $1.50, CO2 $0	682.0	1,263.0	1,035.0	521.0
Gas $2.00, CO2 $0	685.0	1,261.0	1,026.0	519.0
Gas $3.00, CO2 $0	518.0	1,252.0	1,011.0	509.0
Oats Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	6.0	3.0	0.0
Gas $1.50, CO2 $0	0.0	10.0	5.0	0.0
Gas $2.00, CO2 $0	0.0	10.0	5.0	0.0
Gas $3.00, CO2 $0	0.0	8.0	2.0	0.0
Wheat Ethanol (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	221.0	393.0	513.0
Gas $2.00, CO2 $0	0.0	187.0	350.0	386.0
Gas $3.00, CO2 $0	0.0	12.0	232.0	121.0
Total Ethanol (million gallons)				
Gas $1.00, CO2 $0	1,751.0	2,836.0	2,746.0	2,143.0
Gas $1.50, CO2 $0	1,751.0	3,643.0	8,641.0	13,644.0
Gas $2.00, CO2 $0	1,751.0	3,643.0	8,642.0	13,642.0
Gas $3.00, CO2 $0	1,750.0	3,643.0	8,644.0	13,642.0
Biodiesel				
Soy Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	111.9	219.1	0.0	384.8
Gas $2.00, CO2 $0	498.8	636.0	329.6	797.8
Gas $3.00, CO2 $0	1,130.1	1,236.7	1,148.3	1,394.3
Corn Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	0.0	0.0	0.0
Gas $2.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $3.00, CO2 $0	0.0	0.0	0.0	30.5

Continued

	2000	2005	2010	2015
Edible Tallow Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	2.0	21.3	37.1
Gas $1.50, CO2 $0	0.0	8.4	27.5	43.0
Gas $2.00, CO2 $0	0.0	13.1	30.8	45.7
Gas $3.00, CO2 $0	4.6	19.8	36.7	51.2
Nonedible Tallow Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	7.6	46.9	79.0
Gas $1.50, CO2 $0	0.0	20.6	59.6	91.1
Gas $2.00, CO2 $0	0.0	30.1	66.1	96.6
Gas $3.00, CO2 $0	12.9	43.8	78.2	107.8
Yellow Grease Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	0.0	0.0	0.0
Gas $1.50, CO2 $0	0.0	16.3	0.0	76.8
Gas $2.00, CO2 $0	30.7	75.8	44.9	137.8
Gas $3.00, CO2 $0	115.0	156.3	158.5	219.7
Total Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0.0	9.6	68.2	116.2
Gas $1.50, CO2 $0	111.9	264.4	87.1	595.8
Gas $2.00, CO2 $0	529.5	755.0	471.4	1,077.9
Gas $3.00, CO2 $0	1,262.7	1,456.5	1,421.8	1,803.4
Carbon Dioxide Equivalent Prices				
Lignocellulostic Ethanol				
Bagasse Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	1.0	417.0	382.0
CO2 $10, Gas $2.00	0.0	0.0	213.0	35.0
CO2 $50, Gas $2.00	0.0	0.0	297.0	242.0
CO2 $100, Gas $2,00	0.0	0.0	390.0	245.0
Corn Stover Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	0.0	3,741.0	9,618.0
CO2 $10, Gas $2.00	0.0	395.0	3,909.0	8,116.0
CO2 $50, Gas $2.00	469.0	1,909.0	6,262.0	12,221.0
CO2 $100, Gas $2,00	982.0	2,401.0	6,039.0	12,960.0

Continued

	2000	2005	2010	2015
Wheat Residue Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	0.0	842.0	0.0
CO2 $10, Gas $2.00	0.0	0.0	878.0	2,997.0
CO2 $50, Gas $2.00	434.0	500.0	174.0	0.0
CO2 $100, Gas $2,00	437.0	523.0	933.0	0.0
Sorghum Residue Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $10, Gas $2.00	0.0	0.0	1.0	0.0
CO2 $50, Gas $2.00	1.0	1.0	1.0	1.0
CO2 $100, Gas $2,00	1.0	1.0	261.0	1.0
Barley Residue Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $10, Gas $2.00	0.0	0.0	0.0	59.0
CO2 $50, Gas $2.00	0.0	0.0	1.0	1.0
CO2 $100, Gas $2,00	0.0	0.0	3.0	1.0
Rice Residue Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $10, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $50, Gas $2.00	0.0	0.0	0.0	189.0
CO2 $100, Gas $2,00	0.0	0.0	0.0	140.0
Traditional Ethanol				
Corn Wet Mill Ethanol (million gallons)				
CO2 $0, Gas $2.00	1,066.0	2,184.0	2,261.0	2,737.0
CO2 $10, Gas $2.00	1,103.0	2,061.0	2,432.0	2,196.0
CO2 $50, Gas $2.00	846.0	1,212.0	1,501.0	988.0
CO2 $100, Gas $2,00	331.0	718.0	1,017.0	296.0
Sorghum Ethanol (million gallons)				
CO2 $0, Gas $2.00	685.0	1,261.0	1,026.0	519.0
CO2 $10, Gas $2.00	648.0	1,179.0	1,023.0	238.0
CO2 $50, Gas $2.00	0.0	21.0	407.0	0.0
CO2 $100, Gas $2,00	0.0	0.0	0.0	0.0

Continued

	2000	2005	2010	2015
Oats Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	10.0	5.0	0.0
CO2 $10, Gas $2.00	0.0	9.0	5.0	0.0
CO2 $50, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $100, Gas $2,00	0.0	0.0	0.0	0.0
Wheat Ethanol (million gallons)				
CO2 $0, Gas $2.00	0.0	187.0	350.0	386.0
CO2 $10, Gas $2.00	0.0	0.0	182.0	0.0
CO2 $50, Gas $2.00	0.0	0.0	0.0	0.0
CO2 $100, Gas $2,00	0.0	0.0	0.0	0.0
Total Ethanol (million gallons)				
CO2 $0, Gas $2.00	1,751.0	3,643.0	8,642.0	13,642.0
CO2 $10, Gas $2.00	1,751.0	3,644.0	8,643.0	13,641.0
CO2 $50, Gas $2.00	1,750.0	3,643.0	8,643.0	13,642.0
CO2 $100, Gas $2,00	1,751.0	3,643.0	8,643.0	13,643.0
Biodiesel	2,000.0	2,005.0	2,010.0	2,015.0
Soy Biodiesel (million gallons)				
CO2 $0, Gas $2.00	498.8	636.0	329.6	797.8
CO2 $10, Gas $2.00	805.5	883.2	540.5	715.9
CO2 $50, Gas $2.00	1,568.9	1,698.3	1,406.5	1,530.8
CO2 $100, Gas $2,00	2,472.0	2,560.8	2,266.6	2,356.6
Edible Tallow Biodiesel (million gallons)				
CO2 $0, Gas $2.00	0.0	13.1	30.8	45.7
CO2 $10, Gas $2.00	0.0	13.5	30.0	39.5
CO2 $50, Gas $2.00	0.0	5.5	28.0	40.4
CO2 $100, Gas $2,00	0.0	0.0	17.1	32.9
Nonedible Tallow Biodiesel (million gallons)				
CO2 $0, Gas $2.00	0.0	30.1	66.1	96.6
CO2 $10, Gas $2.00	1.8	30.9	64.6	83.9
CO2 $50, Gas $2.00	0.0	14.7	60.6	85.8
CO2 $100, Gas $2,00	0.0	0.0	38.5	70.5

Continued

	2000	2005	2010	2015
Yellow Grease Biodiesel (million gallons)				
CO2 $0, Gas $2.00	30.7	75.8	44.9	137.8
CO2 $10, Gas $2.00	67.8	102.4	69.5	109.6
CO2 $50, Gas $2.00	167.5	204.2	177.9	208.5
CO2 $100, Gas $2,00	282.7	312.9	285.2	309.4
Total Biodiesel (million gallons)				
CO2 $0, Gas $2.00	529.5	755.0	471.4	1,077.9
CO2 $10, Gas $2.00	875.2	1,030.1	704.6	948.8
CO2 $50, Gas $2.00	1,736.4	1,922.6	1,673.0	1,865.5
CO2 $100, Gas $2,00	2,754.7	2,873.6	2,607.4	2,769.4
Market Prices and Quantities				
Corn ($ per bushel)				
Gas $1.00, CO2 $0	2.1	2.1	2.0	2.0
Gas $1.50, CO2 $0	2.1	2.1	2.1	2.1
Gas $2.00, CO2 $0	2.1	2.1	2.1	2.0
Gas $3.00, CO2 $0	2.1	2.2	2.1	2.1
Soybeans ($ per bushel)				
Gas $1.00, CO2 $0	5.1	4.8	5.4	4.5
Gas $1.50, CO2 $0	5.2	5.0	5.4	5.0
Gas $2.00, CO2 $0	5.8	5.8	5.9	5.8
Gas $3.00, CO2 $0	7.0	6.8	7.2	7.0
DDGS ($ per 1,000 lbs)				
Gas $1.00, CO2 $0	41.3	41.2	43.0	40.9
Gas $1.50, CO2 $0	41.2	40.1	41.5	38.8
Gas $2.00, CO2 $0	41.1	39.7	40.6	38.5
Gas $3.00, CO2 $0	38.0	36.5	38.8	37.4
SoybeanMeal ($ per ton)				
Gas $1.00, CO2 $0	173.3	172.8	182.8	173.0
Gas $1.50, CO2 $0	172.8	172.6	182.8	171.3
Gas $2.00, CO2 $0	172.1	171.9	178.6	171.3
Gas $3.00, CO2 $0	172.1	170.8	173.2	171.3

Continued

	2000	2005	2010	2015
Corn (million bushels)				
Gas $1.00, CO2 $0	9,571.7	10,531.4	11,511.0	12,265.4
Gas $1.50, CO2 $0	9,571.7	10,565.9	11,559.7	12,446.0
Gas $2.00, CO2 $0	9,574.1	10,568.1	11,554.9	12,467.0
Gas $3.00, CO2 $0	9,567.9	10,573.1	11,549.1	12,491.4
Feedlot Beef Slaughter ($ per cwt)				
Gas $1.00, CO2 $0	72.6	73.7	76.1	86.6
Gas $1.50, CO2 $0	72.6	73.8	76.6	87.4
Gas $2.00, CO2 $0	72.6	74.3	77.2	88.2
Gas $3.00, CO2 $0	73.3	75.0	78.8	89.7
Soybeans (million bushels)				
Gas $1.00, CO2 $0	3,108.9	3,225.9	3,345.1	3,377.9
Gas $1.50, CO2 $0	3,108.7	3,225.8	3,346.7	3,424.1
Gas $2.00, CO2 $0	3,117.6	3,237.4	3,355.8	3,443.6
Gas $3.00, CO2 $0	3,143.3	3,268.3	3,388.7	3,467.1
DDGS (million lbs)				
Gas $1.00, CO2 $0	5.4	8.2	6.6	1.8
Gas $1.50, CO2 $0	5.4	12.1	11.9	8.8
Gas $2.00, CO2 $0	5.4	11.8	11.4	7.7
Gas $3.00, CO2 $0	4.1	10.1	10.1	5.1
SoybeanMeal (million tons)				
Gas $1.00, CO2 $0	44.8	47.4	46.8	49.7
Gas $1.50, CO2 $0	45.4	50.4	47.8	55.5
Gas $2.00, CO2 $0	49.0	54.5	51.1	59.5
Gas $3.00, CO2 $0	55.3	60.3	60.5	65.1
Feedlot Beef Slaughter (million cwt)				
Gas $1.00, CO2 $0	357.5	376.7	417.8	449.7
Gas $1.50, CO2 $0	357.0	379.1	417.8	452.5
Gas $2.00, CO2 $0	356.8	382.7	418.5	451.5
Gas $3.00, CO2 $0	359.5	384.9	419.1	452.3
Agriculture Exports				
Corn (million bushels)				
Gas $1.00, CO2 $0	2,112.0	2,307.0	2,578.0	2,882.0
Gas $1.50, CO2 $0	2,106.0	2,173.0	2,399.0	2,641.0
Gas $2.00, CO2 $0	2,099.0	2,146.0	2,373.0	2,670.0
Gas $3.00, CO2 $0	2,023.0	2,090.0	2,347.0	2,638.0

Continued

	2000	2005	2010	2015
Soybeans (million bushels)				
Gas $1.00, CO2 $0	1,081.0	1,108.0	943.0	1,063.0
Gas $1.50, CO2 $0	1,059.0	1,037.0	961.0	961.0
Gas $2.00, CO2 $0	925.0	886.0	846.0	817.0
Gas $3.00, CO2 $0	688.0	671.0	503.0	601.0
Welfare				
U.S. Producers ($ million)				
Gas $1.00, CO2 $0	32,592	35,154	42,540	55,260
Gas $1.50, CO2 $0	31,472	35,620	42,061	55,926
Gas $2.00, CO2 $0	31,836	36,983	42,979	56,531
Gas $2.00, CO2 $10	34,533	38,231	45,274	66,701
Gas $2.00, CO2 $50	64,716	51,247	59,123	97,888
Gas $2.00, CO2 $100	103,895	72,041	79,975	150,886
Gas $3.00, CO2 $0	33,686.9	38,600.0	45,821.7	58,222.5
U.S. Consumers ($ million)				
Gas $1.00, CO2 $0	1,548,997	1,583,130	1,632,390	1,644,579
Gas $1.50, CO2 $0	1,548,830	1,582,601	1,632,410	1,643,918
Gas $2.00, CO2 $0	1,547,904	1,580,704	1,630,545	1,642,821
Gas $2.00, CO2 $10	1,546,762	1,579,596	1,628,408	1,634,976
Gas $2.00, CO2 $50	1,535,590	1,568,879	1,616,968	1,621,897
Gas $2.00, CO2 $100	1,521,724	1,554,043	1,603,454	1,603,684
Gas $3.00, CO2 $0	1,544,615	1,578,100	1,626,662	1,639,965

FASOM-GHG Results-Crop Yield Improvements

	2000	2005	2010	2015
Total Ethanol (million gallons)				
Gas $1.00, CO2 $0	1,751	2,999	3,005	2,476
Gas $1.50, CO2 $0	1,751	3,644	8,643	13,643
Gas $2.00, CO2 $0	1,751	3,643	8,641	13,644
Gas $3.00, CO2 $0	1,750	3,644	8,642	13,643
Total Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	14	75	271
Gas $1.50, CO2 $0	112	407	259	1,029
Gas $2.00, CO2 $0	528	914	763	1,450
Gas $3.00, CO2 $0	1,263	1,606	1,535	2,283
U.S. Welfare				
U.S. Producers ($ million)				
Gas $1.00, CO2 $0	32,594	34,020	40,375	56,198
Gas $1.50, CO2 $0	31,563	34,761	40,009	57,180
Gas $2.00, CO2 $0	31,874	35,797	41,258	57,760
Gas $3.00, CO2 $0	33,703	37,408	44,934	59,360
U.S. Consumers ($ million)				
Gas $1.00, CO2 $0	1,548,974	1,585,102	1,636,467	1,647,214
Gas $1.50, CO2 $0	1,548,719	1,584,501	1,636,350	1,646,536
Gas $2.00, CO2 $0	1,547,842	1,582,902	1,634,474	1,645,344
Gas $3.00, CO2 $0	1,544,612	1,579,960	1,630,575	1,642,457

FASOM-GHG Results-Technological Improvements

	2000	2005	2010	2015
0.5% Production Cost Decrease				
Total Ethanol (million gallons)				
Gas $1.00	1,751	2,835	2,746	2,143
Gas $1.50	1,751	3,643	8,641	13,644
Gas $2.00	1,751	3,643	8,642	13,641
Gas $3.00	1,750	3,642	8,644	13,642
Total Biodiesel (million gallons)				
Gas $1.00	0	10	68	116
Gas $1.50	112	264	87	596
Gas $2.00	529	755	472	1,078
Gas $3.00	1,263	1,456	1,422	1,803
1.0% Production Cost Decrease				
Total Ethanol (million gallons)				
Gas $1.00	1,751	2,835	2,746	2,143
Gas $1.50	1,751	3,643	8,641	13,644
Gas $2.00	1,751	3,643	8,642	13,641
Gas $3.00	1,750	3,642	8,644	13,642
Total Biodiesel (million gallons)				
Gas $1.00	0	10	68	116
Gas $1.50	112	264	87	596
Gas $2.00	529	755	472	1,078
Gas $3.00	1,263	1,456	1,422	1,803

FASOM-GHG Results-No U.S. Government Subsidies

	2000	2005	2010	2015
Lignocellulostic Ethanol				
Bagasse Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	499	471	428	388
Gas $2.00, CO2 $0	490	466	430	386
Gas $3.00, CO2 $0	479	447	405	382
Corn Stover Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	18	1,785	6,078	12,053
Gas $2.00, CO2 $0	182	1,784	6,092	11,361
Gas $3.00, CO2 $0	247	1,910	6,248	12,288
Wheat Residue Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	181	844	0
Gas $2.00, CO2 $0	0	240	844	203
Gas $3.00, CO2 $0	0	325	843	0
Sorghum Residue Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	1	0
Gas $2.00, CO2 $0	0	0	1	0
Gas $3.00, CO2 $0	0	0	1	0
Rice Residue Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	0	228
Gas $2.00, CO2 $0	0	0	0	718
Gas $3.00, CO2 $0	0	0	0	0

Continued

	2000	2005	2010	2015
Traditional Ethanol				
Corn Wet Mill Ethanol (million gallons)				
Gas $1.00, CO2 $0	296	296	296	296
Gas $1.50, CO2 $0	831	845	988	974
Gas $2.00, CO2 $0	831	845	988	974
Gas $3.00, CO2 $0	831	832	988	974
Sorghum Ethanol (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	401	362	304	0
Gas $2.00, CO2 $0	246	308	290	0
Gas $3.00, CO2 $0	193	130	158	0
Total Ethanol (million gallons)				
Gas $1.00, CO2 $0	296	296	296	296
Gas $1.50, CO2 $0	1,749	3,644	8,643	13,643
Gas $2.00, CO2 $0	1,749	3,643	8,645	13,642
Gas $3.00, CO2 $0	1,750	3,644	8,643	13,644
Biodiesel				
Soy Oil Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	0	0
Gas $2.00, CO2 $0	0	0	0	0
Gas $3.00, CO2 $0	344	485	195	638
Edible Tallow Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	9	24
Gas $2.00, CO2 $0	0	1	20	35
Gas $3.00, CO2 $0	0	13	33	46
NonEdible Tallow Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	22	53
Gas $2.00, CO2 $0	0	6	45	74
Gas $3.00, CO2 $0	2	31	70	98

Continued

	2000	2005	2010	2015
Yellow Grease Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	0	0
Gas $2.00, CO2 $0	0	0	0	16
Gas $3.00, CO2 $0	21	55	27	111
Total Biodiesel (million gallons)				
Gas $1.00, CO2 $0	0	0	0	0
Gas $1.50, CO2 $0	0	0	31	78
Gas $2.00, CO2 $0	0	7	65	125
Gas $3.00, CO2 $0	368	584	324	893
U.S. Welfare				
U.S. Producers ($ million)				
Gas $1.00, CO2 $0	31,913	33,233	40,433	54,745
Gas $1.50, CO2 $0	30,828	32,129	39,142	52,679
Gas $2.00, CO2 $0	29,775	30,965	37,610	51,657
Gas $3.00, CO2 $0	28,039	31,507	37,150	50,881
U.S. Consumers ($ million)				
Gas $1.00, CO2 $0	1,549,173	1,583,997	1,633,218	1,644,605
Gas $1.50, CO2 $0	1,549,033	1,583,778	1,633,188	1,644,900
Gas $2.00, CO2 $0	1,549,040	1,583,284	1,633,054	1,644,372
Gas $3.00, CO2 $0	1,548,063	1,581,273	1,630,852	1,643,261

APPENDIX 2

All conversions are from National Agricultural Statistics Service (2005), and Davis and Diegel (2006).

1 barrel oil = 42 U.S. gallons

1 British Thermal Unit = 1055 Joules

1 short ton = 0.9072 metric ton (tonne)

1 bushel wheat = 60 pounds

1 bushel corn = 56 pounds

1 bushel oats = 32 pounds

1 bushel barley = 48 pounds

1 bushel grain sorghum = 56 pounds

1 bushel soybeans = 60 pounds

1 bushel flaxseeds = 65 pounds

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