THREE ESSAYS ON BIOENERGY PRODUCTION

IN THE UNITED STATES

A Dissertation

by

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ABSTRACT

This dissertation examines future prospects of bioenergy production in the United States. The analysis examines three issues on liquid fuel and cellulosic ethanol. First, the amount that costs need to decrease in order to make cellulosic ethanol competitive, considering both production and market penetration costs. Second, the potential effect of mandate relaxations and carbon market related payments on liquid fuel production potential. Third, the effects of ignoring or considering asset fixity of refinery construction on liquid fuel production and market penetration.

These analyses are framed using a theoretical graphical analysis then are empirically carried out using a version of the U.S. agricultural sector mathematical programming model FASOMGHG which is augmented and expanded to accommodate the issues examined. The main findings are: 1) processing costs of cellulosic ethanol need to be reduced by at least 70% to make cellulosic ethanol production fully cost competitive; 2) removal of market penetration barriers also are also a big contributor to the market presence of bioethanol; 3) carbon pricing and other market mechanisms provide incentives for more ethanol production; 4) greenhouse gas payments entail additional revenues flowing to the bioethanol industry and as a result, increase volumes of total ethanol produced and 5) asset fixity provides a major barrier to ethanol production increases.

Furthermore under asset fixity: 1) cellulosic ethanol production is reduced when mandates hold; 2) cellulosic ethanol production is virtually eliminated when mandates are not in place; 3) asset fixity has a more significant impact on the amount of ethanol produced when no market penetration barriers are in place; 4) asset fixity influences the generation of biodiesel by changing its feedstock structure.

DEDICATION

To my Parents: Grazyna and Adam Wlodarz

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Writing a doctoral dissertation is a challenge. There may have been insurmountable hurdles on my way to the Ph.D. if I had not received support from my doctoral committee. Therefore, I would like to take this chance to express my gratitude to all of them.

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NOMENCLATURE

AEO	Annual Energy Outlook published by the U.S. Department of Energy
AF	Asset Fixity holds
BGY	Billion Gallons per Year
CB	Corn Belt
CO2e	Carbon dioxide equivalent
CornOilNFG	Non-food grade corn oil
EIA	Energy Information Administration, the U.S. Department of Energy
EISA	Energy Independence and Security Act
FASOMGHG	Forest and Agricultural Sector Optimization Model with Greenhouse Gases
GHG	Greenhouse Gases
GP	Great Plains
LS	Lake States
M	RFS2 biofuel mandates hold
NAF	Asset Fixity does not hold
NE	Northeast
NM	RFS2 biofuel mandates do not hold
NP	No market penetration barriers exist

NPV	Net Present Value
NREL	National Renewable Energy Laboratory
P	Market penetration barriers are in place
PNWE	Pacific Northwest - East side (agriculture only)
PNWW	Pacific Northwest - West side (forestry only)
PSW	Pacific Southwest
RFS2	The U.S. Environmental Protection Agency Renewable Fuel Standard
RM	Rocky Mountains
SC	South Central
SE	Southeast
SSPulp	Sweet Sorghum Pulp
SW	Southwest
USDA ERS	The U.S. Department of Agriculture Economic Research Service

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1. INTRODUCTION

Domestic production of bioenergy using feedstocks from agricultural land can reduce the USA's greenhouse gas emissions and at the same time decrease the country's dependence on imported energy resources. It can also have environmental and commodity price implications. This dissertation will examine the USA's potential for bioenergy production using cellulosic feedstocks coming from crop residues and energy crops. It examines the energy market penetration, agricultural market effects, environmental consequences and potential greenhouse gas (GHG) emission reductions.

Analytically the dissertation will augment and use the Forest and Agriculture Sector Optimization Model with GHG accounting (Lee 2002; Adams et al. 2005; Beach et al. 2010) to simulate economic and environmental consequences of different technological factors related to bioenergy production. This will be done in a three part study.

The first study examines the degree of technological progress necessary to achieve economic profitability for cellulosic ethanol production plus the social welfare costs of mandates. Specifically, the essay will generate information on the welfare cost of satisfying cellulosic ethanol mandates and the consequence of processing cost drops on the costs of meeting the RFS2 mandates. Furthermore, the impact of downward sloping ethanol demand on the volume of ethanol produced is observed.

The second study examines the impact of a GHG offset pricing market and the effect of mandate relaxations on bioethanol production. This is done by modeling GHG pricing as a cap-and-trade form of market payment for the reduction in net greenhouse gas emissions on a carbon dioxide equivalent basis. These payments are designed to provide incentives for use of agricultural and bioenergy activities that reduce net GHG emissions and in part reflect the internalization of the externality from GHG emissions. The work estimates the extent to which they make emission-efficient ethanol production more profitable. Carbon dioxide equivalent (CO2e) prices will be varied in the range from $0 per metric ton CO2e to $100 and FASOMGHG will be run to simulate the impact on the amount and form of ethanol produced in the United States. Mandate relaxation will be applied to some scenarios.

The third study examines the consequences of asset fixity on performance of bioenergy production using the framework of putty clay modeling. In particular, ethanol plants are large, expensive entities and once built become available for use throughout their economic life with a large amount of sunk fixed cost. The effects of this fixity are modeled by incorporating a facility investment module into FASOMGHG to examine the consequences of bioenergy investment incurring cost and locking in capacity to handle a given feedstock mix for the life of the plant in a particular region.

The main objective of this dissertation is to provide information on the United States' potential to enhance national energy security by utilizing agricultural land for bioenergy feedstock production. The final outcome will be quantification of needed technological improvements to increase the total net bioenergy produced by the agricultural sector and the associated economic benefits/costs and environmental impacts. These results could serve as inputs to the policy decision making and appraisal process conducted by the EPA and the USDA.

The reminder of this dissertation is structured as follows:

- Chapter 2 presents the study which aims at quantifying the decrease in processing cost of cellulosic ethanol needed to assure its economic cost competitiveness.
- Chapter 3 presents the impact of carbon pricing, various market structures and biofuel mandate relaxations on the production of conventional and cellulosic bioethanol in the United States.
- Chapter 4 presents the study on the effects of the asset fixity characteristic of refinery construction including how it is included in the FASOMGHG model and the consequent results on the structure of bioenergy production in the United States.
- Chapter 5 presents conclusions, limitations of the studies and directions for future research.

2. COST DECREASE AND CELLULOSIC ETHANOL COMPETITIVENESS

This section presents the results of the study in which the processing cost of second generation or lignocellulosic ethanol is analyzed. The impact of changes in processing cost, the EPA mandates, and fuel substitution barriers on volume of liquid biofuel produced are examined. Furthermore, a framework with a price elastic demand for ethanol is introduced to reflect growing presence of ethanol in the US fuel market.

2.1 Synopsis

Since 2001 ethanol production from corn has increased greatly. Along with this production has come an impact on food availability and prices. As a result, second-generation biofuels produced from lignocellulosic materials have been gaining attention. This chapter reports on an investigation regarding the economic and technological prospects for lignocellulosic based bioethanol production in the United States. To achieve this, we conduct an agricultural sector analysis considering various forecasts for technological progress and removal of penetration barriers. We find that processing costs must be at least 25 % lower than those currently projected by NREL for cellulosic ethanol to be economically competitive at the levels implied by the Renewable Fuel Standard (RFS2) by 2020. Furthermore, we find that with such cost declines the amount of corn ethanol produced would be significantly lower than the current level. We project that fuel substitution infrastructure barriers are a substantial obstacle for market penetration and that a drop-in fuel version would penetrate to a much greater extent.

2.2 Introduction

The production of crop ethanol from sources such as corn imposes strains on food prices and land use for agriculture (Abbott et al. 2011; Tyner 2007). Ethanol from cellulosic agricultural materials has the potential to meet RFS mandates without exerting as much pressure on food prices as total reliance on corn ethanol due to higher yields, lower land competition and utilization of non-edible parts of the crop plants. However, there are uncertainties in the future cost and substitutability of cellulosic ethanol production and market penetration. It is estimated that current ethanol market is able to absorb 14 billion gallons of ethanol per year (Babcock 2013). Greater usage of liquid fuels in the form of ethanol requires more flex-fuel cars, plus altered distribution networks and points of sale that can accommodate liquid fuels with a greater share of ethanol. Infrastructure adjustments are necessary to accommodate corrosive characteristics of ethanol. Such modifications will cost money.

The possibility of cellulosic ethanol has been known since the 1880s (Sheehan 2000), but has not yet been fully commercialized. Production rates are currently lower than the potential anticipate when the 2007 Energy Independence and Security Act was passed, and costs have not yet reached a level where they would be competitive with conventional fossil fuels or starch-based ethanol (Wyman 2007). This chapter reports on an examination of how cost, technological progress and infrastructure compatibility would influence the production and market penetration of cellulosic ethanol along with impacts on commodity markets.

Another item examined in this study is inclusion of an ethanol demand curve. Evidence shows the ethanol price is changing as a response to increasing ethanol production volumes (Du and Hayes 2008), therefore the effect of replacing an exogenous ethanol price by a price elastic demand framework in examined.

2.3 Literature review

There have been many studies that have investigated cellulosic ethanol production. Tyner et al (1979) investigated and did an early examination of various possibilities for producing energy from agricultural sources. They evaluated and compared viability of bioenergy production from crop grains, residues and forage crops. Apland et al. (1981) analyzed the economics of biofuel production from crop residues and indicated that improvements in harvest methods and feedstock transportation are prerequisites for achieving profitability. Later, McCarl and Schneider (2000 and 2001) investigated potential of bioenergy produced from biofeedstocks as a way of creating GHG offsets. Farrell et al. (2006) conclude that “large-scale use of ethanol for fuel will almost certainly require cellulosic technology”. After careful examination of current cellulosic ethanol production status, Dwivedi et al. (2009) state that “production of cellulosic ethanol presents a challenge in terms of development of a commercially viable conversion technology”. Babcock et al. (2011) show that under current technology “emergence of a cellulosic ethanol industry is unlikely without costly government subsidies". Lau and Dale (2009) indicate that efficiency of enzymatic hydrolysis[1] and fermentation needs to increase to make lignocellulosic ethanol production competitive. The EPA RFS2 analysis document (EPA 2009) also indicates that improved enzyme technology and reaction biochemistry are essential for making production of cellulosic ethanol more cost-effective. Furthermore, several companies (e.g. BP, Coskata, DuPont Danisco Cellulosic Ethanol, Range Fuels, Poet) have been considering cellulosic ethanol production (EPA 2009). , So far, none of them has achieved lignocellulosic ethanol production on an industrial scale and some (e.g. British Petroleum) have withdrawn from the arena. This study attempts to answer what production cost conditions need to emerge to make lignocellulosic ethanol production economically competitive.

2.4 Theoretical framework

Before carrying out an empirical analysis a basic economic analysis of the likely consequences will be carried out using graphical economics. In this study, one issue involves the market impact of biofuel mandates imposed by the EPA Renewable Fuel Standards and we will examine the consequences in terms of crop and cellulosic ethanol plus the total ethanol market.

Figure 1 presents the situation before mandates are introduced. Excess supply for crop ethanol combined with supply of cellulosic ethanol creates more ethanol in the market and leads to a flatter aggregate supply curve (AS). Substantial demand for

[1] Enzymatic hydrolysis breaks down cellulose into sugars, mostly into glucose, which can be further utilized for the production of ethanol. That biochemical process happens with use of enzymes (which are biological catalyst). Enzymes break down the polymers from cellulosic biomass into monomeric sugars (definition adapted from Yang et al. 2011).

cellulosic ethanol causes the aggregate demand curve (AD) to shift out and raises the total ethanol selling price in the market.

The free market case – no mandates in place

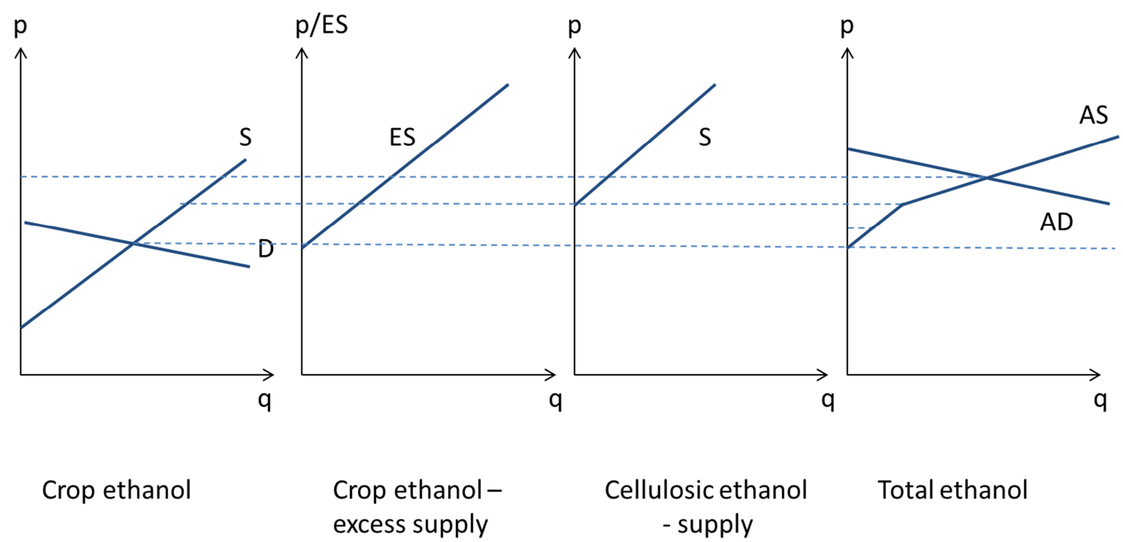

Figure 1. The free market case for total ethanol production – before introduction of the mandates.

Figure 2 depicts the situation with mandates in place. As one can observe in panel a), the excess supply of crop ethanol and higher price of ethanol are classic distortions caused by governmental regulations (in this case the EPA mandates). After introduction of cellulosic ethanol to the market (panel b) the total ethanol supply curve shifts down and the equilibrium price and quantity get established at the level required by the mandate. Introduction of cellulosic ethanol lowers the market price of ethanol (as a consequence of increase in supply).

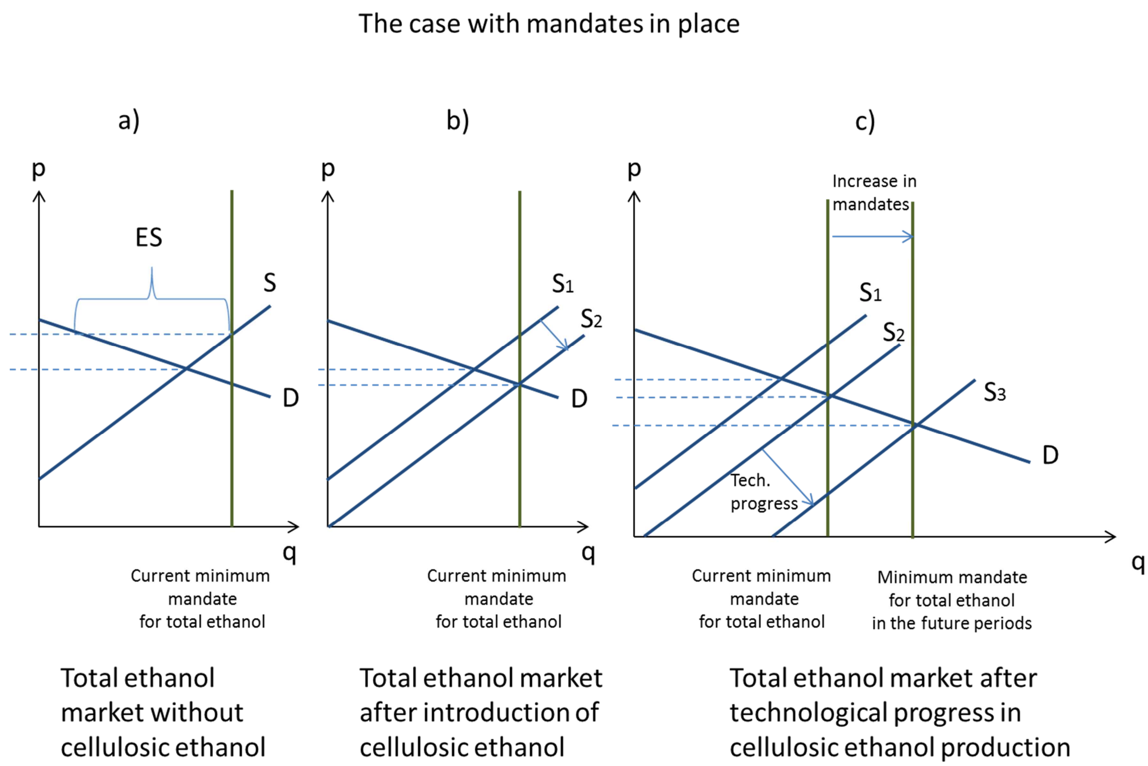

Figure 2. Total ethanol production under the EPA RFS2 mandates.

The impact of technological progress on cellulosic ethanol production will be also examined (figure 2, panel c). Decreases in processing costs will cause the cellulosic ethanol supply curve to shift down (panel c). As a result, when the market clears, the total ethanol selling price will go down and the quantity of ethanol sold in the market will increase. This also shows that the levels implied by future mandates will only occur in the free market if technological progress in cellulosic ethanol production is large enough.

Finally, we conceptualize the removal of market penetration barriers for ethanol by creating a fuel substitutability infrastructure[2] in the figure 3. At the same time, we apply the concept of elastic ethanol demand curve and combine it with the fuel substitution infrastructure. Until a certain level (5 BGY) there are no costs associated with ethanol penetration as it is assumed that currently existing fuel infrastructure is appropriate for the small shares of ethanol in the fuel blends. When the ethanol increases its presence in the market, there are some costs associated with higher volumes of ethanol. For example, when the amount of ethanol reaches 25 BGY one needs to account for $0.98 per gallon of additional costs related to increased market penetration of ethanol caused by essential investment in flex-fuel car fleet and liquid biofuel distribution networks. Babcock (2013) suggested that the cost of potential infrastructure investment could be paid by: i) taxpayers (e.g. in the form of corn subsidies diverted from corn farmers to installation of E85 infrastructure), ii) owners of retail gas stations, iii) oil companies which through investment could reduce their compliance costs. The penetration costs presented in figure 3 are based on estimates from The Department of Energy, Energy Information Administration (EIA 2009). The elastic ethanol demand curve framework makes the demand curve downward sloping. The discussion on chosen value of ethanol demand elasticity is presented in the later sections of this chapter.

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[2] Fuel substitutable infrastructure is the infrastructure which could handle any type of fuel: regular gasoline and fuel blends with variety of ethanol content: E10, E15 and E85. It can be understood as the infrastructure which allows various fuel blends to become substitutes.

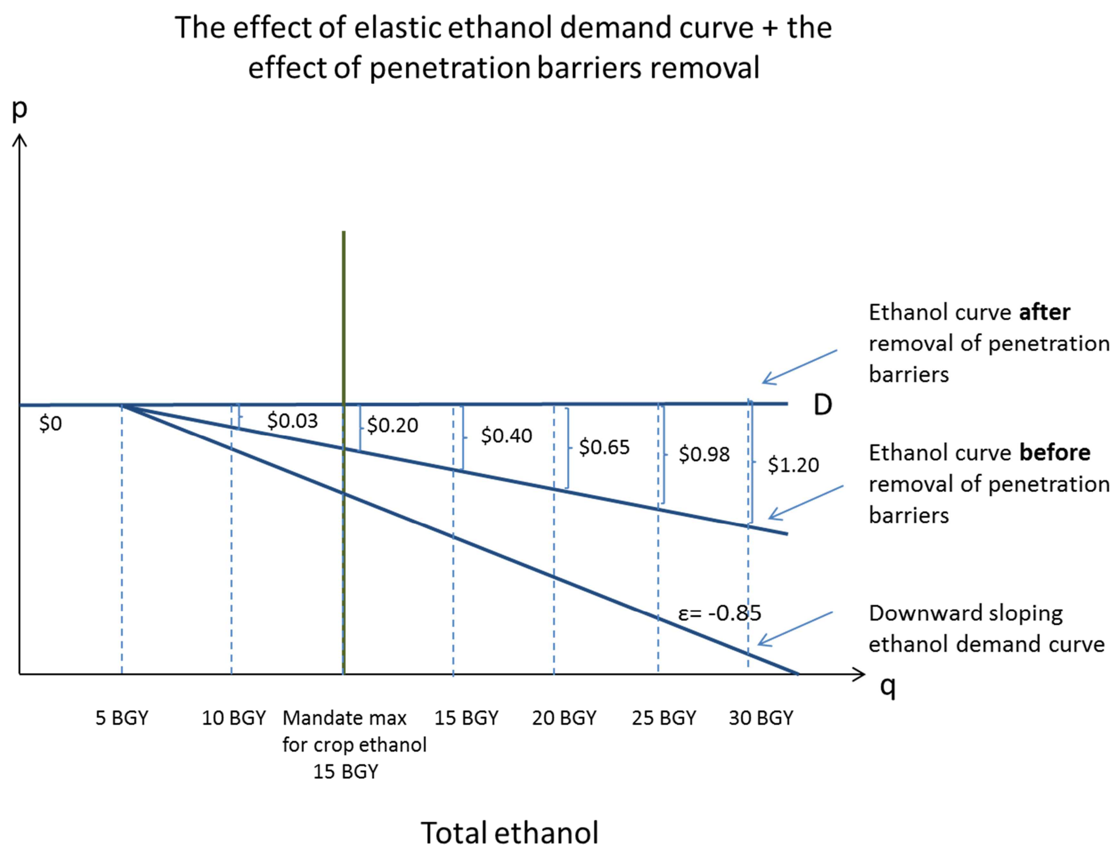

Figure 3. The effect of elastic ethanol demand curve and removal of penetration barriers on the total ethanol market.

2.5 Methodology

This study is carried out in the FASOMGHG modeling framework as discussed below using a scenario analysis approach across alternative assumptions regarding the

- level of processing costs,
- cost of achieving infrastructure compatibility,
- price elastic nature of economic demand for ethanol,

- level of government imposed mandates

In the model solutions attention will be paid to the volume of ethanol production from various feedstocks (e.g. corn, switchgrass, corn stover), commodity prices and the welfare cost of meeting the EPA RFS mandates.

2.5.1 Description of FASOMGHG

The modeling approach is based on the Forest and Agricultural Sector Optimization Model (FASOMGHG) that has been used in the EPA RFS analysis (EPA 2009; Adams et al. 2005; Beach et al. 2010; Beach and McCarl 2010).

FASOMGHG is a dynamic, nonlinear programming model of the U.S. forest and agricultural sectors (Lee 2002; Adams et al. 2005; Beach et al. 2010). It solves a dynamic optimization problem that maximizes the net present value of the sum of producers' and consumers' benefits (surplus) across the agriculture and forestry sectors. The model accounts for cropping, livestock, forests, pasture, and land competition providing an assessment of the net market effects associated with increasing the demand for renewable fuel feedstocks. FASOMGHG simulates possible changes in equilibrium quantities of agricultural and forest commodities due to market forces. Only the agricultural part will be used herein.

Given available land for conventional and nonconventional crops, agriculture can supply certain amounts of starch-based ethanol and lignocellulosic ethanol. Some excess demand remains in the market if the amount of cellulosic ethanol supplied does not match with amount required by mandates (the initial RFS2 mandate obliged producers to supply 250 million gallons in 2011, but this was reduced to 6.6 million gallons, the actual level of cellulosic production, due to inability of cellulosic ethanol industry to produce commercial quantities). To increase cellulosic ethanol supply, technological progress is needed, mainly in the form of reduced costs of enzymes and improved efficiency of the biochemistry of reactions (figure 4).

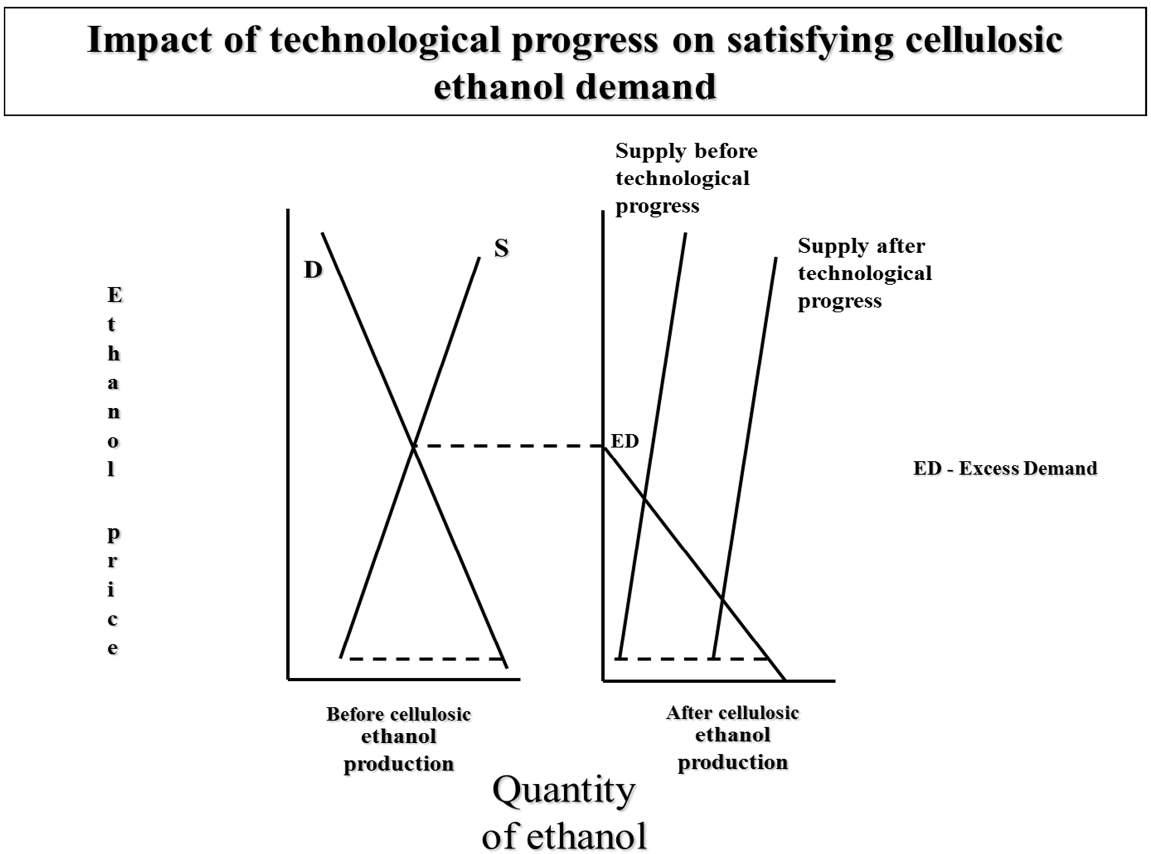

Figure 4. Impact of technological progress on satisfying cellulosic ethanol demand.

In the work, one substantial modification will be introduced into the FASOMGHG model. Up until now, the ethanol price is fixed at an exogenous level in the model. Several studies have shown that the gasoline price is responding to ethanol production and thus that there is downward sloping demand for ethanol (Du and Hayes 2008; Du and Hayes 2009; Anderson 2012). Ethanol production from biofeedstock creates a shock in demand for agricultural products which, in turn, is followed by rising prices (e.g. since the beginning of corn ethanol production in the USA in 2001, the price of corn has more than doubled from \$2.43 per bushel in 2001 to \$5.14 per bushel in 2013). As the biofeedstock is the dominant input for bioethanol production, its rising prices will increase production costs of ethanol. That might result in higher ethanol prices.

To make ethanol price endogenous in the model, a modification of the model is necessary as is an estimate of the demand elasticity. The price elasticity estimate of -0.85 is chosen for the purpose of this study based on an average value of estimates found in existing literature (Gardner 2007; Miranowski 2007; Vedenov and Wetzstein 2008).

The demand curve for bioethanol is assumed to be of the constant elasticity form

$$P = P(Q) = F\, Q^{1/E} \qquad (1)$$

where F is a constant and E the elasticity.

The curves are set up so they pass through a given price quantity point (starting with the base year price and quantity and then later with a quantity growing at the historically observed rate and the price falling at the historically projected rate) with a given elasticity. This point-expansion method results in the final demand curve of the following form:

$$P = P^{'}(Q/Q^{'})^{1/E} \qquad (2)$$

where P' and Q' are price and quantity point through which the demand curve is passed.

Figure 5 presents a graphical representation of the ethanol supply and demand curves. Technological progress is reflected by the supply curve shifting out in the right direction, followed by increasing demand.

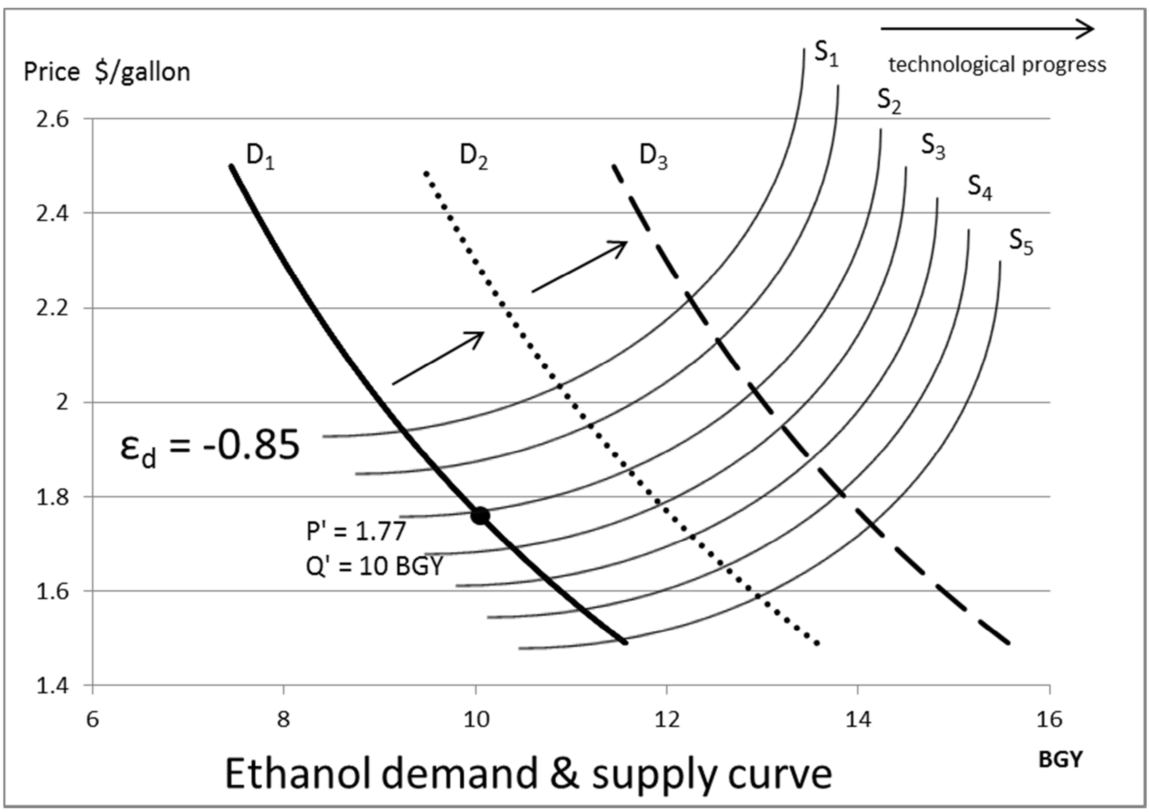

Figure 5. Pictorial representation of the ethanol demand and supply curves and *P'* and *Q'* point.

2.5.2 Approach to cellulosic costs

The National Renewable Energy Laboratory estimated that cellulosic ethanol production processing cost would evolve as portrayed in figure 6 (EPA 2009). This estimate was used in the EPA RFS2 analysis (Beach et al. 2010; Beach and McCarl 2010). Using this work, we examine whether these estimated costs allow for competitive production of cellulosic ethanol and if not how much further they would need to fall.

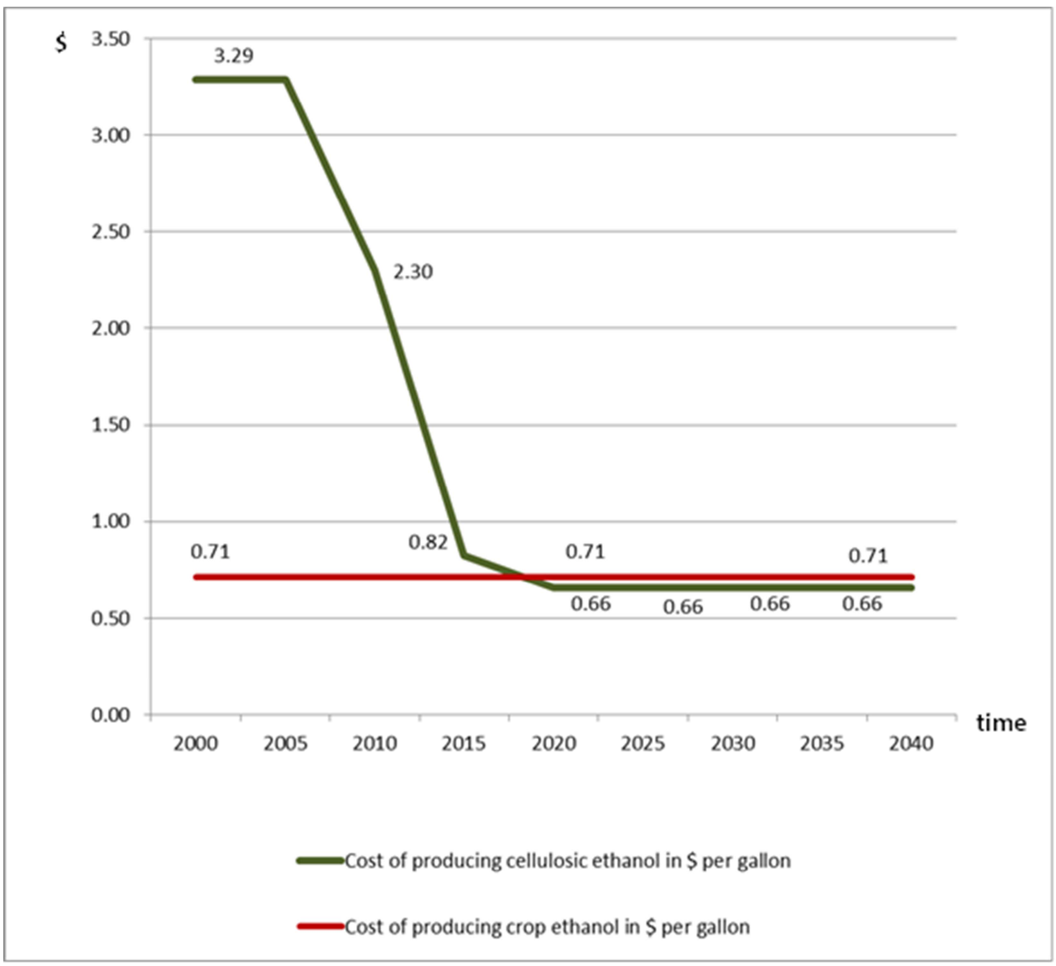

Figure 6. Projection of unitary processing costs of crop and cellulosic ethanol.

Source: National Renewable Energy Laboratory (EPA 2009).

2.5.3 Analysis

All the modeling and scenario analyses were performed using the agricultural component of the FASOMGHG model. FASOMGHG simulates production levels of primary and processed agricultural commodities (e.g. biofuels) while maximizing NPV of consumer benefits and producer profits (total economic surplus). When the ethanol price has been made endogenous, significant ethanol market penetration would lower ethanol prices. Additionally, penetration of ethanol in the market is constrained by an upward sloping cost schedule related to infrastructure (need for ethanol pump related modifications, distribution networks, flex-fuel vehicles etc.).

To examine the issue of processing costs for cellulosic ethanol, we proceed through three steps. First, we examine competiveness under the NREL estimates with and without mandates to see if the NREL projected cost fall leads to competiveness. Second, we look at what the penetration is at various levels of additional cost reduction looking to see how much cost has to fall to achieve the volumes that are specified by the EISA legislation. Lastly, we examine the implications of a drop-in version of the cellulosic biofuel. The "drop-in version" of biofuel is an alternative form other than ethanol that is fully compatible with currently existing infrastructure. It can be "dropped in" current fuel infrastructure without causing malfunctions of vehicle engines or damages in pipelines, tanks and pump stations. It is believed that biofuel will not be absorbed in the U.S. market in the quantities higher than 15-16 BGY without investment in fuel substitution infrastructure which would remove currently existing infrastructure barriers (Babcock 2011; Tyner et al. 2011). Therefore, we look at how potential removal of fuel substitution barriers would affect the biofuel quantities produced and sold in the market.

In this study, we assume that crop biofuel can be produced from the following feedstocks: sweet sorghum, corn grain, wheat, sorghum, spring barley, winter barley, oats, rice, and sugar. Lignocellulosic biofuel can be produced from the following feedstocks: sweet sorghum pulp, switchgrass, miscanthus, energy sorghum, hybrid poplar, willow, soft wood residues, soft wood pulp, hard wood residues, hard wood pulp, bagasse, corn residues, wheat residues, sorghum residues, barley residues, oats residues, and rice residues. Although the model allows for crop biofuel generation from all mentioned crops, effectively, corn grain is the major ingredient for crop biofuel production.

In all scenarios, it was assumed that the major technological breakthrough allowing for cheaper processing costs will happen between years 2012 – 2020 as indicated by NREL (EPA 2009). This technological breakthrough will likely need to be related to reduction of enzyme costs and cheaper biochemistry of reactions as argued by EPA (2009). This assumption influences the results and should be recognized by decision makers in comprehensive assessment of the viability of commercial cellulosic production technology in the coming decades.

2.6 Results on competitiveness of cellulosic ethanol under current processing cost projections

We examined ethanol volumes with and without the RFS2 mandates under the NREL projection of processing costs although when we solved the without case we maintained the maximum on crop ethanol. The resultant model volumes are in figure 7. This shows that the mandates increase ethanol production and alter its composition. When the mandates are in place, most of the ethanol is produced from corn in the years 2015-2020 and cellulosic ethanol volume exceeds crop ethanol starting from 2025. Under the no mandates case where volumes are determined by market price, the amount of crop ethanol produced is significantly lower. The green line called “EIA Total” shows the total ethanol production projection made by the U.S. Energy Information Administration (US EIA 2012). All scenarios presented in this dissertation assume that future price of oil and price of coal and carbon fuels are exogenous to the model and move according to projections from Annual Energy Outlook (U.S. Department of Energy 2012).

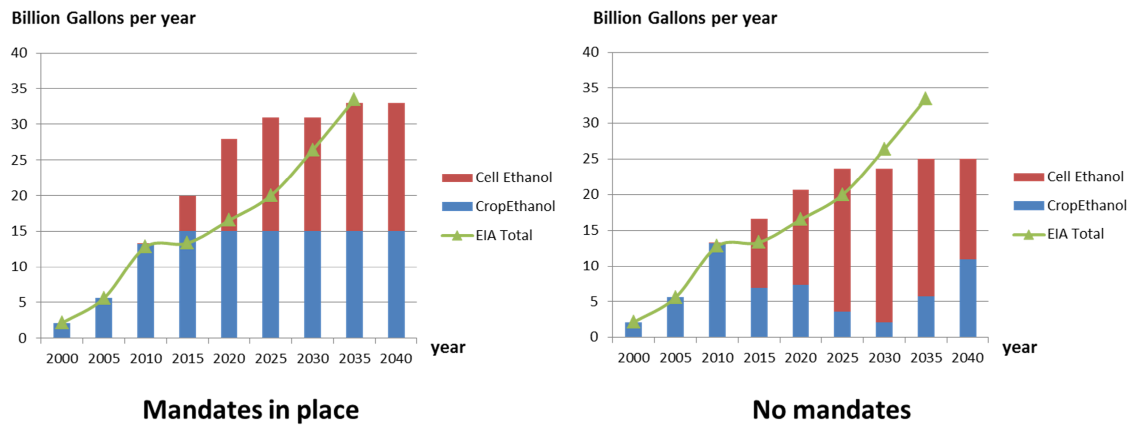

Figure 7. Volumes of crop and cellulosic ethanol produced with and without mandates under current processing cost projections.

We also examined the projected ethanol prices (figure 8) under mandates and the cost of satisfying the RFS2 cellulosic mandates (which is the shadow price on the cellulosic mandate constraints in the FASOMGHG model). We observed that in 2010-4, the extra cost of satisfying the RFS2 for cellulosic ethanol above the crop ethanol cost under the NREL projection would be around \$1.90 per gallon of ethanol whereas in 2020-4 it drops to \$1.30 per gallon and from 2030-4 it amounts to \$0.50 per gallon. This reflects that cellulosic ethanol is initially not cost competitive, but that it becomes more competitive as cost drops. However it never becomes truly competitive under the NREL estimates. This suggests that the mandates cause too much ethanol production in the market from a cost competitiveness point of view.

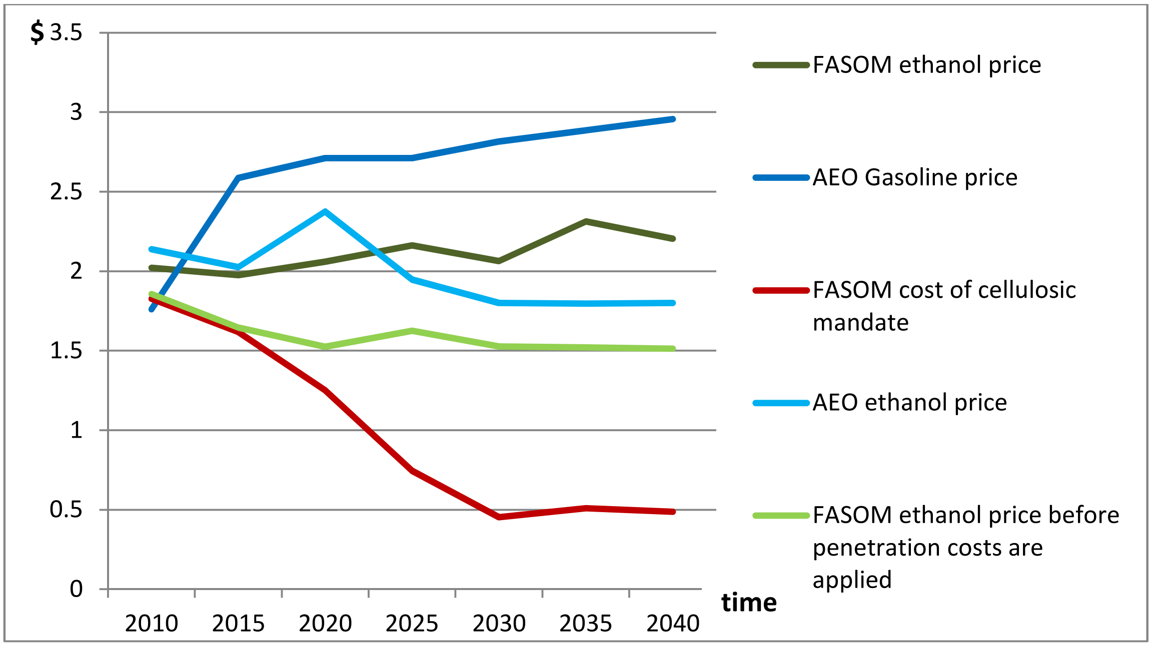

Figure 8. Projected ethanol price and cost of satisfying cellulosic mandate per gallon (Annual Energy Outlook gasoline price projection is for Free On Board[3] (F.O.B.) rack gasoline price).

2.6.1 Competitiveness of ethanol production in the absence of mandates under cellulosic cost reductions

We analyzed the impact of further cellulosic ethanol processing cost reductions to see how much the price has to fall for cellulosic production in order that the volume of total ethanol produced approaches the volumes contemplated by EISA. In this analysis we held crop ethanol production costs constant. Figure 9 shows the effect of decreasing processing costs on production volumes for three different points in time.

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[3] Free On Board rack gasoline price – the price actually charged at the point of loading (not at the pump).

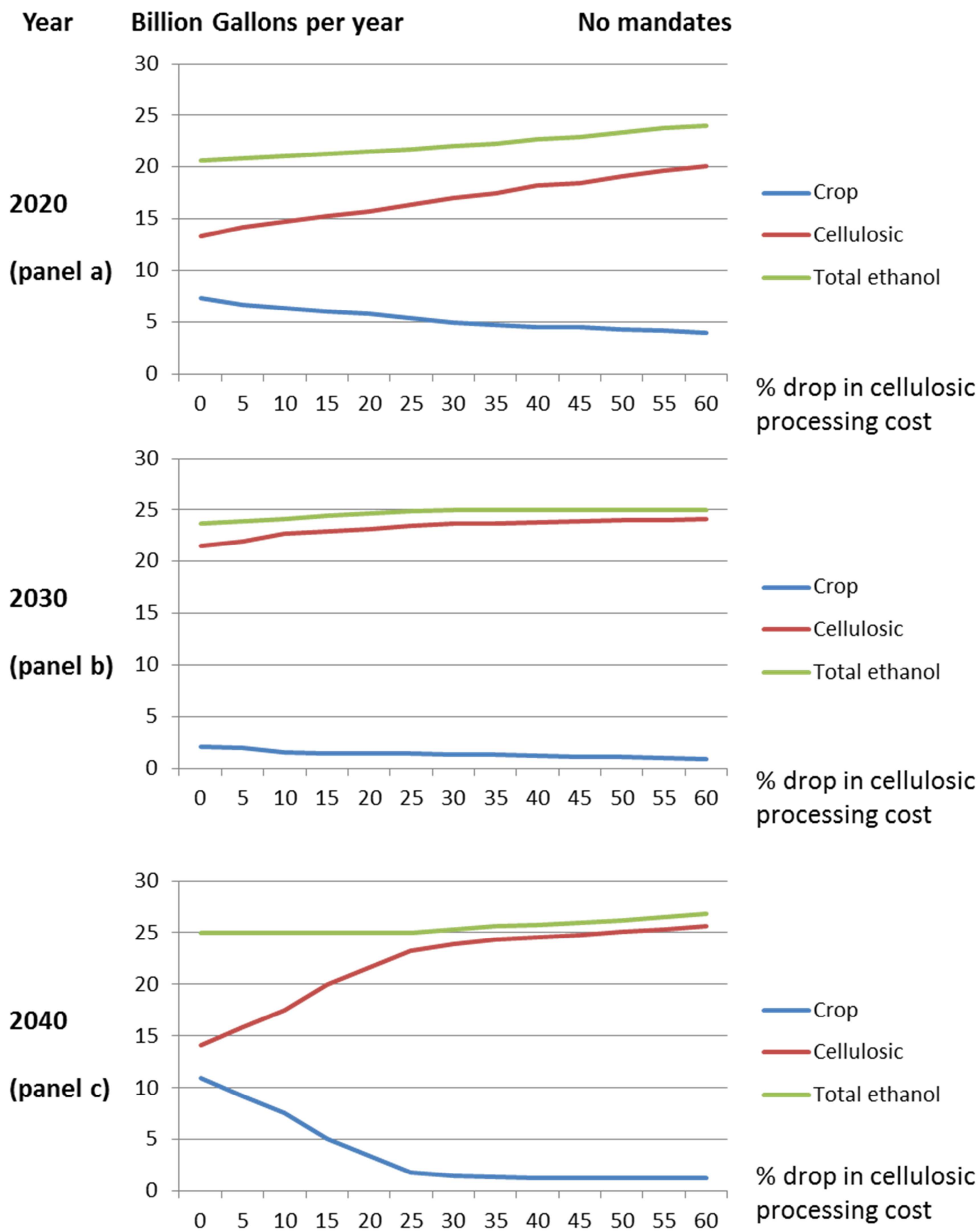

Figure 9. Volumes of crop and cellulosic ethanol under cellulosic ethanol cost reductions.

The results show that decreases in processing costs cause ethanol competition and total volume changes. Namely, as shown in the graphical framework above (figure 9) there is a reduction in crop ethanol and an increase in cellulosic ethanol volumes in the absence of mandates. For example, we find that 50 % drop in processing costs of cellulosic ethanol causes the amount of crop ethanol produced in 2020 drop to around 5 billion gallons per year and in 2040 to drop to around 1 billion gallon per year (figure 9, panel a). These amounts are much smaller compared to current levels of crop ethanol of around 13-14 billion gallons.

At the same time, the 50 % cost drop causes the volume of cellulosic ethanol to increase from 13.3 billion gallons per year to 19 billion gallons per year in 2020. It is also worth mentioning that RFS2 mandate schedule requires cellulosic ethanol to be produced at the level of 16 billion gallons per year by 2022. From the projection of cellulosic ethanol production in 2020 in figure 9 (panel a), we observe that this volume is only achievable under on the order of a 25 % or more decrease in processing cost relative to the NREL estimates. When it comes to the total ethanol volume, the EPA 2022 mandate of 31 billion gallon per year is never achieved, even if the processing costs drop by 60 % (figure 9, panel a) as crop prices rise enough to not make this possible.

2.6.2 Effect of drop-in characteristics on production volume of cellulosic biofuel

In this section, we examined how drop-in fuel characteristics affect biofuel volumes. We analyzed the competiveness of biofuel production in the absence of penetration costs and no mandates in force. We will examine scenarios without mandates and again with diminished cellulosic biofuel production costs. Figure 10 presents comparison of biofuel volumes between scenarios with penetration cost barriers (P) and those without (NP).

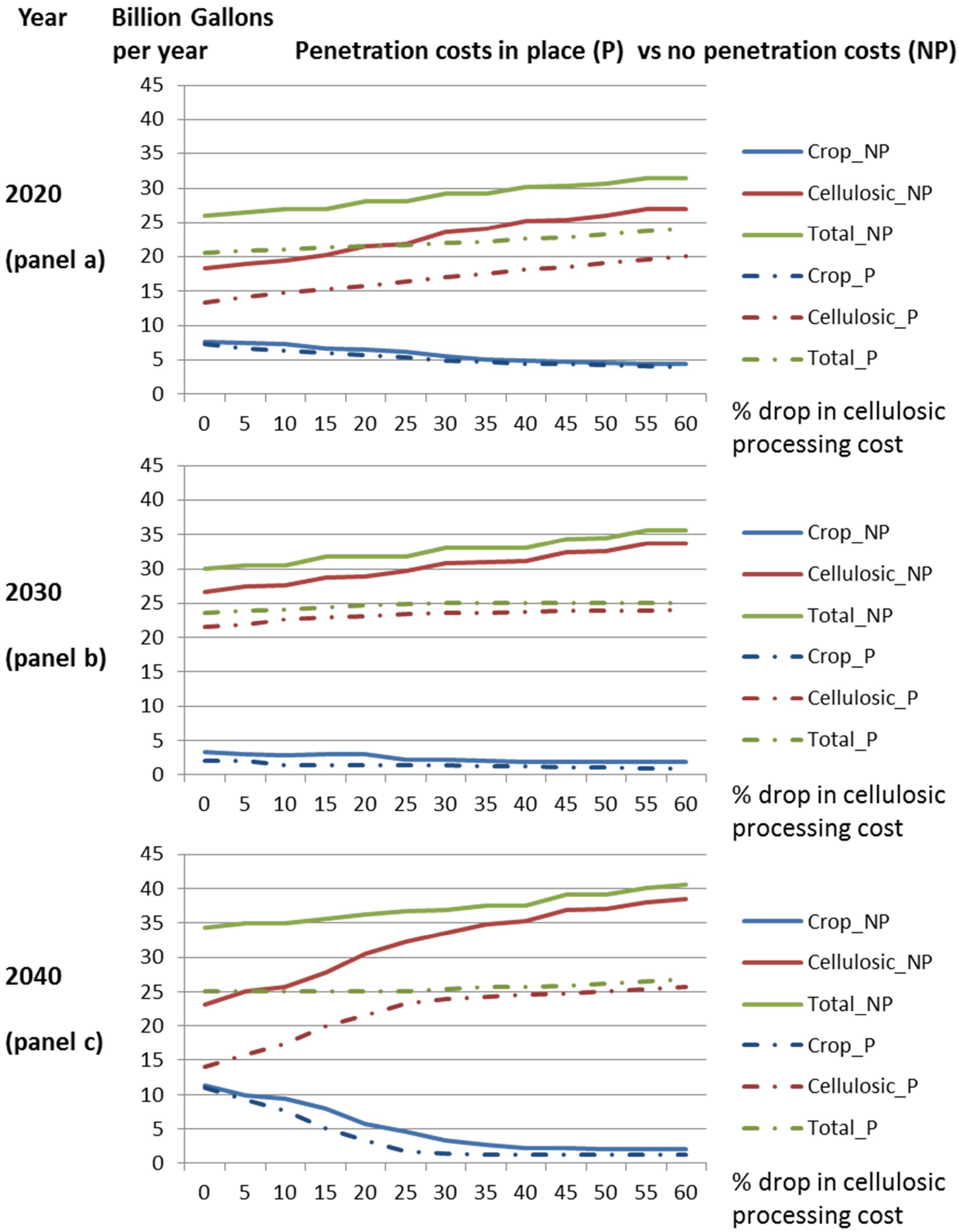

Figure 10. Volumes of crop and cellulosic ethanol under cellulosic ethanol cost reductions for drop-in versus non drop-in fuels.

We notice that drop-in fuels lead to an increase in total ethanol volume especially the volume of cellulosic biofuel. This implies that future expansion of liquid fuel production would be enhanced with fuel forms that are compatible with existing infrastructure avoiding penetration barriers. Moreover, figure 10 shows how drop-in characteristics of fuels cause a lesser decrease in processing costs to be needed to achieve mandates. The cellulosic biofuel EPA 2022 mandate of 16 billion gallons per year is exceeded in 2020 with no further reduction in processing costs required (figure 10, panel a). The total biofuel 31 billion gallon per year 2022 mandate is now achievable under a 50 % or more reduction in processing cost.

2.6.3 Effect of price elastic ethanol demand on production volumes of crop and cellulosic ethanol

The final issue, we examine is the impact of the introduction of price elastic ethanol demand. The ethanol price elasticity is taken as an average of values found in peer-reviewed literature. Gardner (2007) refers to Miranowski's study (2007, unpubl.) in which price elasticity equals -0.89. Another study conducted by Vedenov and Wetzstein (2008) estimated the demand price elasticity of ethanol at the level -0.81 (using Tobit 2SLS procedure). A price elasticity value -0.85 is chosen for this study and is used over the whole 40-year optimization period included in the model.

We found the expected result that when considering price elastic ethanol demand. The amount of cellulosic and corn ethanol produced became lower as the higher volumes caused a price fall and lowered market penetration.

2.6.4 Feedstock structure of cellulosic ethanol

The feedstock structure of cellulosic ethanol produced is also analyzed. Figure 11 presents feedstock supply for two scenarios: one with mandates in place and no market penetration costs, another with no mandates and no market penetration costs in place. The processing cost assumptions follow the NREL projection presented in figure 6. In these results, the feedstock structure in terms of input ingredients used for bioethanol generation changes from one year to another, and sometimes, production of ethanol from one particular feedstock varies greatly between the years (e.g. ethanol from sweet sorghum pulp). That result is counterintuitive because it indicates possible abandonment of production facilities between time periods or capital disinvestment. That issue will be addressed by introduction of asset fixity concept into the modeling framework in the fourth chapter of this dissertation.

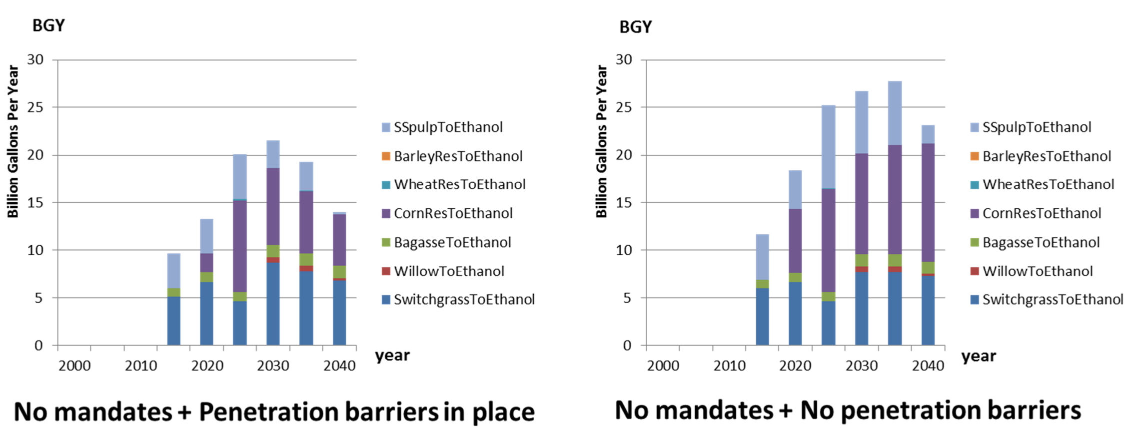

Figure 11. Feedstock supply for generated cellulosic ethanol for two chosen scenarios.

Next three figures (figure 12, 13, and 14) also present feedstock structure of ethanol produced across three regions: Corn Belt (CB), South Central (SC) and Southeast (SE). As observed, in CB region facilities producing ethanol from corn in the dry milling process (CornDry) are present in the years 2005 – 2015 and then they virtually disappear between 2020-2030. They later come back to the production portfolio in 2040 (for the scenario with penetration barriers in place) or in 2035 and 2040 (for the scenario with no penetration barriers). A similar pattern is displayed for switchgrass facilities which are present only between 2025-2035 and later vanish in 2040. This situation would effectively mean capital disinvestment or abandonment of capacity and it does not reflect actual processes and decisions made in the industrial setting. The same can be said for South Central and Southeast regions (figure 13 and 14). For example, for South Central region switchgrass operation starts in 2020, continues through 2025 and later it disappears in 2030-2040. This lack of production continuity in terms of its location, feedstock structure, and irreversibility of capital investment will be corrected in the fourth chapter of this dissertation through the introduction of the asset fixity concept.

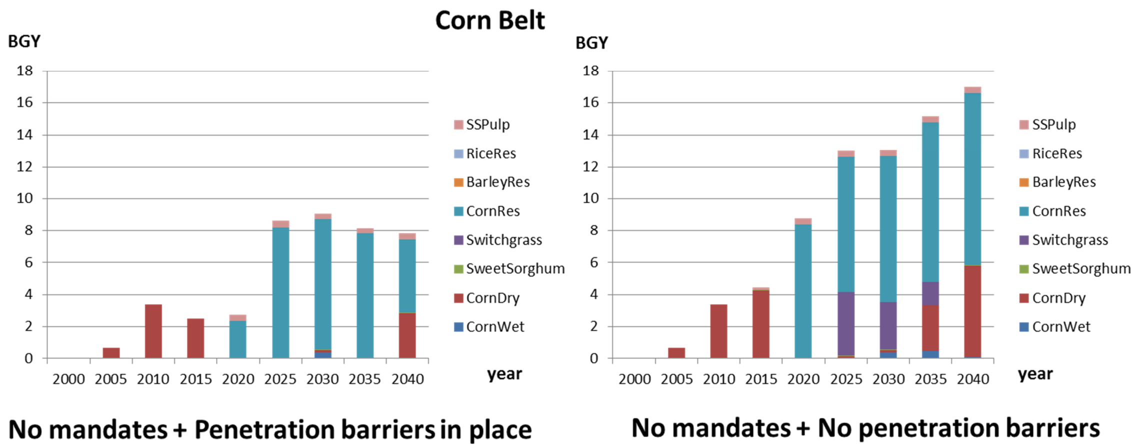

Figure 12. Feedstock supply for generated cellulosic ethanol for two chosen scenarios in the Corn Belt region.

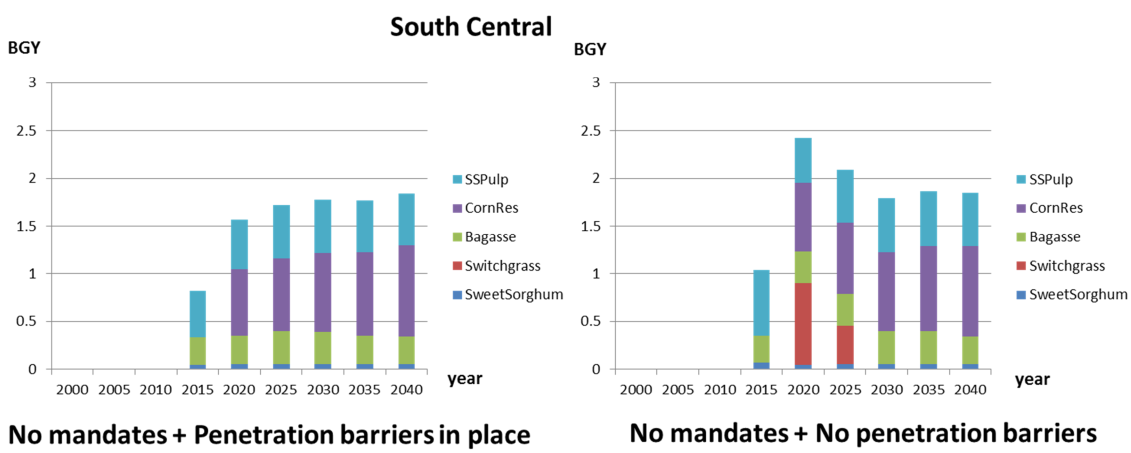

Figure 13. Feedstock supply for generated cellulosic ethanol for two chosen scenarios in the South Central region.

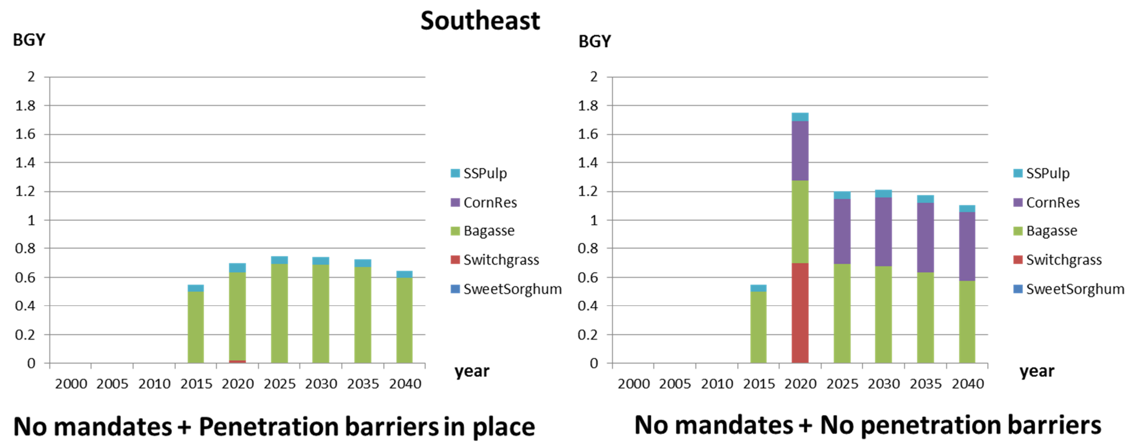

Figure 14. Feedstock supply for generated cellulosic ethanol for two chosen scenarios in the Southeast region.

2.7 Conclusions

This chapter reported on an examination of the consequences of cellulosic processing cost and ethanol infrastructure related modification cost decreases as they affected market penetration coupled with the effects of achieving drop-in fuel status. Under existing cellulosic processing cost projections that the desired volumes of production are only achieved under mandates with the cellulosic and crop ethanol volumes being non-cost competitive at the RFS2 peak required volumes. We also find that for cellulosic ethanol to penetrate the market at the levels contemplated by EISA that cost would needs to fall by at least 25%. The total levels of ethanol contemplated by EISA are not achieved until we achieve very large drops in production costs (ranging up to 65%).

Finally, a drop-in fuel variant boosts biofuel penetration and allows achievement of the EISA total ethanol volume goals when coupled with 15% or more further cost decreases in cellulosic production costs. That implies that it will be impossible to meet the level of ethanol production required by the EPA RFS2 mandates by 2022 without significant technological breakthrough in the lignocellulosic biofuel production technology, investment in fuel substitution infrastructure (e.g. E85 infrastructure) or production of more substitutable fuels (e.g. biobutanol).

3. LIQUID FUELS PRODUCTION UNDER CARBON PRICING

3.1 Synopsis

Today, many countries are increasing the biofuel share in national energy supply, mainly to strengthen their domestic energy security and to protect against sudden oil price hikes. Some biofuels also provide greenhouse gas emission offsets, becoming a part of a climate change mitigation framework. Second-generation liquid biofuels (e.g. lignocellulosic ethanol, algae fuel, biomethanol) are under an ongoing research effort investigating conversion technologies and economic feasibility. In this chapter, we will concentrate on the economic impact of carbon pricing and mandates on the volume of bioethanol produced. We will also examine cost-efficiency and profitability, and implications for global commodity markets. We will analyze the emergence of drop-in fuels (e.g. fuels that can be used in existing infrastructure) and the relative difference this makes in the potential for future market penetration.

3.2 Introduction and major concerns

Agriculture and the science community today are actively pursuing renewable energy production. Many research and implementation efforts involve producing ethanol or other liquid biofuels from non-food agricultural feedstocks in a cost-efficient manner. Various feedstocks are being considered including crop residues, energy crops (e.g. switchgrass, miscanthus, hybrid poplar, willow and others), logging residues, and agriculture/forest processing byproducts. At the same time, current market penetration barriers (like car capabilities, service stations, and pipelines) pose a significant barrier to further ethanol market expansion (Szulczyk et al. 2010; Tyner et al. 2011; Wlodarz and McCarl 2013).

The main purpose of this chapter is to report on an economic investigation of current and future prospects for agricultural feedstock based liquid biofuels expansion developing information on:

- The effects of carbon dioxide credit prices (cap-and-trade permit prices).
- The effect of infrastructure barriers on market penetration under carbon pricing.
- Tipping points that stimulate cellulosic ethanol.

3.3 Literature review

The possibility of second generation biofuels production from agricultural materials has been explored by many (Tyner 1979; Apland et al. 1982; McCarl and Schneider 2000). Bioethanol from crop residues, wood residues and energy grasses can provide GHG offsets with potentially lower demand shocks in the food commodity markets. Farrell et al. (2006) found that bioethanol production on the large industrial scale will definitely require further development of the lignocellulosic ethanol production technology. The need for further improvements in the biochemistry of reactions and cheaper enzymes is recognized by many (EPA 2009; Dwivedi et al. 2009; Babcock et al. 2011; Lau and Dale 2009). The first chapter of this dissertation showed that processing costs need to decrease by at least 25% to make cellulosic ethanol production economically viable. Chovau et al. (2013) analyzed the cost of cellulosic ethanol production and they claim that lignocellulosic ethanol will become more economical and environmentally attractive than corn ethanol. Littlewood et al. (2013) indicate that production modes utilizing less costly agricultural residues e.g. sugarcane bagasse are preferred from an economic standpoint (Alonso-Pippo et al. 2013). Governmental subsidies or carbon emission pricing mechanisms (Schneider and McCarl 2003) have also been found to increase the viability of lignocellulosic bioethanol production.

There are some studies which investigate the possibility of drop-in liquid fuels such as butanol or methanol (Lee et al. 2008; Green 2011; Qureshi and Blaschek 2000; Ezeji et al. 2007). Drop-in fuels do not have corrosive characteristics. They do not require major infrastructure adjustments. Both service points and distribution networks are appropriate for drop-in fuels dissemination.

3.4 Theoretical framework

Before carrying out an empirical analysis a basic economic examination of the likely consequences will be performed using a graphical economic model framework. In this study, one issue involves the impact of carbon dioxide equivalent pricing on the total ethanol market and examines the consequences in terms of the total ethanol market and the petroleum fuel market.

Figure 15 presents demand and supply shifts in the total ethanol and total petroleum markets as a result of introducing carbon dioxide equivalent pricing. In the first panel S_1 intersects $D_{1,}$ which establishes p_0 and q_0 in both markets. After CO2e prices are introduced, ethanol and petroleum producers need to buy GHG permits to continue their operations and that increases their production costs. The supply curve shifts to the left (S_1 moves to S_2 for both markets) and the magnitude of shift is greater for petroleum producers (on the assumption that GHG emissions from petroleum production are higher than from ethanol production as shown by Farrell et al. 2006 and Fargione et al. 2008). At the same time, fuel blenders' demand for ethanol increases (D_1 moves to D_2) due to the fact that ethanol provides net GHG offsets when used as a substitute for the regular petroleum. The positive demand shock causes an increase in the ethanol price. Some fuel blenders choose to decrease the ethanol content in their blends and they switch back into petroleum. That, in turn, induces an increase in the petroleum demand (demand curve for petroleum shifts out from D_1 to D_2) and is followed by a corresponding increase in the petroleum supply (supply curve shifts from S_2 to S_3). At the end, the equilibrium price (p*) and quantity (q*) in the total ethanol market may end up being higher than initial situation. For the petroleum market, the final price (p*) might be higher and the quantity (q*) consumed might decrease. The intended impact of carbon dioxide equivalent pricing will probably be achieved – by substituting more bioethanol for petroleum creating expected net GHG offsets. The impact depicted in figure 15 is just one example of the array of possible outcomes. In case new oil reserves are discovered in the United States, the supply curve S_3 might shift to the region below initial supply curve S_1. In this instance, the market price of petroleum might go down and the quantity of petroleum consumed might increase more than expected. As a result, it might be difficult to increase bioethanol share in fuel blends sold in the United States.

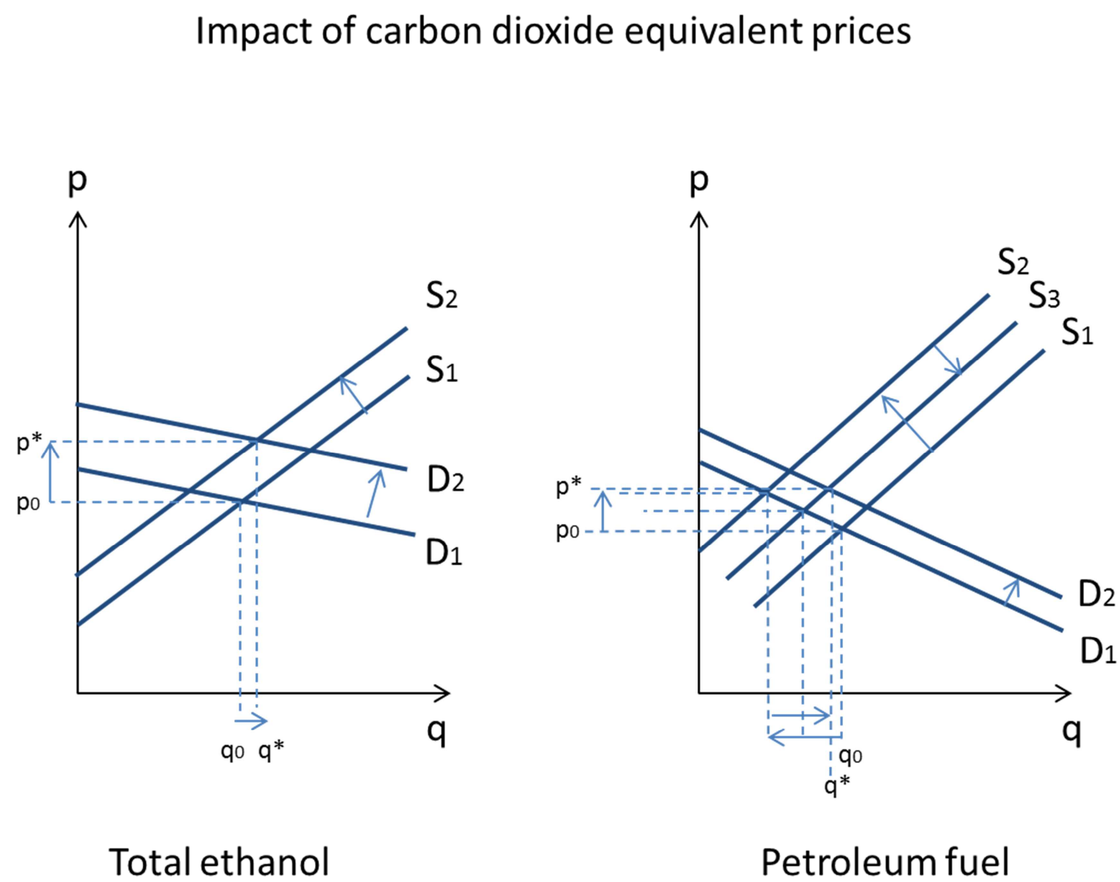

Figure 15. One possible example of the final outcome of an impact of carbon dioxide equivalent pricing on the total ethanol and petroleum fuel markets.

3.5 Methodology

This chapter presents results from a dynamic multi-period analysis of the U.S. agricultural, forestry and bioenergy sectors' responses to changing liquid biofuel governmental mandates and greenhouse gas offset[4] prices. The work undertaken in this study uses a modeling approach to examine the impact of several factors on the future

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[4] Greenhouse gas offset – reduction in the emission of greenhouse gasses achieved to compensate for or to offset the greenhouse gas emissions made in a different sector, market or industry (adapted from Collins English Dictionary – Complete & Unabridged 11th Edition, www.CollinsDictionary.com).

prospects and market emergence of second-generation liquid biofuels and drop-in fuels. The factors examined are

- changes in market penetration costs / infrastructure barriers
- greenhouse gas offset prices

The model used is called FASOMGHG (Adams et al. 2005) and is a 100 year forest and agriculture model with a biofuels production sub-module. The same model was augmented and is used in the study presented in the chapter two of this dissertation. It is dynamic and price-endogenous. It covers agricultural, forestry, and biofuels production with accompanying GHG mitigation activities in 11 U.S. regions and 63 U.S. Sub-State regions, 28 foreign regions for 8 commodities, plus world market for 50+ other commodities. The 40 year period is simulated in 5-year time steps (with a possibility of extension for 100 year period). The forestry and agricultural sectors are linked through land and some commodity transfers. The model has rather detailed coverage of agricultural carbon and non-CO2 plus forest carbon management alternatives. The model was employed and is documented in the

- 2008-9 US Government study on the 2007 EISA renewable fuels standard changes (Beach and McCarl 2010)
- 2006 EPA GHG mitigation study including biofuels (Murray et al. 2005)
- 2007 US Government study on renewable fuels standard changes (McCarl and Cornforth 2007)
- 2004-2007 USDA/DOE Biofuels production possibility study (McCarl et al. 2005)

- 1979 Tyner et al. OTA study plus other biofuel follow-ups (Tyner et al. 1979; Bender and McCarl 1992; McCarl et al. 2000; McCarl and Schneider 2001).

3.6 Cellulosic ethanol processing cost structure

At the moment, processing costs for lignocellulosic ethanol production are a significant barrier to its industrial scale production. Feedstock costs and the cost of enzymes contribute the most to total production costs (EPA 2009; Littlewood et al. 2013; Wyman 2007). Ongoing research in the agricultural and biological area is predicted to lower processing costs (EPA 2009). According to estimations conducted by the National Renewable Fuel Laboratory (EPA 2009) the future processing cost of cellulosic ethanol will decline. (For projections and exact data on ethanol processing costs, refer to figure 6 in the second chapter of this dissertation.) In terms of conventional ethanol, we assume that crop ethanol technology has reached its maturity and the crop ethanol processing costs stay constant in our model.

3.7 Approach to GHG accounting and pricing

FASOMGHG contains accounting procedures which calculate GHG emissions, sequestration and bioenergy offsets by the forestry and agricultural sectors including land use changes. Usage of crop residues and energy crops for the ethanol or electricity production replaces gasoline and coal saving emissions. At the same time, hauling and biomass processing produce emissions, also accounted for in the model. All GHGs are converted to a carbon dioxide equivalent (CO2e) basis using 100-year global warming potential (GWP) values (Beach et al. 2010). Table 1 provides examples of GHG categories.

Table 1. Selected categories of GHG sources and sinks in FASOMGHG.

Carbon_AgFuel	Carbon emissions from agricultural use of fossil fuels
Carbon_agsoil	Carbon sequestered in agricultural soil
Carbon_standingtrees	Carbon sequestered in trees
Carbon_forestproducts	Carbon sequestered in forest products
Carbon_Ethl_Offset	Carbon emissions from gasoline use offset (reduced) by conventional ethanol production
Carbon_Ethl_Haul	Carbon emissions in hauling for conventional ethanol production
Carbon_Ethl_Process	Carbon emissions in processing of conventional ethanol production
Carbon_CEth_Offset	Carbon emissions from gasoline use offset (reduced) by cellulosic ethanol production
Carbon_CEth_Haul	Carbon emissions in hauling for cellulosic ethanol production
Carbon_CEth_Process	Carbon emissions in processing of cellulosic ethanol production
Methane_Enteric	Methane emissions from enteric fermentation by animals
Methane_Manure	Methane emissions from animal manure
NitrousOxide_Fert	Nitrous oxide emissions from crop fertilization
NitrousOxide_Manure	Nitrous oxide emissions from animal manure

Source: Adapted from Beach et al. (2010).

CO2e pricing (or GHG pricing) is modeled as a cap-and-trade market payment for the reduction in net emissions (i.e. a reduction from baseline emissions or an increase in sequestration or bioenergy offsets). They also serve as a form of tax on net emissions increases such as an increase in hauling emissions associated with bioenergy production. GHG payment variables are created which pay a per ton price to the change in each GHG account relative to the baseline. The GHG payments can be either positive or negative in each account based on the net change in GHG (Beach et al. 2010). Table 2 presents the GHG prices in dollars per ton of CO2e (in terms of their global warming potential[5]) which are used in the model.

Table 2. GHG prices used in the model (GHG price signal).

GHG prices used in the model (in $/ton of CO2e)
$0
$1
$5
$12
$15
$30
$50
$100

GHG payments under cap-and-trade schemes are designed to internalize the negative externality arising from GHG emissions. Not only do they provide incentives for use of agricultural and bioenergy activities that reduce net GHG emissions, but they also can make emission efficient ethanol production more profitable by adding revenue streams for the producers of biofuels. The magnitude of these GHG payments is determined by the amount of GHG emission offsets provided.

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[5] Global-warming potential – An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame (definition adapted from IPCC 4th Assessment Report, Working Group I, The Physical Science Basis (IPCC 2007)).

The GHG prices used in this study range from \$0 per metric ton CO2e to \$100. Currently, carbon trading and CO2e prices are in effect in the European Union, under the European Union Emission Trading Scheme. Between 2005 and 2007, the GHG price peaked at \$40 per ton. In 2008-12 the price fluctuated between \$9 - \$40 per ton. The lowest carbon price happened in January 2013 at \$4 per ton. The United States also had a voluntary trading system called the Chicago Climate Exchange. This exchange operated between October 2003 and July 2010 with a price in the range of \$0.05-7.50 which subsequently closed. Ten U.S. states participating in the Regional Greenhouse Gas Initiative (RGGI) sold carbon dioxide credits at the auctions between 2008 and 2012 for the price ranging from \$2.06 to \$3.51 per ton of carbon dioxide. According to EPA estimates, the carbon price would need to rise from about \$20 per ton in 2020 to more than \$75 a ton in 2050 for the CO_2 level in the atmosphere in 2050 to be 83 % less than it was in 2005 as was required by the potential but never passed Waxman-Markey legislation (Feldstein 2009). These higher carbon prices will be transmitted into higher prices of carbon dioxide intensive goods and services. Feldstein (2009) argues that the burden of higher carbon prices would mostly fall on households. The recently proposed Sanders/Boxer Climate Legislation and other regulatory proposals discuss introduction of carbon taxes at the level of \$10-\$35 per metric ton of CO2e.

3.8 Approach to ethanol market penetration costs

Fuel mixes with ethanol content higher than 10% might face constraints because of fuel market infrastructure with more flex-fuel vehicles being needed and distribution networks adjusted (Szulczyk et al. 2010). Based on data and projections made by the

Energy Information Agency (EIA) 2009 Annual Energy Outlook (The U.S. Department of Energy 2009) future penetration costs of E85 are estimated. Calculations reflected the EIA projected increasing difference between price of wholesale ethanol and gasoline as penetration increased (as discussed Beach et al. 2010). Table 3 presents estimation of market penetration costs for ethanol. These costs are additional costs of infrastructure modification, adding to feedstock costs, transportation costs and processing costs incurred in refineries.

Table 3. Market penetration costs for ethanol.

Ethanol Production Volume (billion gallons per year)	Penetration costs ($/gallon)
≤5	0
>5 to 10	0.03
>10 to 15	0.20
>15 to 20	0.40
>20 to 25	0.65
>25 to 30	0.98
>30 to 35	1.20
>35 to 40	1.43
>40 to 45	1.70
>45	1.80

Source: Adapted from Beach et al. (2010).

3.9 Scenario design

Currently ethanol production in the United States is stimulated by mandates set by the US EPA. Renewable Fuel Standards (RFS2) create requirements which oblige fuel blenders to mix ethanol into fuel blends. In our analysis, we make a projection of future volume of ethanol production with mandates in place until 2040. Then, we observe how these volumes change once market penetration costs are removed. This endeavor helps us in understanding how adjustments in current fuel distribution network and car fleet could influence total amount of ethanol produced and sold in the USA.

Second, we look at the projected amount of ethanol produced under a situation with no mandates in place. That investigation provides us with the projection of possible ethanol production should the US EPA decide to waive all renewable fuel mandates. Again, we look how these estimated amounts are impacted by removal of ethanol market penetration barriers. Our next steps include examination of changes in volume of ethanol produced as a response to increasing CO2e prices. By doing this, we are able to see what level of CO2e price stimulates higher volumes of ethanol production and we can verify at which CO2e price ethanol production reaches volumes mandated by the RFS2. We repeat the same exercise for two cases: first one with a market situation with no mandates in place but with market penetration barriers present, second one with no mandates and no market penetration barriers. In our analysis, we assume that the presence of carbon trading markets is a substitute for the EPA mandates because carbon trading mechanism is supposed to provide incentives similar to standard quantity requirements. We do not examine the impact of changes in CO2e prices on the volume of ethanol produced when the EPA mandates hold.

At the end, we compare CO2e price effect on ethanol produced under two scenarios: with and without market penetration barriers in place in order to look at the magnitude of impact of market penetration removal on total ethanol produced in the USA. All in all, the outcomes of these scenarios provide enough information for decision makers to assess potential benefits which could arise from introduction of carbon pricing and trading mechanisms as well as positive environmental and economic consequences from removing market penetration barriers. We investigate the impact of factors mentioned above on quantity of crop and cellulosic ethanol produced at three points of time (i.e. 2020, 2030 and 2040). In all scenarios, we also assume that the existence of cap-and-trade carbon dioxide credit market allows oil producers to buy carbon dioxide permits from the ethanol producers. Moreover, all other entities engaged in greenhouse gas emitting activities are assumed to be able to participate in the market for carbon permits.

3.10 Results

3.10.1 Volume of ethanol produced under four different market scenarios

Our initial analysis examines ethanol production volumes between now and 2040. We consider four different scenarios altering the presence of the EPA RFS 2 mandates (EPA 2009) and market penetration costs. Figure 16 presents ethanol production volumes with and without penetration costs under a mandate. When a drop-in type fuel is produced avoiding market penetration costs we find increased ethanol market supply. Our second comparison analyzes the impact of penetration barriers when mandates are not present (figure 17). Without a mandate, less crop ethanol is produced than with mandates and more cellulosic ethanol is produced after 2020, mainly due to lower processing costs. Furthermore, the removal of market penetration costs has a stronger impact on ethanol volumes reflecting the greater flexibility allowed.

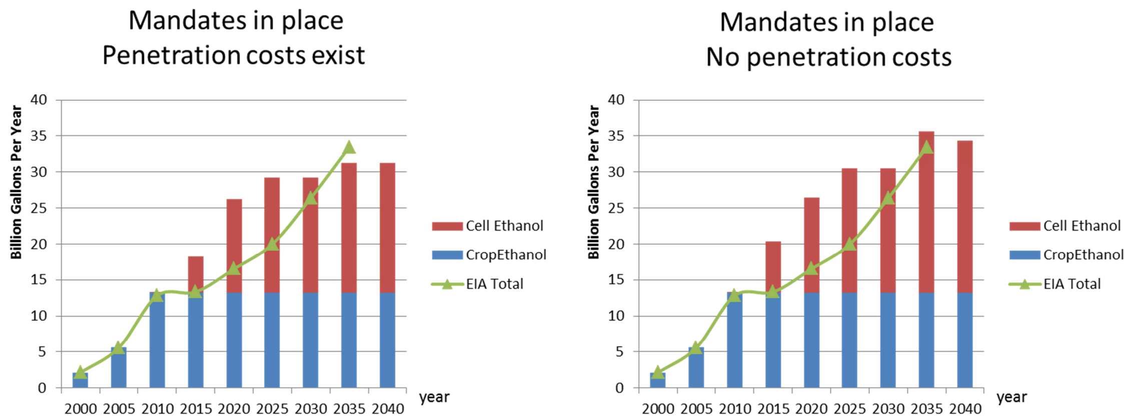

Figure 16. Projection of ethanol produced under "mandates in place" scenario. Comparison between scenarios with and without penetration costs.
EIA Total is a benchmark – projection of total ethanol production in the United States provided by the Department of Energy, Energy Information Administration (EIA 2012).

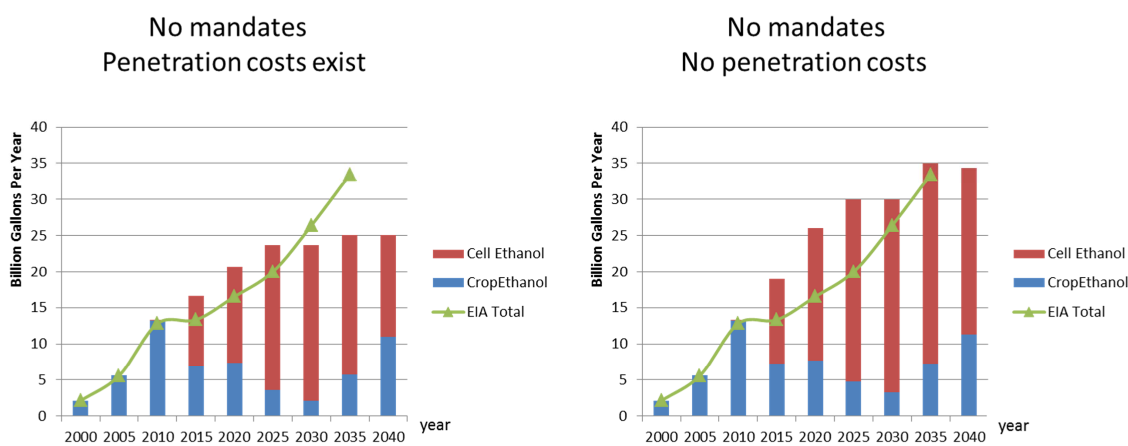

Figure 17. Projection of ethanol produced under "no mandates hold" scenario. Comparison between scenarios with and without penetration costs.
EIA Total is a benchmark – projection of total ethanol production in the United States provided by the Department of Energy, Energy Information Administration (EIA 2012).

3.10.2 Volume of ethanol produced under various carbon dioxide prices

Next we examine the impact of adding carbon prices. First we consider the case with no mandates in place, but with market penetration barriers (figure 18). There total ethanol production volume increases slightly under increasing carbon price, and ultimately reaches about a 10% increase in total production. Simultaneously cellulosic ethanol replaces crop ethanol production due to its enhanced GHG emission offset efficiency (see McCarl 2007 for estimated offset rates).

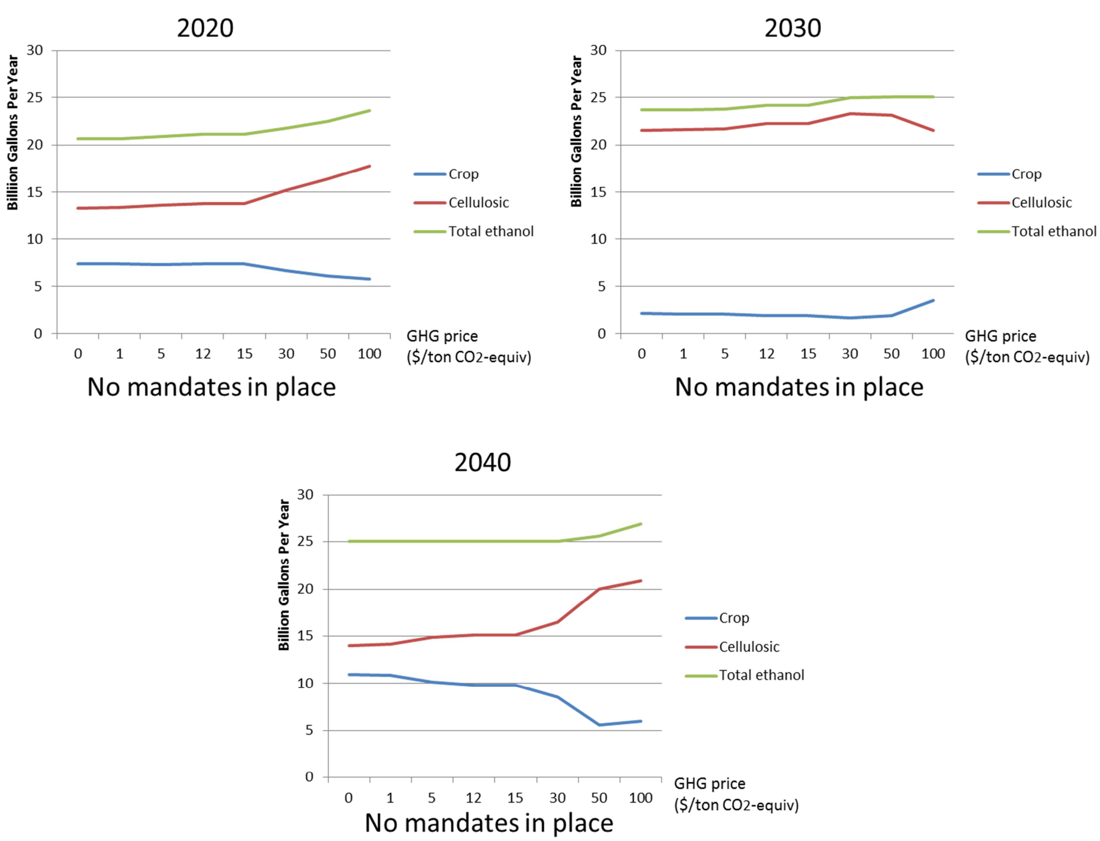

Figure 18. Projection of future crop and cellulosic ethanol production under varying GHG prices (at three points of time) for "no mandates in place" scenario.

We also examine the projections of future ethanol production under “no mandates and no penetration costs in place” scenario for three points of time (figure 19). It can be observed that removal of market penetration costs drives ethanol volumes up. In 2020, the amount of total ethanol produced fluctuates between 25 and 30 billion gallons per year (depending on the GHG price), in 2030 the amount of total ethanol is in the range of 30 and 35 billion gallons per year, and in 2040 the total ethanol amount reaches 40 billion gallons per year under GHG price of $50 per ton of CO_2e. GHG payments provide additional revenues to biofuel producers and increase volumes. At the same time, we see that only under scenarios with no penetration costs and a carbon payment the total volume of ethanol produced reaches the RFS2 biofuel mandate levels. Thus it appears that in the absence of a carbon trading schemes or a drop-in fuel it is highly unlikely that the EPA RFS2 mandate will be met.

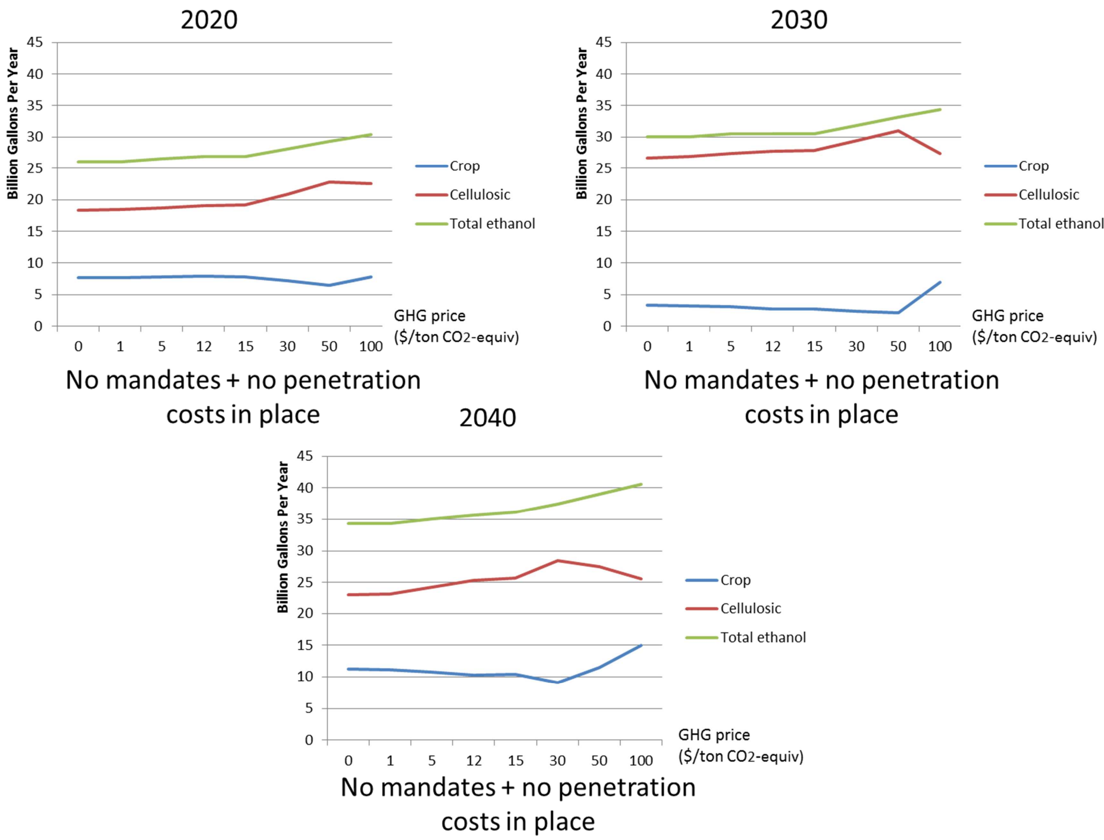

Figure 19. Projection of future crop and cellulosic ethanol production under varying GHG prices (at three points of time) for "no mandates and no penetration costs in place" scenario.

3.10.3 Impact of penetration barriers removal on total ethanol production

We examine impact of penetration costs removal on the total volume of ethanol produced. We assume that scenario with no penetration costs could be a case of all drop-in biofuels which do not require adjustment in infrastructure before their distribution in the market. Some innovative liquid biofuels like butanol or methanol are free from corrosive properties and they could be distributed and sold to the end-consumer through the currently existing distribution networks and pumping stations.

In the figure 20, removal of penetration barriers raises the total ethanol production by around 5 billion gallons per year under all considered GHG prices in 2020. In 2030 the situation looks slightly different. Under $0 carbon price and scenario with no penetration costs, the amount of ethanol produced is around 6-7 billion gallons higher than under the scenario with penetration costs in place. Under $100 carbon price this difference between two scenarios amounts to 10 billion gallons per year. For example, under the assumptions that ethanol provides GHG offsets by displacing fossil fuels (e.g. gasoline) and that these can be sold in a carbon market, the possible revenues from the sale of GHG credits could finance the cost of installing E85 infrastructure. This would relax infrastructure constraints allowing more ethanol to be sold and absorbed in the market in turn creating incentives for higher volumes of ethanol production. Some discrepancies could also be noticed in the projections for 2040. Under $0 carbon price the total amount of ethanol under no penetration costs exceeds the total amount of ethanol under scenario with penetration costs by 10 billion gallons per year. Once the carbon price reaches $100 per ton of CO_2e, the gap between both scenarios amounts to almost 15 billion gallons per year.

In general, these projections display the pattern which reflects the impact of penetration costs removal on the amount of total ethanol produced. The removal of penetration barriers enables ethanol to be absorbed by the market and encourages growing consumer ethanol demand. The existence of penetration barriers and lack of investments aiming at their reduction might hamper further development of the ethanol industry.

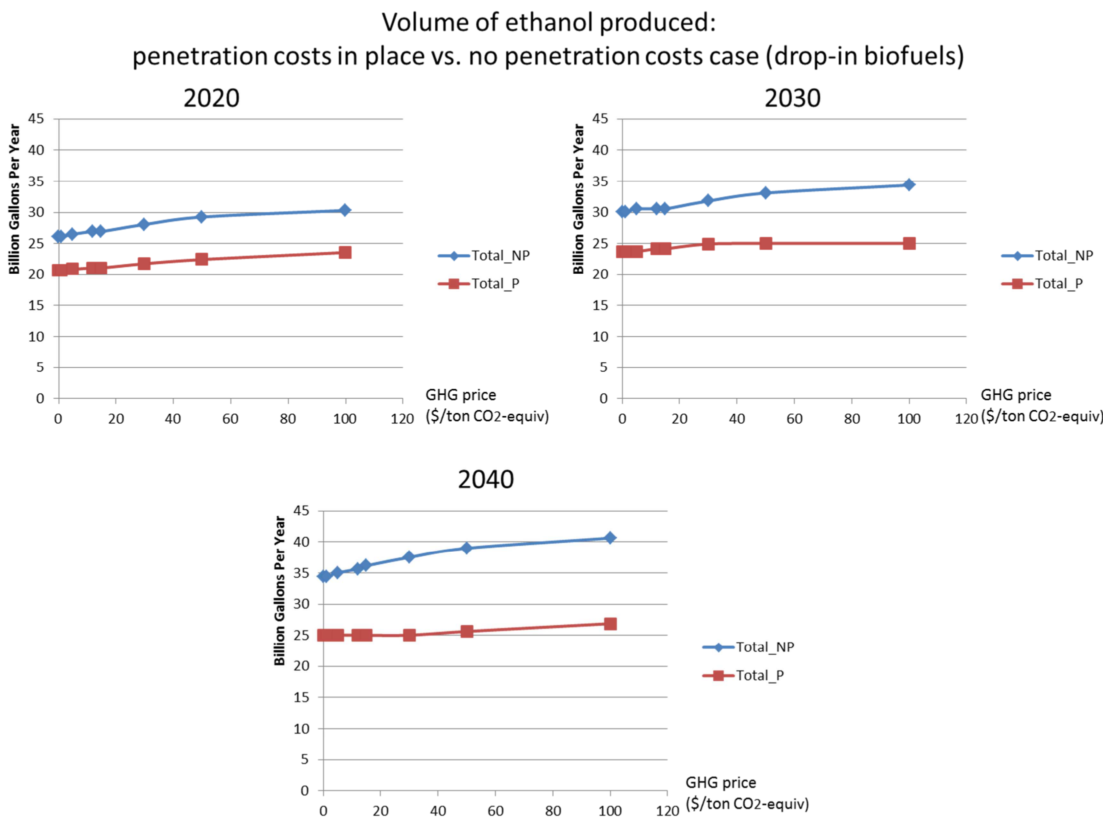

Figure 20. Total volume of ethanol produced under varying GHG prices. Comparison between scenarios with and without penetration costs.

3.11 Conclusions

We find that ethanol mandates create volumes that are generally higher than would occur in the free market (especially volumes of crop ethanol), and that market penetration costs and carbon prices are big influences in biofuel market penetration. Namely,

- positive carbon prices, lower infrastructure costs or some other cost reduction are needed to provide economic incentive for second-generation liquid biofuels production if they are to reach mandated levels,

- removal of market penetration barriers (costs) through e.g. expanded flex-fuel car fleet and essential adjustments in distribution networks etc. could enhance the presence of the second-generation biofuels and their share in the total U.S. fuel market.

4. ASSET FIXITY AND BIOENERGY INVESTMENT

The third dissertation essay addresses the ways that asset fixity or the putty clay nature of facility construction affects bioenergy feedstock mix and costs of meeting the mandate.

4.1 Synopsis

The pattern of feedstock use by region that resulted in the studies conducted in the first and second chapters showed large spatial and temporal variation in the exact feedstock uses and places of use over time. Consider the following example: in the scenario with no mandates and no penetration barriers in place analyzed in the first chapter (see figure 11), the amount of ethanol produced from sweet sorghum pulp goes down from 8.7 BGY in 2025 to 1.9 BGY in 2040. The problem with this is that refining facilities are not mobile and typically can handle only one type of feedstock and once built are likely dedicated to that feedstock for their remaining functional life plus involve fixed cost of initial construction. The need arises to account for the fact that once capacity is built, it stays there for the economic life of the asset. That concern will be addressed by using a one-time fixed cost investment module and capacity utilization operating module where the investments persist for a fixed number of years in the future. Moreover, production capacity accounting over time will be added.

4.2 Literature review

Asset fixity emerges when established production facilities are designed for a particular use or type of inputs and they cannot be utilized in other production process or for other input (Williamson 1979). In the process of ethanol production, asset fixity means that plants constructed for processing one type or class of biofeedstocks cannot process other types or classes of biofeedstocks. After investing in expensive ethanol production facility, fixed assets become immobile and inflexible in terms of a number of design elements like feedstock capabilities. That leads to a barrier to exit and a high cost of leaving a particular market. The barriers to exit lead to zero depreciation of assets because their economic value is equal to zero after their economic life ends. It is also assumed that these particular fixed assets cannot be sold in the market or transformed into any other valuable good at the end of their economic life.

The problem of asset fixity was the subject of many agricultural economics studies since the first half of the twentieth century (Galbraith and Black 1938; Johnson 1958; Edwards 1959). Because asset fixity poses a significant obstacle for the process of ongoing market-driven economic adjustment, also development economists referred to that concept (Schultz 1964; Robinson 1965; di Tella 1982; Ward 1993). That issue was further discussed by Ward and Hite (1999) who perceived asset fixity as a reason for lack of unilateral rural development across regions.

Altman et al. (2007) investigated the connection between the contract horizon and asset fixity for Iogen Company – a Canadian cellulosic ethanol producer. His main conclusion was that the longer the contract is, the more profitable production is due to the fact that Iogen's invented enzymes were feedstock specific and the switch between different biofeedstocks would be costly. Conley and George (2008) provide evidence that the U.S. corn moves along similar transportation pathways due to asset fixity – corn ethanol processing facilities stay in the same place for many years. Only recently some projects of converting ethanol plants into biobutanol plants have emerged e.g. Butamax, the venture between BP and DuPont companies, plans to invest in retrofitting currently existing ethanol plants into biobutanol production facilities (Drajem 2013).

Asset fixity issue may also affect form of the production function. One of the approaches when it happens is the putty-clay model which is often used for energy industry modeling (Hochman et al. 2010; Atkeson and Kehoe 1999; Fuss 1977; Fuss 1978; Berg 1984; Moffitt 1978). Another framework in which asset fixity plays important role is the irreversibility of investment[6]. Harchaoui and Lasserre (2001) tested the option value theory of irreversible investment and found evidence that the "putty clay" models of investment behave well in demonstrating capacity levels at Canadian copper mines. Many other researchers also investigated the irreversibility of investment in biofuels and bioenergy. Van Zon and Fuss (2005) noted that investment in facilities producing electricity is usually irreversible and later they applied their clay-clay – vintage portfolio approach to electricity generation under climate change policy in the UK (van Zon and Fuss 2006). Murto and Nese (2003) showed that when the investment

[6] Irreversible investment – can be perceived as a reasonable characteristic of most investments (Bernanke 1980). "Once a machine tool is made, for instance, it cannot be transformed into anything very unlike a machine tool without a loss of economic value that we can take to be prohibitive" described Bernanke (1980).

in the energy facilities is irreversible, it might be optimal to postpone the investment decision. They based their study on the theory of irreversible investment under uncertainty (Dixit and Pindyck 1994). While waiting longer with a decision on irreversible investment more information becomes available and gets collected before new capacity is built and huge up-front fixed investment cost incurred. In the later periods, once investment is made, capacity costs become sunk cost and the only remaining costs related to production capacity are variable cost of maintenance and variable costs of production.

The putty-clay modeling assumes that the form of production function depends on the age of the production unit. If the production unit exists and is in use, the applicable production function will adopt input use in fixed proportions. If the production unit is to be built, the respective production function will permit the substitutability between inputs. Therefore, the putty-clay models reflect fixedness of production assets. In these models, once the production facility is constructed and designed to accept certain structure of inputs, there is no way to change that input structure later. If the putty-clay models are used for energy industry modeling, they will clearly reflect that incentives today might have a huge impact on investments and future production processes and profitability of operation.

Leif Johansen (1959) was the first one who included putty-clay approach in his deterministic growth model. The features of this approach were also examined by Robert M. Solow (1962), David Cass and Joseph Stiglitz (1969). One application of putty-clay models for energy modeling can be found in Atkeson and Kehoe (1999) as they compare energy use price responsiveness for the U.S. economy in two models: the putty-putty Pindyck-Rotemberg model with adjustment costs and putty-clay model. Their conclusion is that the energy use of all entities generating Gross Domestic Product in the United States is elastic in cross-section data, but it is inelastic in time-series data which proves the existence of asset fixity and fixed input proportions (i.e. existing production facilities need specific amount of energy, regardless of its price changes).

As Hochman et al. (2010) indicates putty-clay modeling is frequently exploited to examine what effect environmental regulations have on various industries and moreover, it helps in examining the technological progress response to regulations. Bibas and Mejean (2012) examine the viability of bioelectricity production from biomass and they account for asset fixity by considering putty-clay modeling approach which introduces “inertia in the renewal of capital stock and technical systems”.

Conducting possible retrofits is a concept related to putty-putty and putty-clay models. In putty-clay models existing production units does not allow for flexibility of input structure. The necessary modernization and investments involved with them might be a natural part of the ethanol business operation. There are several researchers who investigated the retrofits of ethanol plants.

Singh and Eckhoff (1997) investigated retrofits of conventional dry-grind ethanol plant with the quick germ process which increases the co-product value in the dry-grind ethanol production process by recovering germ before fermentation. This idea is continued by Rodriguez et al. (2010) who extend the quick germ processing by a fiber component (transforming it into quick germ-quick fiber process). The authors claimed that this retrofit would decrease processing costs of corn ethanol by 13.5 ¢/gallon. Also, Plevin and Mueller (2008) discuss corn-ethanol plant retrofitting as a way of decreasing processing costs and reducing final product Global Warming Intensity (ethanol GWI). Cuzens and Miller (1997) suggested retrofitting sugar mills with acid hydrolysis which effectively allows for bagasse ethanol processing alongside with table sugar production. They claimed that their retrofitting strategy reduces heat and energy losses.

All referred studies emphasize the significance of asset fixity in industrial production processes and the role of retrofits in lowering processing costs.

4.3 Motivation

Asset fixity emerges when production facilities are designed and built for a particular use or type of inputs in a particular place and they cannot be utilized in other production process or for other input or at any other place (Williamson 1979). In the process of ethanol production, asset fixity means that plants constructed for processing one type of biofeedstocks cannot process other types of biofeedstocks nor can a plant in one place operate at another place.

Asset fixity also affects form of the production function. Before the plant is built it can be built of many different forms with a wide choice of feedstocks. Once it is constructed the applicable production function can only use select feedstocks.

Prior bioenergy studies on the feedstock structure of ethanol production exhibit feedstock mixes and processing locations that vary widely between years (see EPA, RFS analysis, the second chapter of this dissertation). That cannot be the case in reality. Once the production facility is constructed in one period of time, it will be utilized for the length of the economic life of that asset. Also the nature of the sunk fixed cost of production means the facility generally will not be abandoned unless extraordinary circumstances arise which justify exit from the market (e.g. unexpected regulatory or market price changes). This study adjusts FASOMGHG to reflect asset fixity. This is achieved by separating biofeedstocks processing into investment and operating components where the investment involves a fixed cost and yields ethanol production capacity that persists for a fixed number of years into the future. It is assumed that to change the class of feedstock processed in a given plant one would have to close and sell the currently existing plant (which is not likely due to heavy initial capital investment) and invest capital in another plant for a different class of feedstock or in another location.

4.3.1 Graphical analysis

Asset fixity concept affects biofeedstock use for bioenergy production both in terms of geographical location and type of feedstock used. Dynamic economic efficiency equates future and present uses of capital in the bioenergy industry by maximizing net present value of benefits derived from its use (Tietenberg and Lewis 2009). This determines the most economically efficient allocation of investment capital over time periods. Asset fixity impacts the pace of investment in new production capacity by favoring production in existing plants. This impact can be observed over time and simplified two-period graphical analysis of asset fixity concept is presented in this section. Pictorial representation of the asset fixity concept illustrates why market favors bioenergy produced in existing facilities and how demand growth stimulates new investments in production capacity.

Figure 21 presents visual graphical analysis of the asset fixity concept. The framework employs a two time period framework much has been used in analyses of depletable resources (see Tietenberg and Lewis 2009). In the first period, the ethanol is supplied to the market from a mixture of existing and new capacity. There the market entry price for a new plant is above the entry price for an existing plant due to the fixed costs associated with building new production capacity. In the second period, the existing capacity is enlarged by plants built in the first period (therefore the supply curve S_2 reflects more capacity to supply biofuels to the market from the existing plants). Through time more plants are constructed and move into the existing capacity category. The fixed capital costs of the preexisting capacity are sunk fixed costs, and the supply costs from those plants include only maintenance and variable costs. If the total ethanol price stays at the level p_1 or below, then there is no demand for ethanol from new capacity and there in no construction new plants. However, if the demand grows and shifts out to the right (from AD_1 to AD_2), the price of ethanol rises from p_1 to p_2, this then causes investment in new production capacity. In general the market favors ethanol from the existing plants (because its production costs are cheaper) and only if demand grows by significant amount there are enough future revenue incentives to invest into the new ethanol plant. While not shown here the existing plants create a fixity both regionally and in terms of feedstock use. The fixed capacity is fully dedicated to a specific region and also limits feedstock use to the class of feedstocks for which the refinery was initially constructed. The supply curve for new plants is also flatter to reflect the fact there is larger capability to expand production but constructing new facilities while the existing facilities have a steeper cost curve since they can only raise production by employing more expensive forms of operation within the bounds of their fixed capacity.

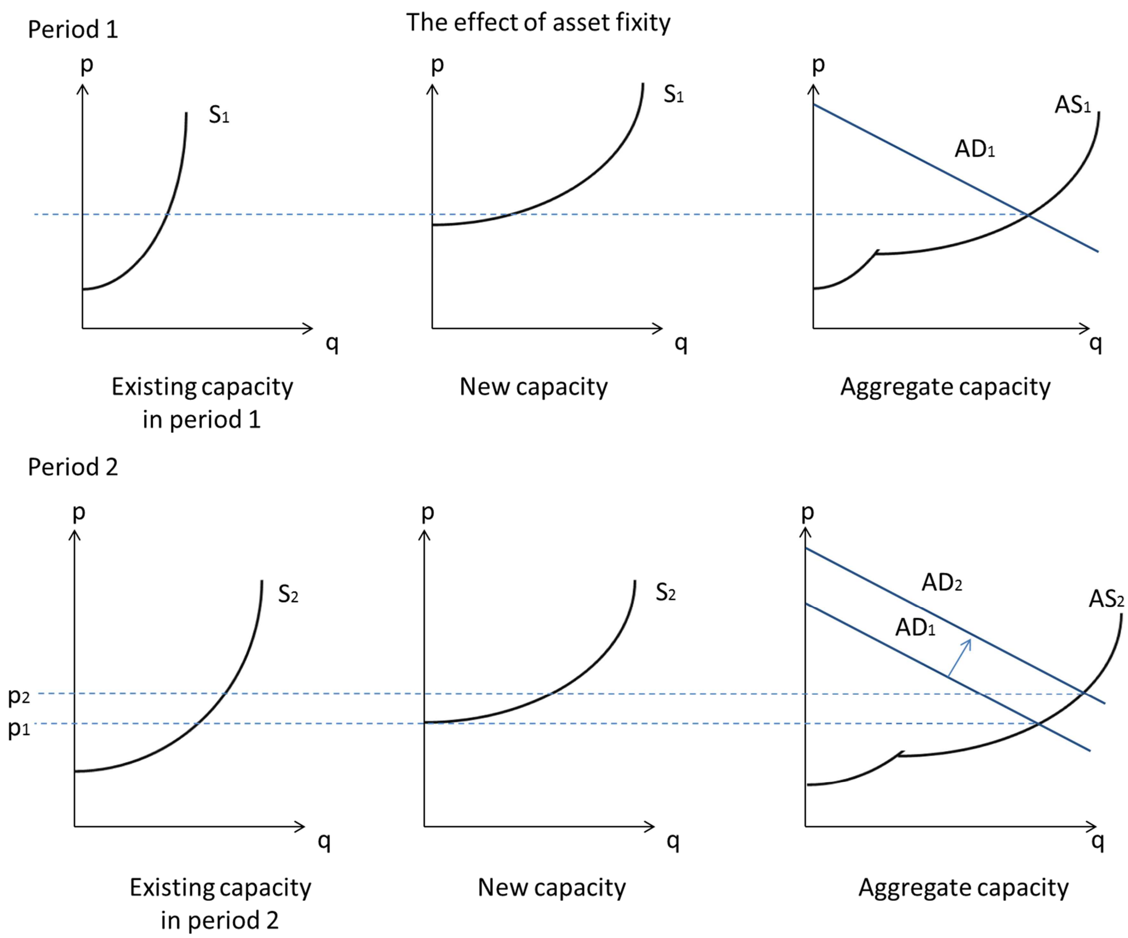

Figure 21. Visual representation of asset fixity concept depicted dynamically over two time periods.

4.4 Methodology

In this study, the agricultural module of the FASOMGHG model will be used. We will discuss the new variables and new constraints added to account for asset fixity.

Total production costs of bioethanol include five categories: feedstock costs, hauling costs, operating costs, capital costs and transportation and storage costs (Szulczyk et al. 2010).

The main idea of this study is based on separating fixed ethanol processing costs from the variable ethanol processing costs. The goal is the ability to reflect in the model the nature of fixed capital investments in production capacity and the persistence of that capacity plus its limited scope in terms of possible feedstocks. We also need to reflect the subsequent use of that capacity only if it has been constructed with attendant variable costs and feedstock usage from substitutable feedstocks. Then, Net Present Value (NPV) of the plant construction will be accounted for in the optimization process. By introducing the new investment and operating module, we will add to the model capacity accounting and capacity depreciation calculation. The results of capacity accounting will have impact on investment decisions made in the next periods. Making investment in the bioenergy industry is irreversible with large sunk fixed costs. Introducing asset fixity for the bioenergy facilities under the assumption that once built the asset cannot be used for other purposes is suggestive of a dynamic model with no salvage value[7] (i.e. lack of

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[7] Salvage value – the estimated value that an asset will realize upon its sale at the end of its useful life (adapted from “The Complete Real Estate Encyclopedia”).

retrofitting possibilities effectively assigns zero economic value to plants after their economic life ends).

The aim of the study will be achieved by introducing following constraints for each biofeedstock ingredient:

Amount of feedstock f_i in period t location l used to produce ethanol
≤ sum (Plant life, constructed capacity to produce ethanol produced from feedstock f_i at time t-plant life in location l)

for all i, l and t within the life of the plant.

Mathematically, it could be represented as:

$$P4_{ilt} < P3_{ilo} D_{ilt} + \sum_{tt}^{T} CAP_i Build_{ilt-tt} \qquad (3)$$

where

$P4_{ilt}$ - production use of feedstock i in location l in period t

$P3_{ilo}$ - initial production capacity of type i in region l

D_{ilt} - amount of the initial capacity of type i in region l that is usable by biofuel producer in period t

tt - how long ago capacity is constructed; where tt=0 means it is newly built; t =1 means it was built one period ago, t=T meaning it was built by biofuel producer the last period before its economic life expires

T - economic life of the facility

$Build_{ilt-tt}$– amount of production capacity of type i constructed in period t-tt in region l

CAP_i – the processing capacity in tons of feedstock i that can be refined when a refinery of type i is constructed

The added constraints as defined above require that to produce ethanol from a given ingredient, we need to have capacity in place which would allow to produce bioenergy from that chosen ingredient. This investment variable is named: "AGREGPROCESSCAPACITY" (meaning "AddBiofuelCapacity") in FASOMGHG with the capacity constraint named "AGPROCESSCAPACITY" (in the file model_structure.gms). For each asset fixity class there is one appropriate AGREGPROCESSCAPACITY variable.

These variables also have the fixed costs of the processing capacity in the objective function which is the cost of capital construction plus the annual fixed costs of plant utilization.

Introduction of asset fixity creates an up-front accounting of fixed cost associated with ethanol production. We take fixed cost per unit of production capacity and multiply it by the total capacity for each capacity class. The outcome is the fixed construction cost of the bioenergy plant per typical year in the five-year-period. Then, we multiply this fixed cost by the annuity factor[8] to put all fixed cost into the dollars of the first year of the five-year-period. At the end, we apply the discount rate to receive the net present

[8] Annuity factor – present value of $1 paid for each of t assumed periods; "mathematical figure showing the present value of an income stream that generates one dollar of income each period for a specified number of periods" (adapted from Barron's Business Dictionary).

value of fixed cost, providing it was all realized in the first year of the five-year-period. The net present value of the fixed cost can be expressed by the equation 4.

$$NPV\ of\ FC = \sum_{p=0}^{P} \frac{1}{(1+r)^{5p}} a_t * (cost\ per\ unit\ of\ capacity_i * capacity_i) \qquad (4)$$

where

a_t is the period specific annuity factor expressed by

$$a_t = \sum_{t=0}^{4} \frac{1}{(1+r)^t} \ for\ 0 \leq p \leq P-1$$

and

$$a_t = \frac{1}{r}\ for\ \ p = P$$

P – the period until which the projection of ethanol production is made and the model is run

p – identifier of the specific five-year time period

r – discount rate for period p at the assumed level of 4%

NPV of FC – net present value of capacity fixed cost

a_t – annuity factor specific for a given time period

By adding new terms to the objective function of the optimization problem, augmenting mathematical program with new constraints and applying up-front accounting of fixed costs associated with building ethanol production facilities, we reflect that to produce more bioethanol one has to build more bioethanol plants inherently associated with big fixed costs and fixed immobile capacity.

4.5 Study specific assumptions for asset fixity case

While implementing asset fixity structure into the FASOMGHG model, a number of assumptions were introduced. We categorize each feedstock used to produce a given bioenergy commodity (for crop ethanol, cellulosic ethanol, pyrolysis, biodiesel and bioelectricity production) into one of the asset fixity classes/categories following categorization presented in table 4. By doing this, asset fixity concept is introduced into both biofuels and bioelectricity generation.

Table 4. Asset fixity classes applied to the FASOMGHG model.

Bioenergy form	Capacity Class	Bioenergy Production Process
Crop Ethanol	DryMillEthanolCapacity	CornDryToEthanol, SorghumToEthanol
Crop Ethanol	WetMillEthanolCapacity	CornWetToEthanol
Crop Ethanol	SugarEthanolCapacity	SugarToEthanol
Crop Ethanol	SweetSorEthanolCapacity (SweetSor=Sweet Sorghum)	SweetSorghumTOEthanol
Crop Ethanol	WheatEthanolCapacity	SWWheatToEthanol HRWWheatToEthanol SRWWheatToEthanol DWheatToEthanol HRSWheatToEthanol

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
Crop Ethanol	OatsEthanolCapacity	OatsToEthanol
Crop Ethanol	RiceEthanolCapacity	RiceToEthanol
Crop Ethanol	BarleyEthanolCapacity	WinBarleyToEthanol SprBarleyToEthanol
Cellulosic Ethanol	SspulpCellEthanolCapacity (sspulp=sweet sorghum pulp)	SSpulpToEthanol
Cellulosic Ethanol	BagasseCellEthanolCapacity (CellEthanol = Cellulosic Ethanol)	BagasseToEthanol
Cellulosic Ethanol	ResidueCellEthanolCapacity	CornResToEthanol WheatResToEthanol SorghumResToEthanol BarleyResToEthanol OatsResToEthanol RiceResToEthanol
Cellulosic Ethanol	GrassCellEthanolCapacity	SwitchgrassToEthanol
Cellulosic Ethanol	WoodCellEthanolCapacity	HybridpoplarToEthanol WillowToEthanol

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
Bioelectricity	WoodElecCapacity	HybridpoplarToElec WillowToElec
Bioelectricity	WoodElecCofireCapacity	HybridpoplarToCofire5 HybridpoplarToCofire10 HybridpoplarToCofire15 HybridpoplarToCofire20 WillowToCofire5 WillowToCofire10 WillowToCofire15 WillowToCofire20
Bioelectricity	GrassElecCapacity	SwitchgrassToElec
Bioelectricity	GrassElecCofireCapacity	SwitchgrassToCofire5 SwitchgrassToCofire10 SwitchgrassToCofire15 SwitchgrassToCofire20

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
Bioelectricity	CropResidueElecCapacity	CornResToElec SorghumResToElec WheatResToElec BarleyResToElec OatsResToElec RiceResToElec
Bioelectricity	CropResidueElecCofireCapacity	CornResToCofire5 CornResToCofire10 CornResToCofire15 CornResToCofire20 SorghumResToCofire5 SorghumResToCofire10 SorghumResToCofire15 SorghumResToCofire20 WheatResToCofire5 WheatResToCofire10 WheatResToCofire15 WheatResToCofire20 BarleyResToCofire5 BarleyResToCofire10

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
		BarleyResToCofire15 BarleyResToCofire20 OatsResToCofire5 OatsResToCofire10 OatsResToCofire15 OatsResToCofire20 RiceResToCofire5 RiceResToCofire10 RiceResToCofire15 RiceResToCofire20
Bioelectricity	BagasseElecCapacity	BagasseToElec
Bioelectricity	BagasseElecCofireCapacity	BagasseToCofire5 BagasseToCofire10 BagasseToCofire15 BagasseToCofire20
Bioelectricity	SspulpElecCapacity	SSpulpToElec
Bioelectricity	SspulpElecCofireCapacity	SSpulpToCofire5 SSpulpToCofire10 SSpulpToCofire15 SSpulpToCofire20

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
Bioelectricity	LigninElecCapacity	LigninToElec LigninHWToElec LigninSWToElec
Bioelectricity	LigninElecCofireCapacity	LigninToCofire5 LigninToCofire10 LigninToCofire15 LigninToCofire20 LigninHWToCofire5 LigninHWToCofire10 LigninHWToCofire15 LigninHWToCofire20 LigninSWToCofire5 LigninSWToCofire10 LigninSWToCofire15 LigninSWToCofire20
Bioelectricity	ManureElecCapacity	ManureToElec BeefManureToElec DairyManureToElec
Bioelectricity	ManureCofireElecCapacity	ManureToCofire5 ManureToCofire10

Table 4. Continued.

Bioenergy form	Capacity Class	Bioenergy Production Process
		ManureToCofire15 ManureToCofire20 BeefManureToCofire5 BeefManureToCofire10 BeefManureToCofire15 BeefManureToCofire20 DairyManureToCofire5 DairyManureToCofire10 DairyManureToCofire15 DairyManureToCofire20
Biodiesel	BiodieselOilCapacity	SoyOilToBiodiesel CornOilToBiodiesel CornOilNFGToBiodiesel CanolaOilToBiodiesel
Biodiesel	BiodieselFatsCapacity	ETallowToBiodiesel NonETallowToBiodiesel LardToBiodiesel

Source: Author of the chapter.

Certain capacities of the bioenergy production facilities are assumed. For example, it is expected that an average sized crop ethanol plant will produce 75 million gallons of ethanol per year (with exceptions of sweet sorghum ethanol plant and barley ethanol plant which are assumed to produce 40 million gallons of ethanol per year). At the same time, the assumed capacity for cellulosic ethanol is 100 million gallons of ethanol per year. In terms of bioelectricity production, the assumed capacity of electrical energy plant utilizing feedstock is 7 TBTUS (equivalent to 2,051,497,490 kWh) per year. We assume that the capital costs associated with the facilities construction account for 35% of total NREL and EPA estimated production costs for both ethanol and bioelectricity.

All bioenergy plants are assumed to have a life span of 30 years. After this period of time the economic value assigned to the production capacity is assumed to be zero. This is a reasonable assumption given published sources and industry information. Wu et al. (2010) assumed 20-year-lifetime for the biomass-based ethanol plant in his study of woody biomass-based ethanol plants in Central Appalachia region. Most industry representatives and experts say that ethanol facilities should have between 30 and 60 years of "useful" and productive life expectancy (Nilles 2006). According to Jeff Lautt from Broin Management, the ethanol industry is reaching its 30-year milestone right now. For the purpose of this study, the low end of the 30-60 range is assumed, to maintain conservative estimation of future ethanol production prospects.

In this study, it is also assumed that substantial initial existing capacity for crop ethanol production is already in place. Ethanol existing capacity assumptions are based on data from Renewable Fuels Association (RFA) supplemented by data from states and company websites. The total capacity for 2002 is used for 2000 FASOMGHG model period, capacity added 2003-2007 is used for 2005 and so on. Capacity for 2015 FASOMGHG period is based on current RFA data on construction/planned expansions. Table 5 summarizes information on existing ethanol production facilities and their capacity used in this study. It presents how much ethanol capacity was built in particular years across different regions in the United States. This data input is disaggregated among ten regions which produce ethanol at the moment.

Table 5. Existing ethanol production capacity across the U.S. regions expressed in millions of gallons per year.

Type of ethanol production	Region in the USA	2000	2005	2010	2015
Dry Mill Ethanol	RM	21.5	197	51.5	0
	PSW	5	63	196.5	0
	SE	0	0.4	165	0
	CB	547	2095	3123	147
	GP	509.3	1810.5	1219	53
	SC	0	35.4	175.5	0
	SW	0	100	255	0
	LS	442.5	583	858	5
	NE	0	50	224	0

Table 5. Continued.

Type of ethanol production	Region in the USA	2000	2005	2010	2015
	PNWE	0	40	109	0
Wet Mill Ethanol	RM	0	0	0	0
	PSW	0	0	0	0
	SE	0	0	0	0
	CB	915	110	205	0
	GP	165	0	330	0
	SC	68	0	37	0
	SW	0	0	0	0
	LS	42.6	0	0	0
	NE	0	0	0	0
	PNWE	0	0	0	0

Source: Author of the chapter (based on data from Renewable Fuels Association and other private sector sources).

4.6 Scenario design

In this study, we will compare the effects of asset fixity consideration to the effects of not using asset fixity under the same scenario setup as the one used in the first chapter. We will analyze all of those scenarios before and after introduction of asset fixity modeling to see how it changes the ethanol production outputs. We take four scenarios following the design presented in table 6 and we analyze them before and after asset fixity is applied in the model by comparing the results.

Table 6. Scenario design used in the study.

	Mandates hold	Mandates do not hold
Penetration barriers are in place	Mandates hold + Penetration barriers are in place	Mandates do not hold + Penetration barriers are in place
Penetration barriers are removed	Mandates hold + Penetration barriers are removed	Mandates hold + Penetration barriers are removed

All the scenarios results are analyzed at the national level and also for three chosen regions: Corn Belt, South Central and Southeast. Results for other regions can be made available by the author upon request.

By making comparison of ethanol production outputs before and after asset fixity application, we will be able to determine what effect asset fixity has on the ethanol production, both in terms of its feedstock breakdown and geographical location. We will also verify if augmenting currently existing model with asset fixity maintains continuity of ethanol production over time periods and reflects the irreversibility of capital investment in the bioenergy production.

4.7 Results

4.7.1 Ethanol and biodiesel production prospects – the case with market penetration barriers for ethanol

In this section, we compare the results of the study presented in the first essay of this dissertation with and without the asset fixity concept applied. This way we are able to assess how asset fixity idea impacts final model results which in this case are future projections of ethanol and biodiesel production in the United States.

Figure 22 depicts a comparison of results for the scenario with ethanol mandates and market penetration barriers in place with and without asset fixity applied. One could easily notice that the presence of mandates forces in required amount of ethanol and the introduction of asset fixity concept does not change the results between two scenarios much. The major change is observed for cellulosic ethanol production starting in 2015. After introduction of asset fixity its amount decreases from 6.5 BGY to 3.2 BGY. It can be concluded that the satisfaction of biofuel mandates under asset fixity occurs, but at the very high cost. For example, under the presence of asset fixity, the total economic welfare decreases by 40 billion of constant 2004 dollars in 2015 or by 83 billion of constant 2004 dollars in 2030. That decrease is estimated cost of mandates satisfaction.

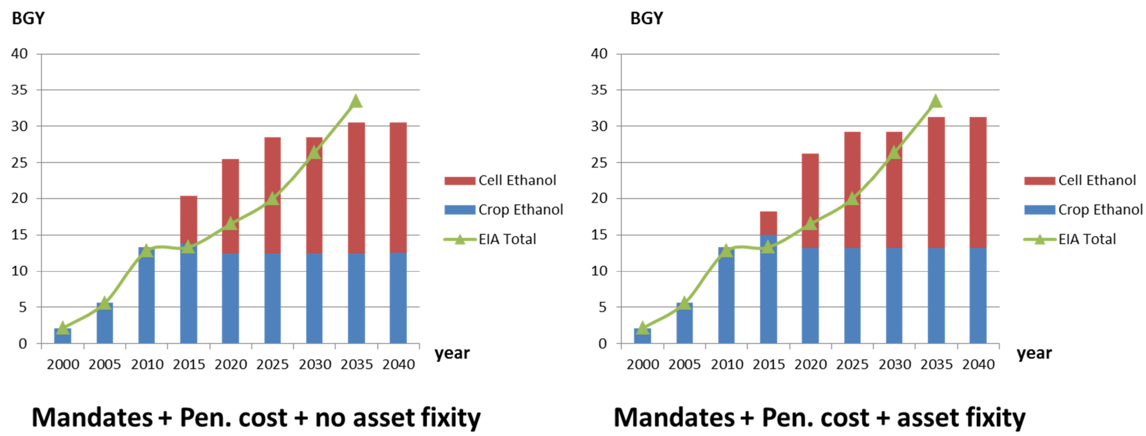

Figure 22. Amount of ethanol produced with mandates and penetration costs in place – comparison between scenarios before and after asset fixity concept application.

The removal of ethanol mandates allows for clear distinction between scenarios with various asset fixity (AF) arrangements. When one compares amounts of ethanol produced before and after asset fixity introduction, it is visible that under asset fixity conditions the amount of cellulosic ethanol produced does not exceed 10 million gallons per year in all considered time periods (figure 23). That is a strong indication of the fact that asset fixity concept and related accounting of capacity capital costs create circumstances unfavorable for investment into large volume cellulosic ethanol production facilities. Under scenario with AF almost no cellulosic ethanol is produced and only crop ethanol is produced at the level 15 billion gallons per year.

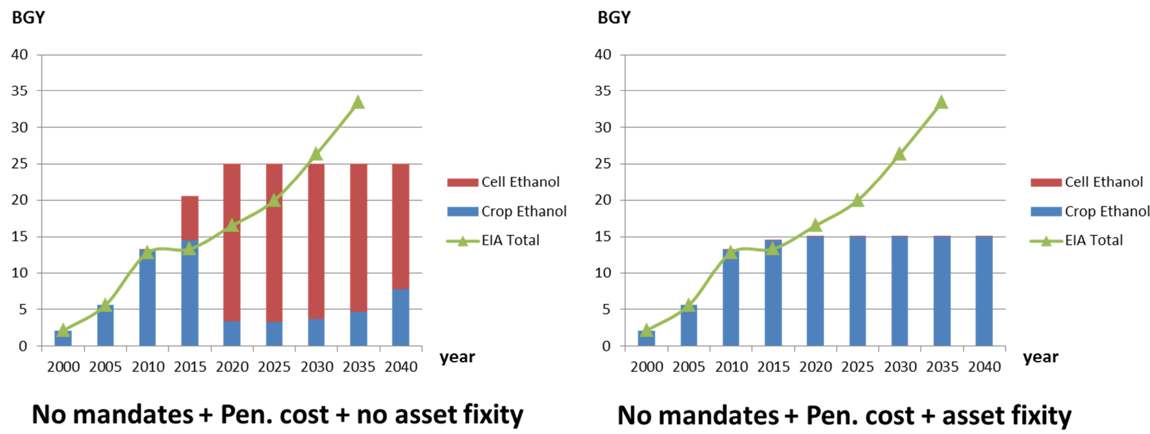

Figure 23. Amount of ethanol produced with penetration costs in place and no mandates – comparison between scenarios before and after asset fixity concept application.

At the same time, we examine how various market and asset fixity arrangements impact amount of biodiesel produced in the US economy. Figure 24 presents total biodiesel production when the penetration barriers for ethanol hold.

The introduction of asset fixity (AF) causes the amount of biodiesel produced to be in the range determined by two other scenarios without asset fixity, i.e. amount of biodiesel produced under scenarios with asset fixity (NM_AF or M_AF) is lower than amount of biodiesel produced under M_NAF scenario and greater than amount of biodiesel produced under NM_NAF scenario. On average, asset fixity does not change the amount of biodiesel produced by more than 0.5 billion gallons per year across all scenarios.

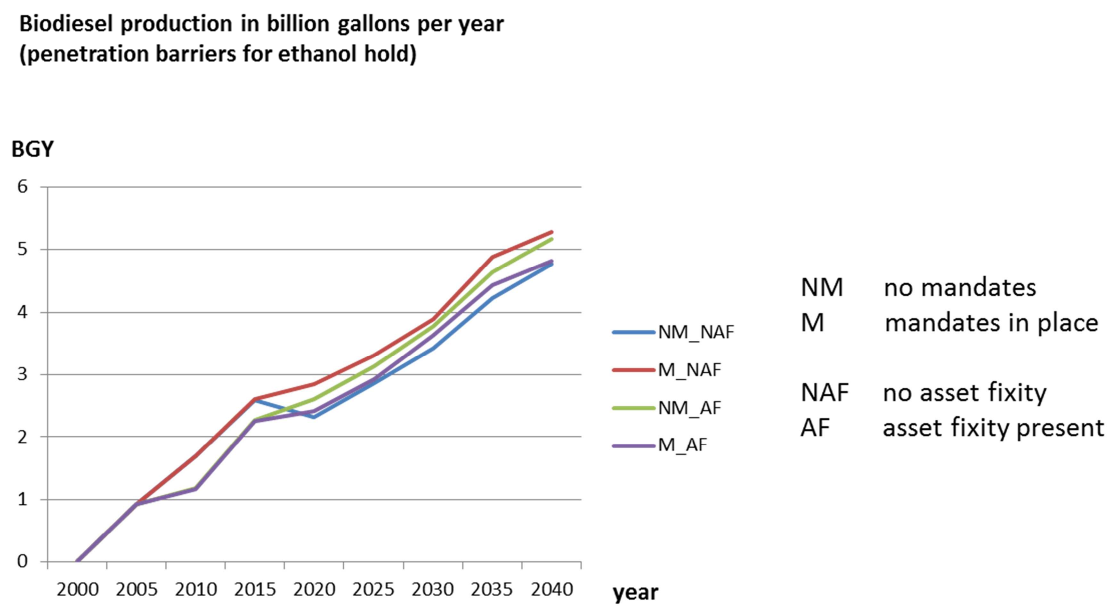

Figure 24. Biodiesel production in the United States expressed in BGY. Projection for four different market scenarios.

The feedstock structure for biodiesel production changes after asset fixity is introduced (figure 25). These changes are especially visible for the case without mandates in place. The majority of biodiesel is produced from soybean oil under all scenarios. That is justified by the fact that soybean oil is the prevailing current feedstock used for U.S. biodiesel production. Non-food grade corn oil (CornOilNFG – a byproduct of corn dry milling with oil separation) is the second largest feedstock used in biodiesel production. Under the scenario with no asset fixity, one can see that biodiesel from corn oil is produced at the level of 0.7 BGY and 0.8 BGY in 2010 and 2015 respectively and then, it goes down to 0.1 BGY in the years 2020-2035. That would effectively mean future capital disinvestment in the biodiesel industry and it does not reflect irreversibility of capital investment. After asset fixity is introduced, the amount of biodiesel produced from corn oil grows steadily from 0.3 BGY in 2005, through 0.7 BGY in 2010 and it stays at the level of 0.85 BGY between 2015 and 2040. This reflects appropriate accounting for asset fixity of biodiesel producing capacity and it shows that asset fixity application prevents sudden regional or feedstock discontinuity in the biodiesel production. One can conclude that whereas total amount of biodiesel does not change significantly after asset fixity concept is introduced, the feedstock structure does change visibly and reflects expected result. The amount of biodiesel produced from non-food grade corn oil remains at a similar level across time. At the same time, the amount of soybean biodiesel is growing continuously, largely due to the cap on corn ethanol.

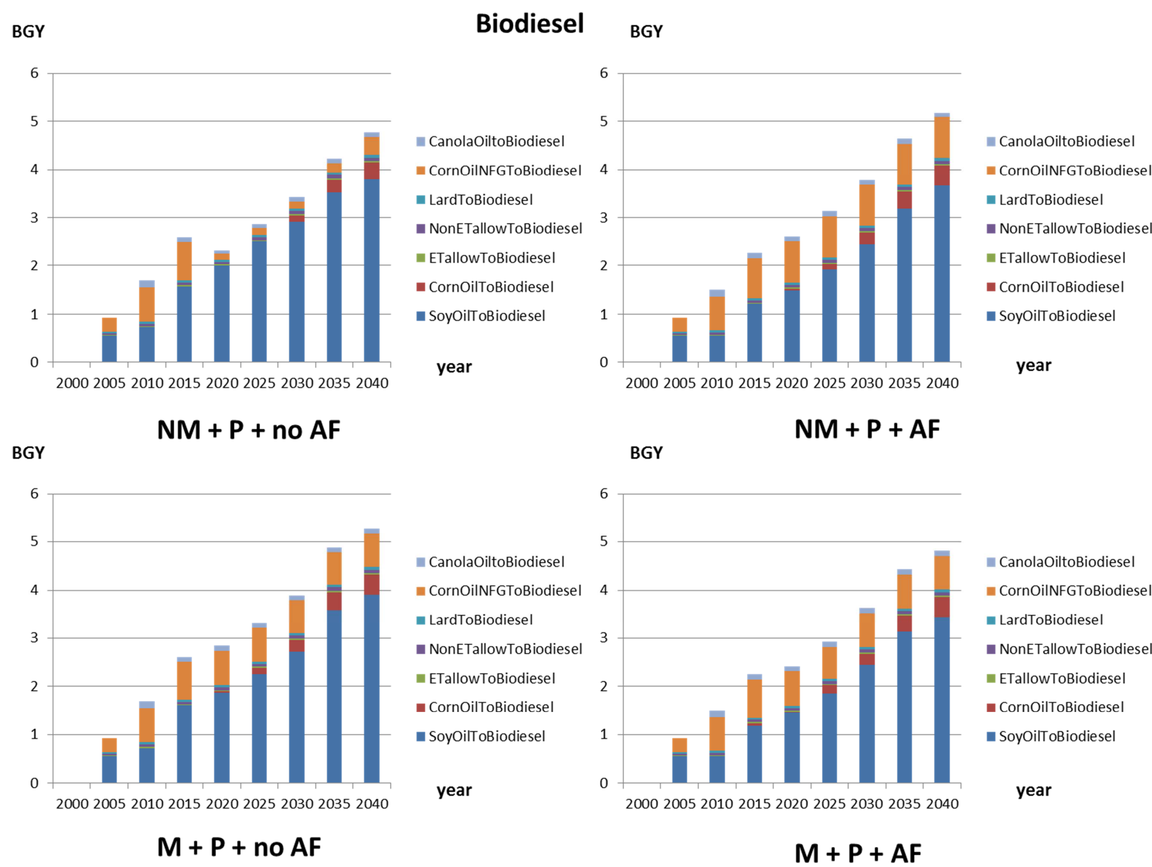

Figure 25. Feedstock structure of biodiesel production in the United States expressed in BGY. Projection for four different market scenarios. Comparison before and after introduction of asset fixity.

4.7.2 Ethanol and biodiesel production prospects – the case without market penetration barriers for ethanol

In this section, we repeat the analysis from the previous section but without presence of market penetration barriers for ethanol. This analysis could also serve as a case study on drop-in fuel blends, i.e. all fuels which do not require adjustments in currently existing infrastructure to increase their market presence[9] - they are ready to be "dropped-in" to existing infrastructure. Again, we compare the results of the study presented in the first essay of this dissertation with and without asset fixity concept applied, under conditions of no market penetration costs for ethanol. This way we are able to assess how asset fixity idea impacts final model results which, in this case, are future projections of ethanol and biodiesel production in the United States.

Figure 26 depicts comparison of results for the scenario with ethanol mandates and no market penetration barriers in place for two cases: before and after asset fixity (AF) is applied. When no market penetration costs are present, the total amounts of ethanol produced are higher across time periods. Although the presence of mandates forces in required amount of crop ethanol, this time the introduction of asset fixity concept changes the results between two scenarios (which did not happen under the situation when the market penetration barriers were present). Before application of asset fixity, the amount of cellulosic ethanol produced equals 11 BGY in 2015, 22 BGY in 2020, 24 BGY in 2025 and 2030 and 26-27 BGY in 2035 and 2040.

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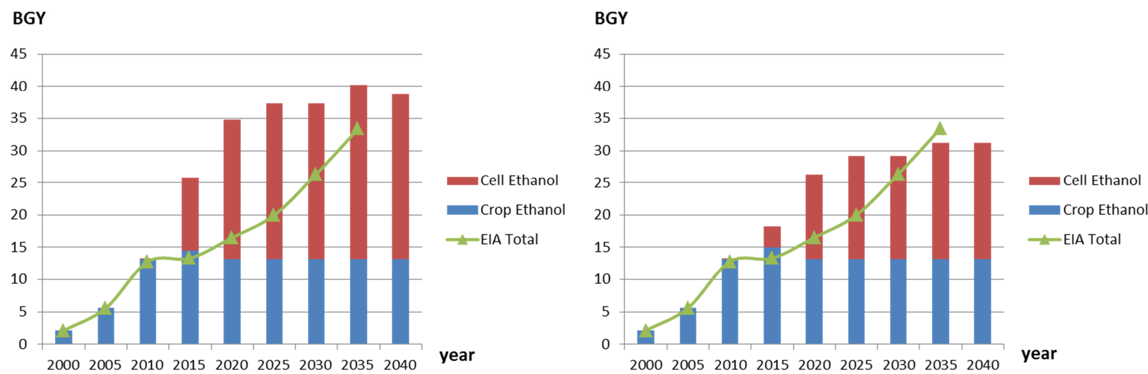
[9] So far biochemists develop several types of fuels which could be considered "drop-in" fuels. These are, for example, methanol and butanol. Several other drop-in technological pathways include: pyrolysis or liquefaction of biomass to bio-oil, hydrotreating algal oils, upgrading of syngas (CO and H2) from gasification, fermentation of sugars to hydrocarbons, catalytic conversion of sugars to hydrocarbons, upgrading alcohols to hydrocarbons (Alternative Fuels Data Center, The U.S. Department of Energy, 2013).



Mandates + No pen. cost + no asset fixity **Mandates + No pen. cost + asset fixity**

Figure 26. Amount of ethanol produced with mandates and no penetration costs in place – comparison between scenarios before and after asset fixity concept application.

However, after the application of asset fixity concept and accounting for the capita cost in the production budgets, the amount of cellulosic ethanol produced goes down to 3 BGY in 2015, 13 BGY in 2020, 16 BGY in 2025 and 2030 and 18 BGY in 2035 and 2040 (on the assumption that mandates hold). Table 7 summarizes quantities of crop and cellulosic ethanol produced before and after asset fixity got applied to the production budgets.

Table 7. Cellulosic ethanol production quantities before and after application of asset fixity with mandates in place. All quantities expressed in BGY (billion gallons per year).

Asset fixity	Crop or cell.	2015	2020	2025	2030	2035	2040
Before	Crop.	14.49	13.24	13.24	13.24	13.24	13.24
	Cell.	11.29	21.62	24.11	24.11	26.94	25.51
After	Crop.	15.02	13.24	13.24	13.24	13.24	13.24
	Cell.	3.22	12.99	15.98	15.98	17.98	17.98

Next, the impact of asset fixity on amount of ethanol produced is examined under no mandates conditions. Figure 27 juxtaposes the relevant projections. Under no mandates, no penetration costs and no asset fixity circumstances the amount of cellulosic ethanol produced is still high and it substitutes the production of crop ethanol (in years 2020-2035 the amount of crop ethanol produced goes down below 10 BGY and it is substituted by high volumes of cellulosic ethanol whose processing costs become cheaper than processing costs of crop ethanol due to assumed technological progress). After the application of asset fixity concept, inclusion of capital costs associated with retrofits and facilities adjustments causes the amount of cellulosic ethanol produced to go down to minimal amounts. Almost all the ethanol is produced in crop ethanol processing facilities, mainly due to the presence of previously developed dry milling and wet milling corn ethanol plants. Table 8 summarizes the quantities of cellulosic and corn ethanol to be produced before and after application of asset fixity and accounting of capital costs. One should note that high volumes of cellulosic ethanol production are only possible if the technological progress in the area of cellulosic ethanol processing is going to follow the path estimated by NREL and presented in figure 6 of this dissertation.

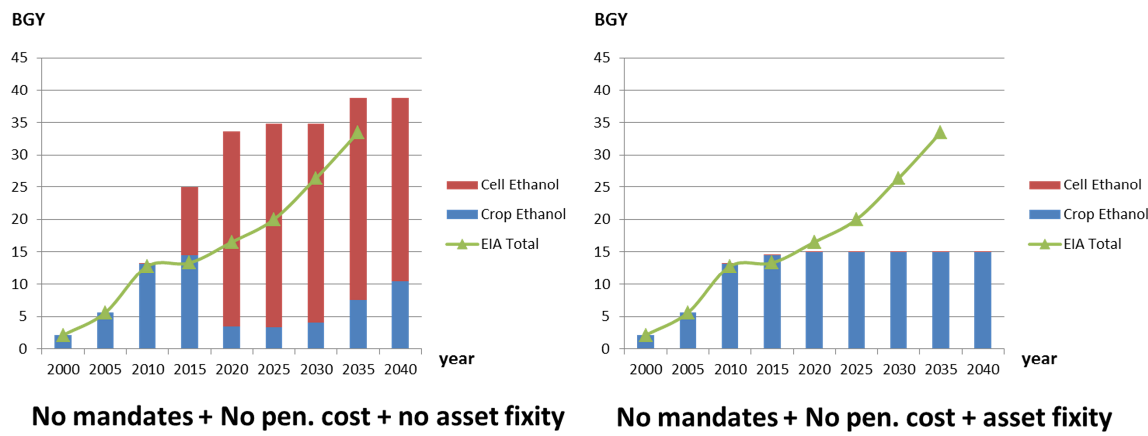


Figure 27. Amount of ethanol produced with no penetration costs in place and no mandates – comparison between scenarios before and after application of asset fixity concept.

Table 8. Cellulosic ethanol production quantities before and after application of asset fixity under no mandates scenario. All quantities expressed in BGY (billion gallons per year).

Asset fixity	Crop or cell.	2015	2020	2025	2030	2035	2040
Before	Crop.	14.49	3.41	3.31	4.10	7.60	10.47
	Cell.	10.53	30.21	31.54	30.76	31.14	28.29
After	Crop.	14.49	15.02	15.02	15.02	15.02	15.02
	Cell.	0.008	0.008	0.008	0.008	0.008	0.008

Under the case of no market penetration costs in place we again observe how various market and asset fixity arrangements impact amount of biodiesel produced in the US economy. Figure 28 presents total biodiesel production in terms of billion gallons per year around different regions of the United States when there are no market penetration barriers for ethanol in place. Asset fixity does not greatly impact the total amount of biodiesel produced with across all scenarios the asset fixity introduction not changing the amount of biodiesel produced by more than 0.5 BGY.

Visible changes in the feedstock mix happen, especially under a situation with no mandates in place (figure 29). Before asset fixity is introduced, the amount of biodiesel produced from non-food grade corn oil decreases from the level of 0.8 BGY in 2015 to 0.1 BGY in the years 2020-2035. After introduction of asset fixity, this production level constantly grows over the years 2005- 2015 and it reaches the level of 0.9 BGY in 2020.

Later, after 2020 it stays at the level of 0.9 BGY until 2040. That reflects the irreversibility of capital investment in the biodiesel production. Still, the predominant feedstock used in the biodiesel production is soybean oil and it accounts for 60 – 75 % of total biodiesel produced in the market.

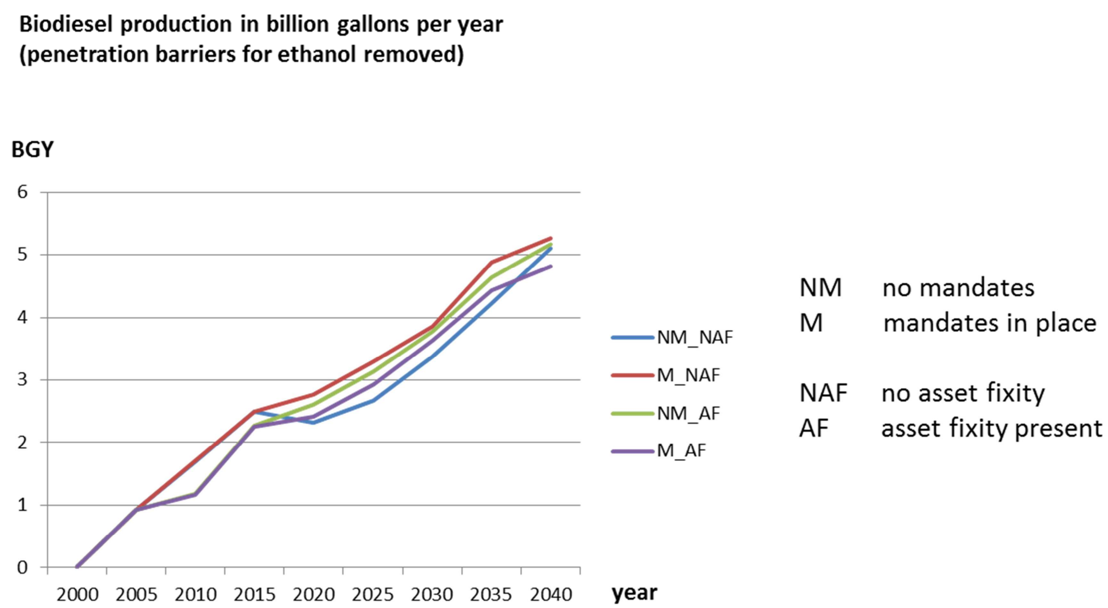


Figure 28. Biodiesel production in the United States expressed in BGY. Projection for four different market scenarios under no market penetration barriers for ethanol in place.

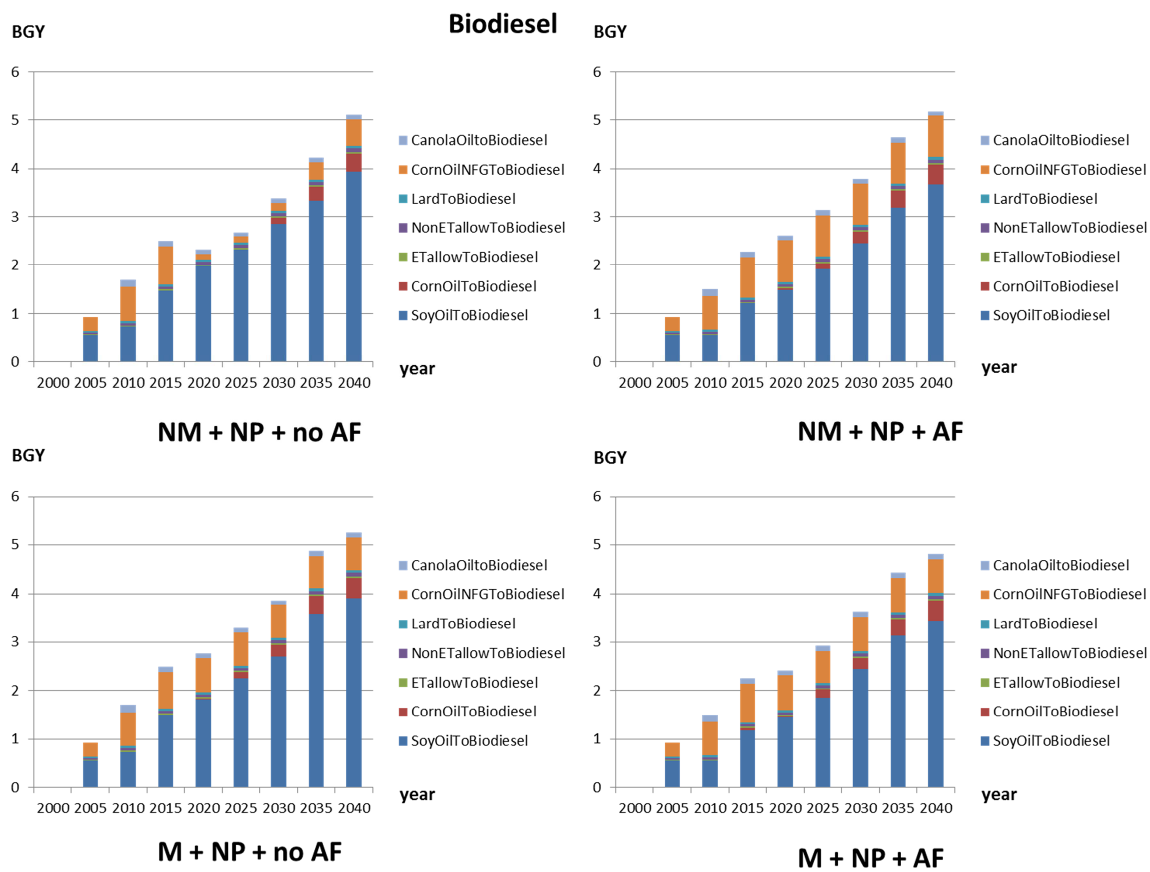


Figure 29. Feedstock structure of biodiesel production in the United States expressed in BGY. Projection for four different market scenarios under no market penetration barriers for ethanol. Comparison before and after introduction of asset fixity.

4.7.3 Feedstock structure of bioethanol produced under asset fixity

It is interesting to look at the structure of ethanol produced in terms of biofeedstock used in the processing process. Scenario with no mandates, no penetration costs and asset fixity holding is chosen for the presentation in this dissertation, however, on request, author can make the structure break down for other scenarios available. Figure 30 presents the break down in terms of biofeedstock ingredients used for the ethanol production. Corn is the dominating crop and constitutes 97%-98% of total ethanol production. Other crop feedstocks contribute around 2 % and bagasse less than 0.06%.

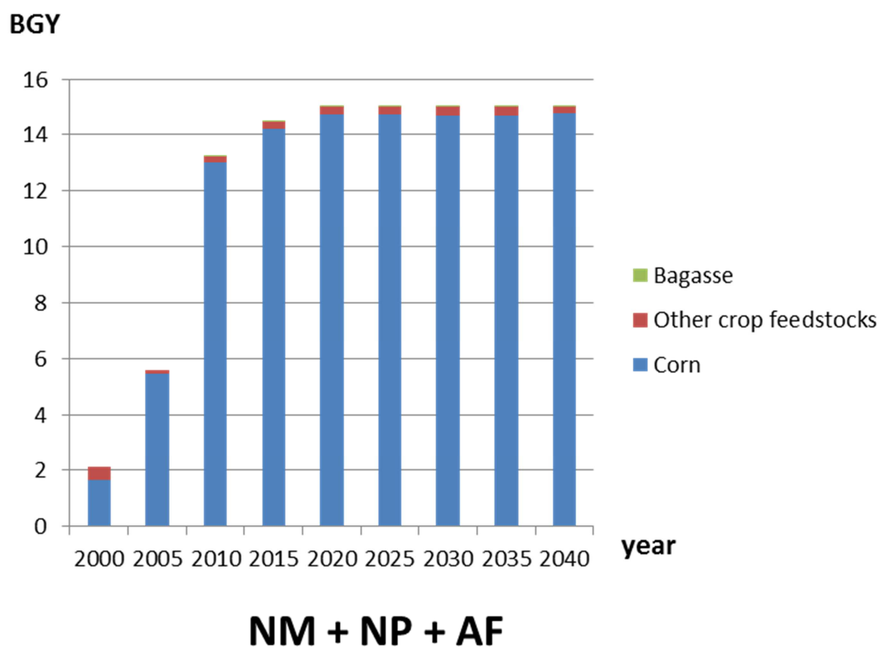


Figure 30. Ethanol produced under scenario with no mandates, no penetration costs and asset fixity holding - feedstock structure break down.

When we consider scenarios with no mandates and no penetration costs in place before and after asset fixity is introduced (figure 31), it can be observed that asset fixity causes corn ethanol to stay at the similar level across all years (15 BGY) and it nearly eliminates market driven cellulosic ethanol production (only bagasse ethanol gets produced in small amount of 9 million gallons per year). Without asset fixity in place, the amount of corn ethanol produced decreases significantly between 2020 and 2040 and gets substituted by cellulosic ethanol from various feedstocks.

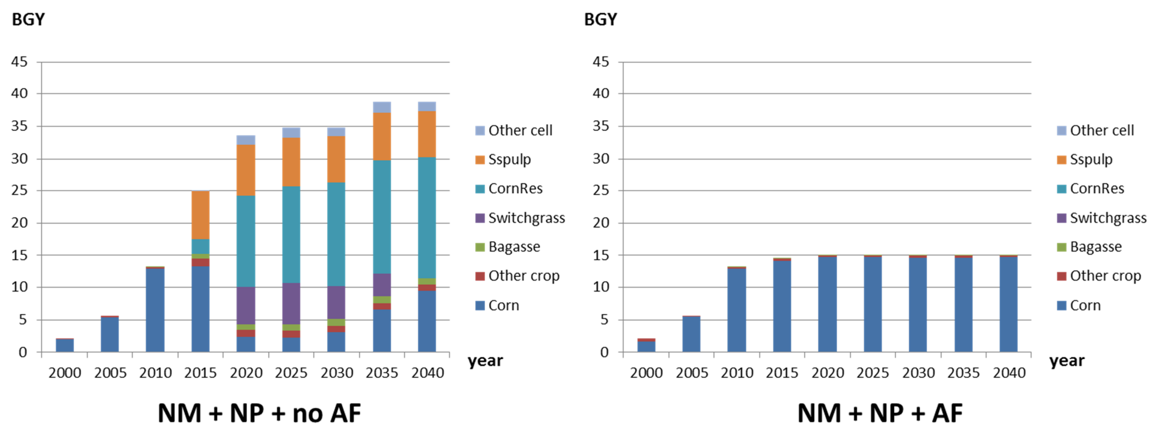


Figure 31. Feedstock structure of ethanol produced under scenario with no penetration costs and no mandates – comparison between scenarios before and after application of asset fixity concept.

We also investigate how asset fixity impacts feedstock structure of ethanol produced under a situation with mandates in place (figure 32). When mandates hold, the amount of corn ethanol is not affected by asset fixity introduction. It is still produced at the mandated level. Regarding cellulosic ethanol, asset fixity lowers the amount of cellulosic ethanol by half. For example, the amount of ethanol from corn residues produced in 2030 is equal to 14 BGY under no asset fixity conditions. After asset fixity is introduced this amount goes down to 7.65 BGY. The same situation happens for ethanol produced from sweet sorghum pulp – before asset fixity it amounts to 7.7 BGY and after asset fixity it is equal to 4.7 BGY. This case shows that asset fixity affects negatively amount of cellulosic ethanol produced, mainly due to necessary irreversible capital investment related to cellulosic ethanol production accounted in an up-front manner.

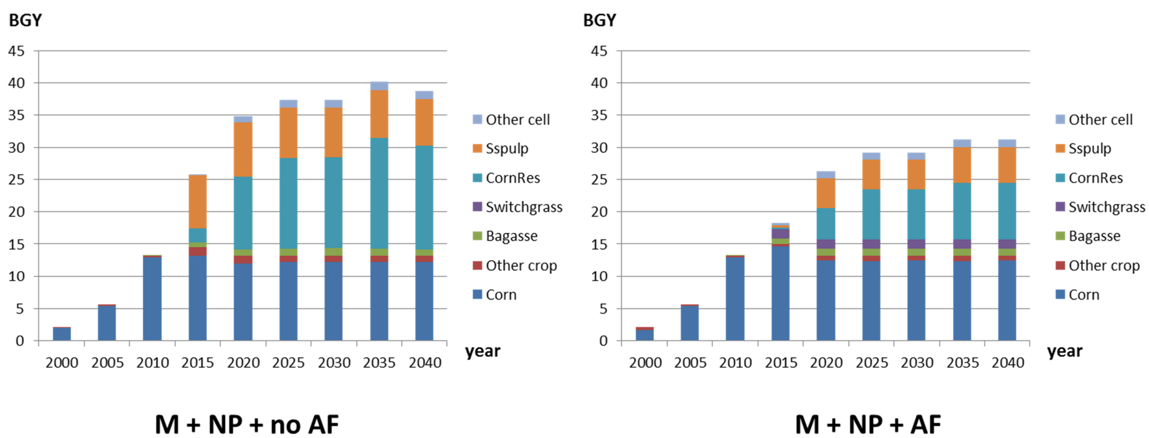


Figure 32. Feedstock structure of ethanol produced under scenario with no penetration costs and with mandates in place – comparison between scenarios before and after application of asset fixity concept.

Asset fixity also changes the feedstock structure of ethanol at the regional level. Feedstock structure of ethanol produced in the Corn Belt, South Central and Southeast regions is analyzed and compared before and after asset fixity introduction (figure 33, 34 and 35). All scenarios presented assume no mandates hold. In the Corn Belt region (figure 33) it can be noted that the asset fixity completely eliminates cellulosic ethanol production which is substituted by the corn ethanol production (mostly via a corn dry milling production process). In the South Central area, exactly the same situation happens (figure 34). In the Southeast region (figure 35) introduction of asset fixity reduces ethanol production greatly and leaves only some corn dry milling operations and bagasse operations at low levels (6 million gallons per year).

After asset fixity introduction the total amount of ethanol produced decreases by around half (Corn Belt) or more than half (South Central and Southeast). Moreover, we do not observe discontinuity of ethanol production in terms of feedstock type and location. Once the production of the certain type of ethanol starts in a chosen region, it stays there for next time periods and it does not suddenly disappear later. This reflects irreversibility of capital investment in the bioenergy production and it complies with the initial intent of introducing the asset fixity concept into this study.

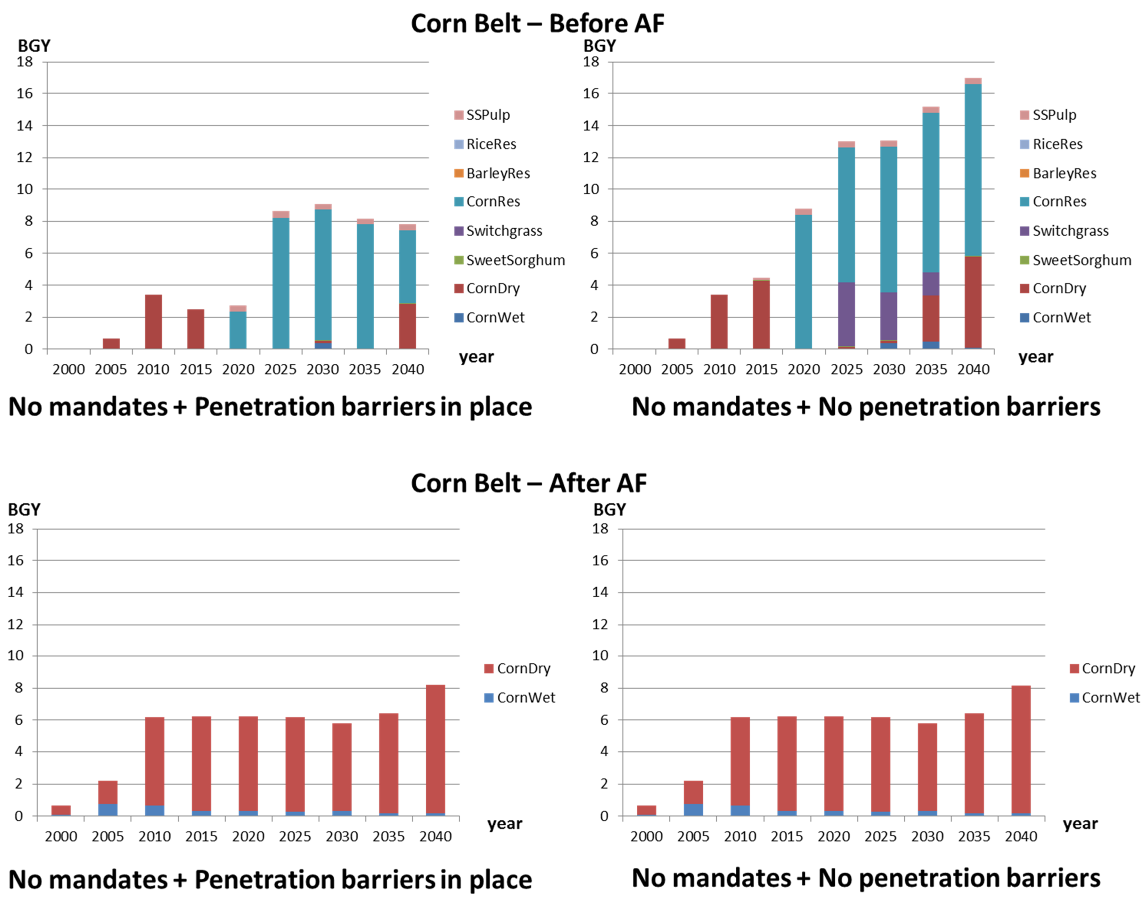


Figure 33. Feedstock structure of ethanol produced in the Corn Belt region under two scenarios – comparison before and after application of asset fixity concept.

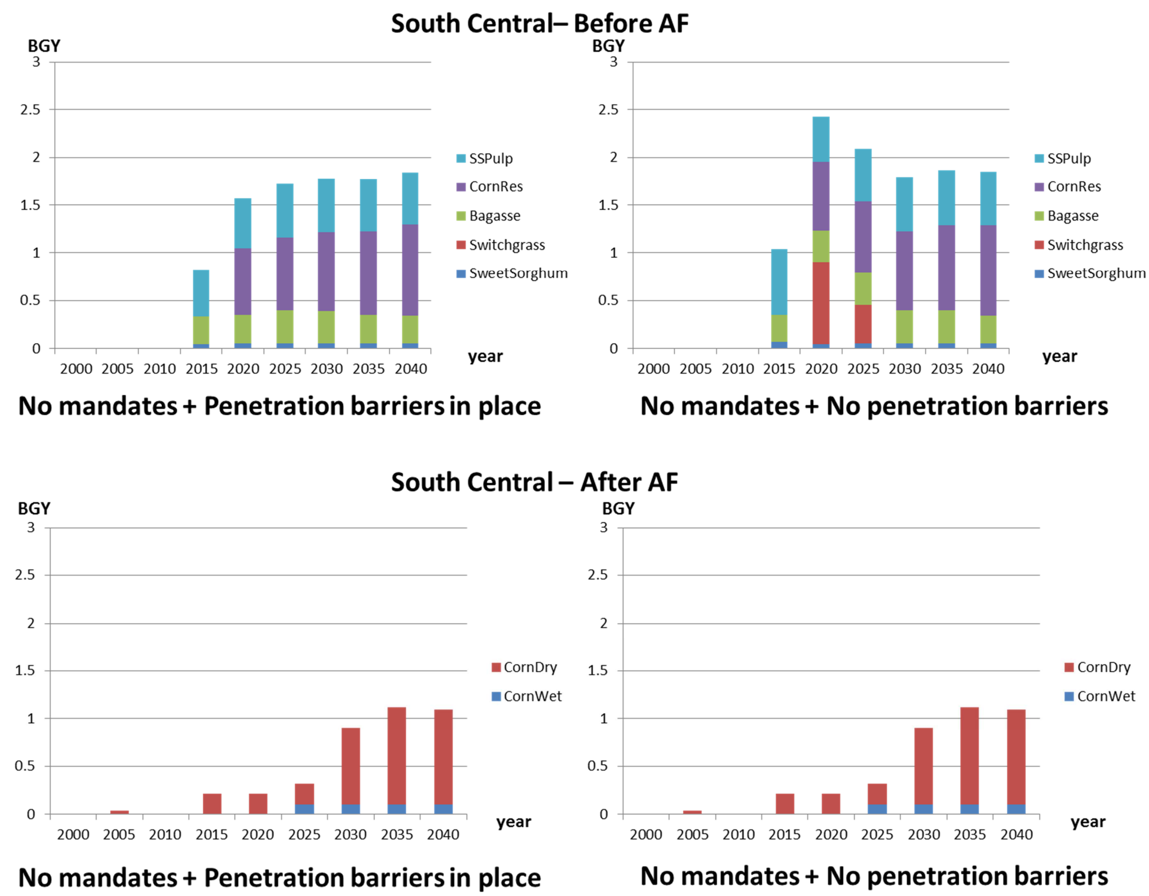


Figure 34. Feedstock structure of ethanol produced in the South Central region under two scenarios – comparison before and after application of asset fixity concept.

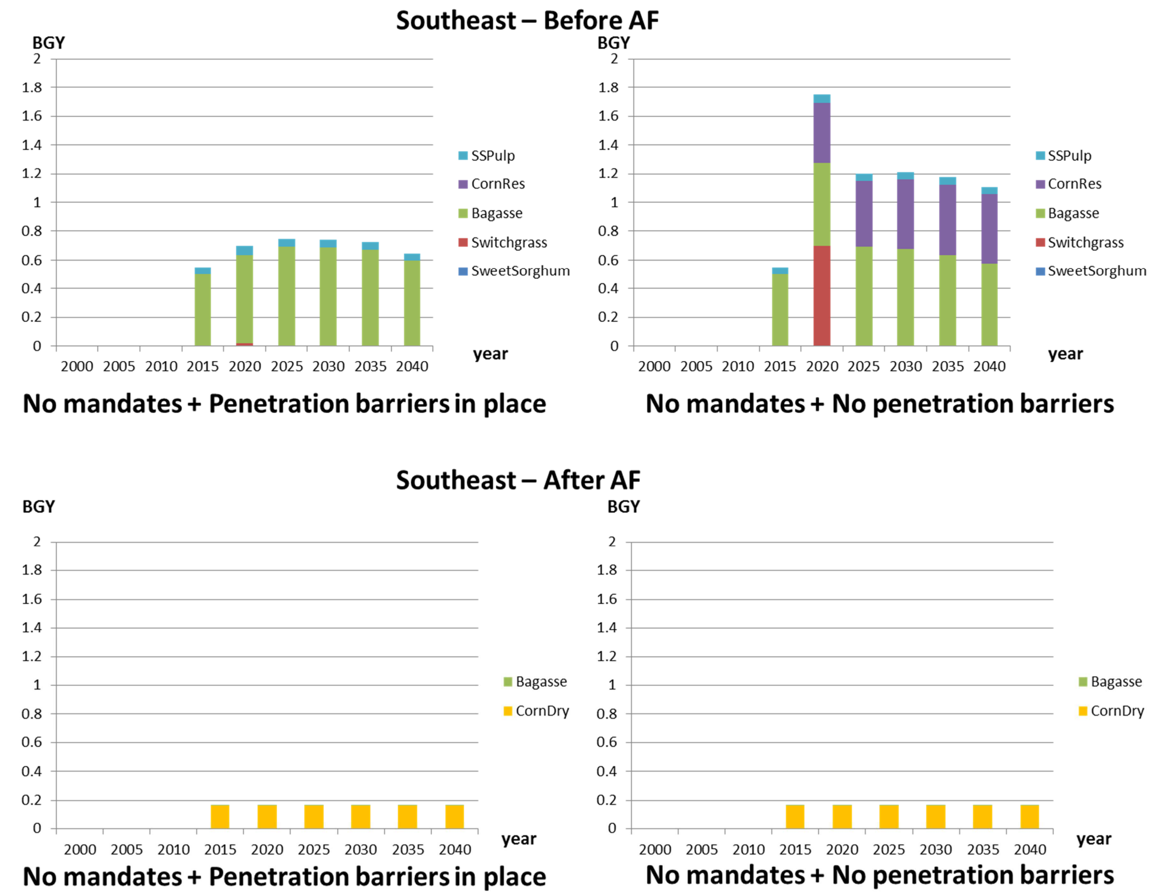


Figure 35. Feedstock structure of ethanol produced in the Southeast region under two scenarios – comparison before and after application of asset fixity concept.

The introduction of asset fixity prevents discontinuities in the production of biofuels, in terms of feedstock used and geographical location of the production process. It reflects the asset fixity using capacity which once built is dedicated to a class of feedstocks and to specific regions. Accounting for fixed assets cost, irreversibility of investment in them and frontloading of capacity costs, all contribute to higher total costs of biofuel production. Total costs of production for the new capacity are much higher than for the existing capacity. As a result, biofuel production in existing capacity is favored over production in the new capacity which still needs to be constructed with substantial upfront capital costs. If one assumes that the technological progress or breakthrough in bioethanol or biodiesel industry will happen some day and the biofuel processing costs will decrease significantly, then marginal costs and variable costs of biofuel production in the newer capacity will be lowered. This is partially reflected in the figure 21 where the supply curve for the new production capacity is flatter than supply curve for the old existing capacity. Innovation transfer and learning might contribute to future marginal cost decreases. Then, the +ethanol (or biofuel) demand growth will provide incentives for decisions makers to undertake production capacity asset investment and with some portion of ethanol supplied from newly constructed capacity.

4.8 Conclusions

This study shows us that incorporating asset fixity features in the model increases the cost of bioenergy production and limits the potential production volumes in non-mandate situations. Introduction of asset fixity almost completely eliminates market driven cellulosic ethanol production, leaving only negligible quantities of bagasse ethanol in the market. Cellulosic ethanol is produced in insignificant amounts because we accounted up-front for investment capital costs associated with plant building in the first period of operation and we raised the cost of biofeedstock by forcing the model to use the same feedstock from the same region (i.e. feedstock growing in the proximity to the plant and compatible with the capacity type of the built plant). As the results indicate, both processing and capital costs of cellulosic biofuel production need to be substantially reduced so as cellulosic biofuel production become economically viable.

Processing costs need to drop by at least 65% from the current level (as it was found in the first chapter of the dissertation) and capital costs need to decrease as well. Governmental subsidies might be needed to start industrial scale cellulosic biofuel production process.

Asset fixity also impacts biodiesel generation. Future projections of biodiesel production do not change by more than 0.5 BGY after asset fixity gets applied for all considered scenarios. However, the feedstock structure of biodiesel changes significantly after asset fixity is introduced and it reflects irreversibility of investment in the biofuel industry. Asset fixity concept prevents future capital disinvestment in the biodiesel industry.

In terms of share of bioethanol in the total amount of fuels consumed, ethanol produced under asset fixity conditions would satisfy around 10% of total national fuel demand and 20% of total national fuel demand when no asset fixity is applied. When it comes to biodiesel production, under asset fixity scenarios biodiesel constitutes no more than 1.6%-2% of total national fuel consumption (as of 2013) and under no asset fixity conditions, this share still does not exceed 2% of total amount of fuels consumed in the USA.

For the purpose of policy making, the conservative projections with asset fixity in place seem to be more appropriate. They represent the irreversibility of capital investment decisions and operation processes in the bioenergy industry more closely.

This study provides rationale for future use of asset fixity concept in modeling of bioenergy production processes. Results of this study display that asset fixity has significant impact on future projections of bioenergy production.

5. CONCLUSIONS

Growing energy consumption, growing population, reliance on fossil fuels and record breaking emissions of greenhouse gases pose threats to many countries in the work including the US. To avoid this many countries are trying to increase the market share of renewables and in the US this results in the U.S. Energy Independence and Security Act. However renewable fuel production has not gone forward as contemplated with significantly less cellulose based fuels. This dissertation conducted analysis of three aspects of liquid biofuel production in the United States. These particular issues are analyzed:

- Future prospects of cellulosic biofuel production and the impact of technological progress and market penetration considerations on the cost competitiveness of cellulosic biofuels;
- The effect of carbon pricing on the production of liquid biofuels;
- The impact of asset fixity concept on biofuel production in the United States.

In Chapter II I analyze the impact of technological progress and market penetration considerations on the volumes of cellulosic biofuel production. I analyze the effect of additional drops in processing and market penetration costs for cellulosic biofuel and scrutinize the impact of these cost changes. This analysis is performed for four different market scenarios with various combinations of the RFS2 mandates and market penetration barriers presence. Furthermore, I augmented the FASOMGHG model with downward sloping demand for biofuels to better reflect the demand-supply market for liquid fuels. Mathematical programming optimization framework is used to perform the analysis.

I find that the cost reducing technological progress path currently projected is not enough to make the production of cellulosic biofuel cost competitive. In particular I find that the level of cellulosic biofuel production required by the Energy Independence and Security Act is only achievable for processing cost drops of 70% or more for cellulosic ethanol technology beyond those currently projected. This level of cost decrease is not likely to be reached by 2020. Furthermore, I find that removal of market penetration costs would boost the market presence of ethanol and allow for achieving the RFS2 mandates at the processing cost reduction of 15% or more. I also note that introduction of an elastic downward sloping demand for ethanol into the modeling framework causes the amount of crop and cellulosic ethanol produced to become lower.

In Chapter III, I relax biofuel mandates and introduce carbon pricing to see how the future production of liquid biofuels in the United States is influenced by these two operations. I assume that CO2e pricing is modeled as a market payment for the reduction in the greenhouse gases net emissions within cap-and-trade market for carbon dioxide credits. I also account for increases in greenhouse gas emissions associated with feedstock hauling inherent for biofuel production. I examine the impact of GHG prices ranging from \$0 per metric ton of CO2e to \$100 per metric ton of CO2e on the total volume of crop and cellulosic biofuel produced. I perform this task for four different market scenarios.

I discover that the RFS2 mandates artificially raise crop biofuel volumes in the manner which is not cost competitive. Without RFS2 mandates, crop biofuel is substituted by cellulosic biofuel whose assumed processing costs become lower than processing cost of crop biofuel after 2020. Furthermore, it is revealed that the introduction of carbon pricing induces a 10% increase in total biofuel production under the situation with market penetration costs in place. I also find that removal of market penetration barriers further stimulates biofuel production and at the price of $50 per ton of CO2e total biofuel volume reaches amounts required by the RFS2 mandates in 2020. It is detected that without carbon pricing or trading schemes or drop-in fuel technology in place it is improbable that the EPA RFS2 mandates will be met.

In Chapter IV, I investigate the effect of asset fixity and putty-clay concept on the biofuel production prospects. The main assumption is that once the production capacity is constructed, it stays there for the economic life of asset. For the purpose of this study, 30-year-life biofuel facilities are assumed. Capital investment costs are accounted for in the production budgets and net present value of fixed costs is allocated to the first year of the plant operation. This approach allows better representation of industrial processes, operation and investment decisions. In this study currently existing biofuel facilities are also taken into consideration and they provide production capacity available from the first time period.

I observe that asset fixity has a significant impact on future biofuel production. The introduction of asset fixity reduces amount of cellulosic biofuel produced and maintains crop biofuel production at the previously observed levels. The effect is even more visible for scenarios with no RFS2 mandates in place or scenarios with no market penetration costs. Asset fixity is found to change the feedstock structure of biofuel both in terms of location and time period. Asset fixity and capital costs accounting influence the amount of biodiesel produced only in a minor way nationally but substantially on a regional basis. This study provides strong justification for the future use of asset fixity idea in the modeling of biofuel and more generally bioenergy production processes.

All studies presented in this dissertation indicate that agriculture sector has potential in providing input into future biofuel production in the United States. With the current state of technology and infrastructure development, crop biofuel, and more specifically, corn ethanol is still the most predominant source of biofuel (14 billion gallons per year of corn ethanol is produced at the moment compared to 7 million gallons per year of cellulosic ethanol). However, expected technological breakthrough in the area of cellulosic biofuel production holds hope for the increased presence of liquid biofuels in satisfying market demand for motor fuels. Carbon pricing or other market incentives and mechanisms internalizing negative externality of GHG emissions could entail more liquid biofuels production. The biodiesel generation might be a promising technology; however, its share in total fuel consumption in the United States is not expected to exceed 2% by 2020. Given these observations one could conclude that these three events need to happen for biofuel to break ground in the United States:

- Removal of market penetration barriers through investment into flex-fuel car fleet and adjustment to the fuels created to permit conditions for drop-in fuel penetration;

- Significant technological breakthrough in the cellulosic biofuel production technology;
- Creation of carbon pricing or trading schemes or other market mechanisms which would entail incentives for more GHG net offsets achievable by bioenergy production.

There are certain limitations of the studies presented in this dissertation. First, our assumption on maturity of crop ethanol technology might not hold until 2040. Innovative ways of utilizing crops for biofuels might arise and thus, could compete with cellulosic ethanol production. Second, one of the major assumptions used for modeling future potential of bioenergy industry is the NREL's estimation of processing costs of cellulosic ethanol and their projected decline over time (EPA 2009). This is one of few estimates available given that virtually no enterprises produce cellulosic ethanol at the large industrial scale up to date and as a result, no data exist to back up the calculations. However, personal communication with subject matter experts indicated that actual unitary processing costs of cellulosic ethanol are currently higher than NREL's estimates. Third, in all studies we use a certain projection of future increases of crop yields, livestock yields, international trade annual shifts and bioenergy feedstock conversion rates. Our results could be sensitive to the chosen levels of these parameters. Fourth, we assume a discount rate of 4% which reflects opportunity costs of capital in forestry and agriculture and one could argue that this discount rate is too low or too high, especially given the intergenerational equity issues associated with climate change. Fifth, this dissertation does not analyze changes in net greenhouse gas emissions as a result of changes in the bioenergy production structure. A possible expansion would include changes in greenhouse gas balances which would follow changes in biofuel and bioelectricity production. Finally, it is assumed in FASOMGHG that all markets clear and that all markets operate under perfect information. In reality, there are sometimes shortages or inventories of goods produced and some agents might benefit from information asymmetry or from exerting market power. These all consideration should be addressed in future research.

In terms of further research, first, one could simulate future biofuel volumes under processing cost declines different from the one estimated by NREL. Furthermore, in this dissertation a projection of future crop yields is used. One might also consider other more optimistic or more conservative projections of crop yields to see the impact of crop science innovations or impact of extreme events like droughts on the future volumes of biofuel produced. Second, one could also investigate tradeoffs between biofuel and bioelectricity generation. Third, the FASOMGHG model could be expanded further and it could include pyrolysis process in which bioenergy products like biochar, bio-oil and biogas are produced. Then, one could analyze economics, GHG offsets and environmental benefits resulting from either burning biochar for electricity and process heat or application of biochar to the agricultural fields as a soil nutrient enhancement.

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