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Analyzing Effects on Biofuels While Integrating the Agricultural Sector to the Energy Market: Linking POLYSYS and MARKAL

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To the Graduate Council:

I am submitting herewith a thesis written by Shreekar Pradhan entitled "Analyzing Effects on Biofuels While Integrating the Agricultural Sector to the Energy Market: Linking POLYSYS and MARKAL." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Economics.

Burton English, Major Professor

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Analyzing Effects on Biofuels While Integrating the Agricultural Sector to the Energy Market: Linking POLYSYS and MARKAL

A Thesis

Presented for the Master of Science Degree

The University of Tennessee, Knoxville

Shreekar Pradhan

December 2011

Dedicated to my father

Late Laxmi Bahadur Pradhan

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ABSTRACT

Two different sectoral models: POLYSYS (agricultural) and MARKAL (energy) are soft-linked in a modeling framework. The linkage benefits the strengths of price dynamics of biofuel crops in POLYSYS and the least cost biofuel supply in MARKAL. As the result the framework can now evaluate implication of biofuel policy in the agricultural and energy sectors simultaneously. This study utilizes the linkage to evaluate the implication of biofuel subsidy policy on the agricultural and energy sectors. Three scenarios are developed. First, the base case assumes current subsidy for corn ethanol and cellulosic ethanol will be continued until 2030. Second scenario (Sub1) assesses the phasing out of the corn ethanol subsidy from 2013 onward while the subsidy for the cellulosic ethanol will be continued until 2030 and the third scenario (Sub2) assesses the phasing out of the subsidy for cellulosic and corn ethanol from 2013 onward. The base case results show that as the demand for cellulosic ethanol increases, prices of dedicated energy crops will increase as high as $77/bu by 2030 also it significantly increases the prices of food crops. Further, the acreages of dedicated energy crops are significantly increased and as a result, the acreages of food crops are significantly reduces. Results in the alternative scenarios show that the phasing out of subsidy to corn ethanol improves service efficiency in the energy sector and while the same will decline when subsidies to corn and cellulosic ethanol are phased out. Phasing out of subsidy to corn ethanol does not significantly affect the crop prices and their acreages while there will be significant effect if subsidy to corn and cellulosic ethanol are phased out. The results show that the linkage is capable to simultaneously evaluate policy impacts on both the energy and agricultural sectors.

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LIST OF ABBREVIATIONS

$	US Dollar
AEO	Annual Energy Outlook
APAC	Agricultural Policy Analysis Center
Bil	Billion
BTL	Biomass-to-Liquid
Btu	British Thermal Unit
CGE	Computable Generable Equilibrium
CHP	Combined Heating and Power
CO_2	Carbon Dioxide
CPI	Consumer Price Index
EDM	Equilibrium Displacement Model
EISA	Energy Independence and Security Act of 2007
FT	Fischer Tropsch
Gal eth	1 gallon ethanol
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Giga Joule
KWh	Kilowatt-hour
M$	Million US Dollar
MM gal	Million gallon
Mt	Million Ton
NREL	National Renewable Energy Laboratory
PJ	Peta Joule (10^{15} Joule)
RFS	Renewable Fuel Standard
SOC	Soil Organic Carbon
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
Yr	Year

CHAPTER 1

INTRODUCTION

1.1 Introduction

Production of bio-liquid fuels (biofuels) from agricultural resources is one of the major components that links agricultural and energy markets. Before ethanol was being produced as a transportation grade fuel from agricultural crops (e.g. corn in the United States (US)), the agricultural market was analyzed with inputs of gasoline, diesel and electricity in the production and transportation of these crops. However, as the production of ethanol as a transportation grade fuel gained momentum because of the policies favoring renewable fuel, the analysis of agricultural markets has no longer been limited to these inputs (Tyner and Taheripour, 2008; Larson et al., 2010). Tyner and Taheripour (2008) indicated that a massive biofuels production may cause new market integrations in the agriculture sector. Further, Larson et al. (2010) foresaw consequences on the land use, soil erosion and carbon emissions as a result of the increased ethanol production in the US.

Currently gasoline is blended with 10% ethanol for transportation grade fuel use resulting in a high correlation (more than 80%) between average prices of ethanol and gasoline (Figure 1.1). Historically there has been a stronger correlation between prices of crude oil and ethanol (more than 85%) but the correlation between prices of crude oil and food crops (corn, soybean) was less than 25%. This indicates that the price of crude oil used to have a minimal effect on these crop prices. However, since 2006, it has been observed that the prices of food crops started following similar oil trends (Figure 1.2). The Renewable Fuels Standards (RFS) were mandated in the Energy Independence and Security Act of 2007 (EISA) and it can be seen in Figure 1.2 that the prices of oil, corn and soybean peaked in 2008. Further, as dedicated energy crops are being produced for ethanol production, the linkage between the agricultural and energy sector will have a new dimension (De La Torre Ugarte, 2003).

Biofuels also have the potential to reduce the use of fossil fuels either in the form of electricity generation or in the form of transportation fuels. Biofuels would also help in reducing CO_2 emissions. Biofuels are produced from agricultural crops and it uses electricity and fossil fuels as inputs during the production and transportation process (Figure 1.3). So, on one hand, it replaces fossil fuels and on the other hand it uses fossil fuels. Also the argument on whether the production of biofuels contributes in the reduction of CO_2 emissions has been a topic of research for many years.

The complexity rises as the level of biofuel production through the use of energy crops competes with other crops used for food (Witzke et al., 2008; De La Torre Ugarte, 2003). An increase in the use of biofuels that are produced from agricultural feedstocks has repercussions on land allocation to the other food crops and their prices (Banse and Sorda, 2009; Dicks et al., 2009; De La Torre Ugarte, 2003). Some have argued that such a phenomena further links biofuel production with an increase in poverty and a large population in the world relies upon food for their existence (OXFAM, 2008; ENS, 2008). However, this may not be the case for second generation biofuels in the future. On the other hand, increased fuel prices as a result of stringent greenhouse gas (GHG) reduction policies in the world will increase the prices of fuel inputs to agriculture, which in turn will increase the cost of production of agricultural products including biofuels, particularly in the case of first generation biofuels (Tyner and Taheripour, 2008).

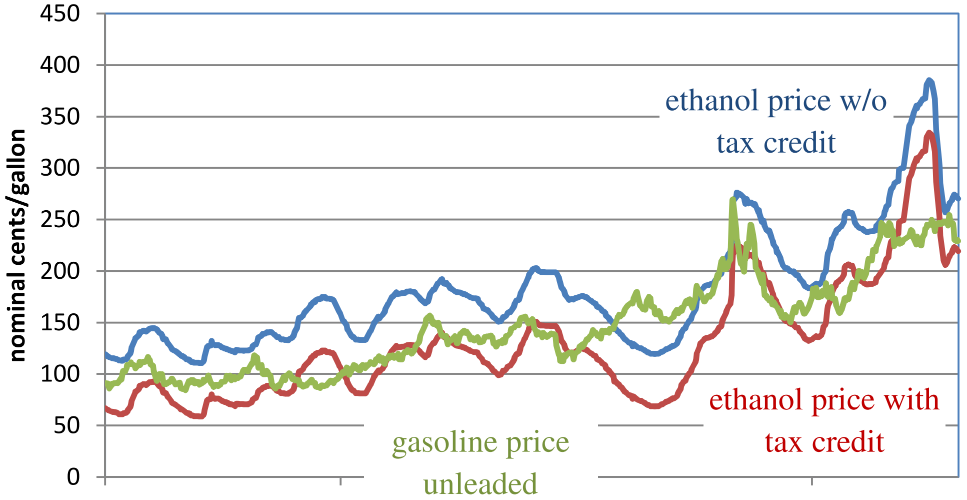

Figure 1.1 Average US price for ethanol and gasoline during 2003-2006 (Source: USEIA, 2007)

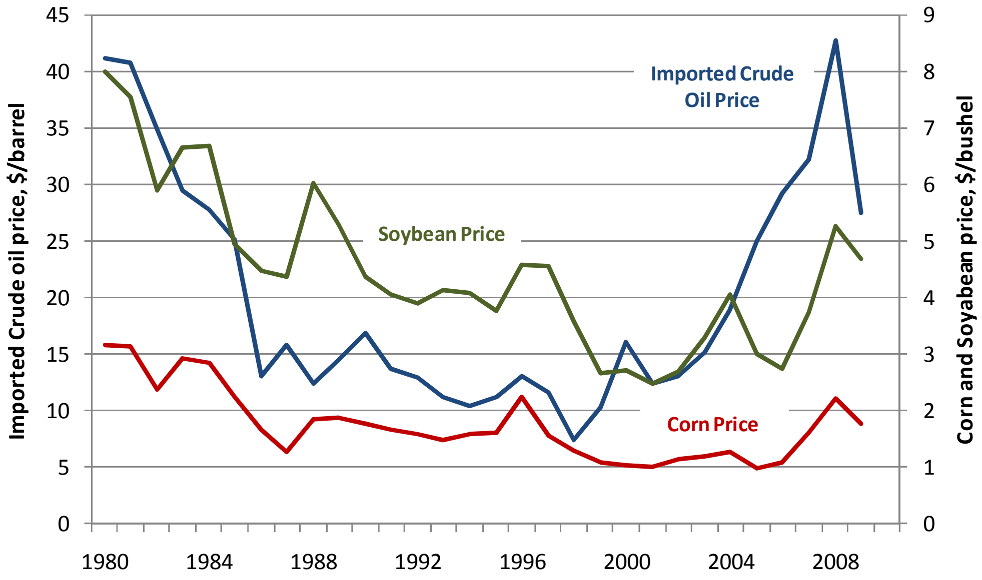

Figure 1.2 Real price for imported crude oil, corn and soyabean during 1980-2009 (CPI: 1982-1984 =1.00; updated price for 2009) (Source: AGMRC, 2009)

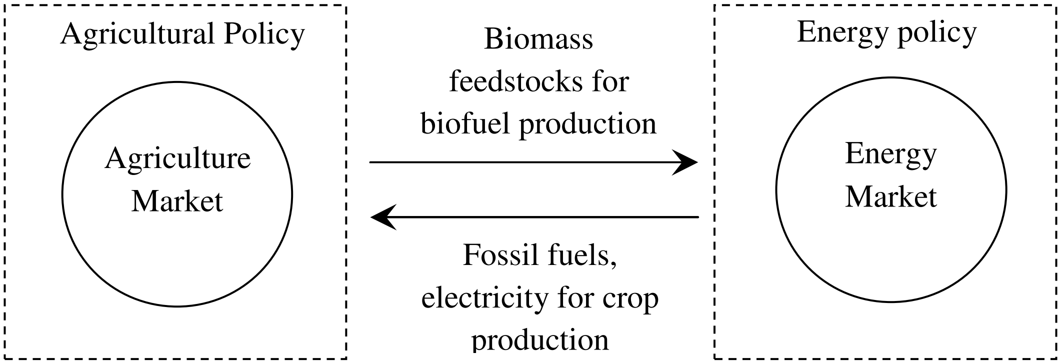

Figure 1.3 Cross-sectoral linkage between the energy and agricultural sectors.

In such a complex issue, the question of how to analyze biofuels has become an important issue for researchers on both the agricultural and energy sectors. The issue becomes critically important when issues related to energy policies are to be analyzed. For example, the recent energy policies -the Energy Security and Investment Act (2007) and American Clean Energy Security Act (2009) (which is presently under debate in the US Senate) are expected to have substantial impacts on the agricultural sector (Hellwinckel et al., 2010; De La Torre Ugarte, 2003). Thus, a modeling framework linking the agricultural and energy sectors is useful for a rational evaluation of effects of biofuels on the energy and agricultural sectors.

1.2 Problem Identification

Currently, biofuels are subsidized in order to make them competitive with petroleum products. This allows biofuels to overcome barriers to entry like adoption of biofuel technology based vehicles, adequate supply from blenders and changing people's perception towards the use of biofuels to increase its demand. The cost of biofuel production is a function of feedstock prices, technology costs and other variable inputs: electricity and fossil fuels. The agricultural market determines the prices of feedstocks required for biofuel production, whereas, the energy market determines the demand of these feedstocks. In the agriculture market the feedstocks compete with other crops while biofuels compete with the conventional fuels (gasoline, diesel, natural gas and electricity) in the energy market. Thus, as the production of biofuels increases, it will also increase pressure on food crop in prices and land uses. Biofuel production has also been linked to the increase in poverty which is thought to have huge repercussions on a large population of the world relying upon food for their existence. However, this may not be the case in second generation biofuels in the future. So, there will also be an issue of adoption of emerging technology and also understanding the nexus between the existing food crop-based ethanol production and adoption of future cellulosic based ethanol production.

Researchers have tried to address the issue by either using standalone modeling frameworks in the field of agriculture and energy or through some general equilibrium models. In most general equilibrium models, biofuels are included as a new sector and it is assumed that biofuels have a similar economic effect as that of other cereal crops (e.g., McDonald, Robinson and Thierfelder, 2006; Dicks et al., 2009). Likewise, those models represent ethanol as a composite output of some intermediate inputs (e.g., sugar, grain (cereal), forestry) and assume a substitution with gasoline and diesel based on their own- and cross- price relation. Further, these models assume that energy crop (switchgrass) production cost is similar to that of other cereal crops and rely on partial equilibrium models for the average cost of production

General equilibrium models depend upon the accounting structure (input-output framework) of a country, which usually does not account for each type of crops separately; many of the results from general equilibrium models are based on aggregated data (Banse and Sorda, 2009; Witzke et al., 2008). In partial equilibrium models such as POLYSYS[1], which has a focus on policy simulation on the agricultural sector, crops are disaggregated. The model levels the demand of biofuels through price elasticities (own- and cross-price elasticities) and thus, it simulates the demand of biofuels as these compete with other crops. Further, it simulates the demand of biofuels considering the availability of land (acreage) and also computes emissions of greenhouse gases from agriculture considering changes in land use and livestock through inter-linked modules. The model, however, assumes a fixed structure of the future technology progress of biofuels production and their cost. In particular, it is assumed in the model that second generation biofuels (cellulosic biofuels) are produced through fermentation. Possibility of advanced biofuels as the cost effective technology in the future is absent in the model. On the other hand, partial equilibrium models such as MARKAL[2], which has a focus on the energy market, assumes the least cost technology for biofuel production based on their marginal costs of production while minimizing the total system cost in the model in a planning horizon. It is assumed in the model that there will be a complete foresight of possible future technologies and their costs. Thus, the model computes the cost of biofuel production based on the selected least cost production technologies. However, crop prices, inputs to the biofuels production, are exogenous to the model and these are normally fixed and taken from partial equilibrium models that focus on the agricultural market. Furthermore, the effect on biofuel production due to other

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[1] See http://www.apac.org for more information on POLYSYS. The Department of Agricultural and Resource Economics has good expertise and resources in this modeling framework. Some brief description on the model is given in the methodology section.

[2] See http://www.etsap.org for more information on MARKAL. Brief description on the model is given in the methodology section.

anticipated effects such as competition with other crops and land use changes are not considered in the model.

1.3 Research Objectives

The primary goal of this study is to link the agricultural sector to the energy sector in a modeling framework so that the linkage can evaluate implications of biofuel policy have in regards to agricultural and energy sectors. In particular, the study seeks to utilize the linkage to explore the following issues:

a) What is the effect on primary energy requirements in the energy sector because of changes in biofuel demands?

b) What are the effects on the prices of food crops and biomass because of the subsidies to corn and cellulosic ethanols?

c) What are the effects on landuse changes when there is a change in subsidy policies?

CHAPTER 2

LITERATURE REVIEW

Various studies have attempted cross-sectoral linkages in the agricultural and energy sectors. In this chapter, the linkages made in different modeling frameworks, their strengths and weaknesses are highlighted. It elaborates the issues with the general equilibrium modeling framework and partial equilibrium modeling framework for analyzing biofuel issues that link the agricultural and energy sectors.

Linking two models that do not integrate with each other by their originality is a challenging task (UNFCCC, 2005). There have been studies to link the agricultural and energy sectors through extending the available information (input-output framework) in general equilibrium models which include biofuel as a composite commodity. Some studies used a partial equilibrium modeling framework in the agricultural or energy sectors. Further, most literatures report multi-sector global models linking the agricultural and energy sectors through biofuels. The present literature is reviewed with a focus on how biofuels are cross-sectorally linked and their level of disaggregation, irrespective to the number of countries and location, so as to understand the rationale behind the proposed present study.

2.1 Biofuel Policies

The Renewable Fuel Standard (RFS) in the Energy Independence and Security Act (EISA) 2007 sets a minimum production target of biofuel production in terms of annual average volume from

2006-2022. The target volume was transportation fuels. EISA requires at least 4 billion gallons of biofuels be produced in 2006 and production ramp up to 36 billion gallons by 2022. The target also includes a threshold production for each of the following categories of biofuels -advanced biofuel, cellulosic biofuel and biomass based diesel. Of the 36 billion gallons of renewable fuel, the RFS requires that at least 21 billion gallons be advanced biofuel. The advanced biofuel includes ethanol produced from cellulose, hemicellulose, lignin, sugar or any starch other than corn starch and it requires the GHG reduction from using the biofuel to be at least 50% less than the lifecycle greenhouse gas emissions of gasoline. Of these 21 billion gallons of the advanced biofuels, there must be at least 16 billion gallons of cellulosic biofuel. The cellulosic biofuels are derived from any cellulose, hemicellulose or lignin and obtain a lifecycle GHG emission displacement of at least 60% of gasoline. So, this has set a target of producing 15 billion gallons of corn based biofuels (conventional biofuels) by 2022.

2.2 General Equilibrium Modeling Framework

In general equilibrium models there has always been a challenge of how to represent biofuels in the models since SAMs (Social Accounting Matrix), the database that most global CGE models use for calibration does not account biofuels activity accurately. Most of the models are based on 2001 SAM database and the most recent SAM published so far is from 2004 (Kretschmer and Peterson, 2009). There has been little production of biofuels until recently and the SAMs database used for such models for calibration give little information on the production and trade patterns of biofuels. Furthermore, current biofuels increments are the output of various governmental support measures and thus, future production and trade patterns may be different from today's patterns depending upon policy assumptions. There have been some efforts to overcome the challenges to include biofuels in general equilibrium models.

In the standard Global Trade Analysis Project (GTAP), biofuels are included as vegetable oil at level with oil and other petroleum products in the petroleum sector's demand (Witzke et al., 2008; Burniaux and Truong, 2002). The model considers biofuel technologies as the process intermediate-to-final products from materials such as cereal grains, oilseeds and sugar beet/cane. Although standard GTAP model does not consider cellulosic biofuels, they are now modeled as a separate commodity in some modified GTAP models. McDonald, Robinson and Thierfelder (2006); Dicks et al. (2009) have modified the GTAP model to include switchgrass based ethanol and evaluated the impacts (GDP, land-use-change) of increasing switchgrass based ethanol production in the USA. The study assumes that the primary input coefficients are the same as those for other US cereal crops and the demand for biofuels production through switchgrass will be derived from the petroleum sector in the US. Likewise, GTAP-E, an extended version of the GTAP model, represents bioethanol as a separate commodity produced from sugar, grain and other forest (agriculture) products and further, it considers a substitution between the bio-ethanol and biodiesel (produced from vegetable oil) through nested Constant Elasticity of Substitution (CES) (Burniaux and Truong, 2002).

2.3 Partial Equilibrium Modeling Framework

Partial equilibrium global models such as –POLES and PRIMES have a focus on energy but they do not explain the production potential of biofuels in agriculture with competition between other crops. In the European Simulation Model (ESIM), which is a partial equilibrium model with a focus on the agricultural sector, all the inputs for biofuel production are considered homogenous with other uses such as food and/or feed. The processing elasticities for cereals and sugar used as inputs for biofuels are similar to those for oilseeds, and functions for the input demand for bioethanol processing are similar to those for biodiesel production. The FAPRI model, a partial equilibrium global model, has a focus on US crops linked with international markets for cotton, dairy, livestock, oilseeds, rice and sugar models. Interestingly, in this model, the total US bioethanol demand is divided into fuel bioethanol demand and a residual demand (industrial and for beverages) (Witzke et al., 2008). Fuel bioethanol is derived from the cost function for refiners blending gasoline with additives, including the US prices of bioethanol and crude oil as well as gasoline supply and policy measures affecting a refiner's bioethanol demand. The model assumes that future technology for advanced biofuels production is uncertain (FAPRI, 2010). AGLINK/COSIMO, a dynamic partial equilibrium global model (focus on OECD countries), has a focus on multi markets –cereals, oilseeds, oilseed processed products, meat and dairy products with special emphasis on domestic trade policies in the represented countries. In the model, bioethanol is considered to be produced from wheat, coarse grains and /or sugar with different conversion rates across feedstock types. The production of bioethanol and biodiesel is modeled in a double-log form depending on time, the cost ratio between biofuels and petroleum-based fuel and an exogenous adjustment factor to take into account the politically determined growth. It is reported that the AGLINK representation of biofuel production is fairly ad hoc due to a lack of empirical data (Witzke et al. 2008). Searchinger et al. (2008) used a partial equilibrium model of agricultural markets (CARD) to quantify the increased demand for land arising from US corn ethanol targets and they used the GREET model to estimate GHG emissions from land conversion.

Also there are arguments about the effectiveness of these types of models to analyze biofuels. Kretschmer and Peterson (2009) claim that there are more possibilities for economic adjustments in general equilibrium models compared to partial equilibrium models. Further, Ghallagher (2008) argues that general equilibrium models represent medium term analysis when markets can adjust while partial equilibrium models represent short term analysis when adjustment is difficult. There are also hybrid models linking partial equilibrium and general equilibrium models (Van der Werf and Peterson, 2009; Melillo et al., 2009), which have been used to evaluate policy impacts of bioenergy policies on land-use change, biodiversity and greenhouse gases.

2.4 POLYSYS Model

The POLYSYS modeling framework is conceptualized as a variant of an equilibrium displacement model (EDM) that simulates changes in economic policy, agricultural management, and natural resource conditions, and estimates the resulting impacts from these changes on the US agricultural sector (APAC, 2010). The model has interdependent modules which simulate (a) crop supply for the continental US, which is disaggregated into 3110 production regions; (b) national crop demands and prices; (c) national livestock supply and demand; and (d) agricultural income. These modules are driven by variables such as planted and harvested area, production inputs, yield, exports, cost of production, demand by use, farm price, government program outlays and net realized income. The model includes fourteen crops: corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, peanuts, sugar cane, sugar beets, dry beans, alfalfa hay, and other hay. Five livestock commodities are also endogenous to the system, including beef, pork, broilers, turkeys, and milk. At present, corn and herbaceous crops are considered as feedstock for ethanol production and soybean is considered feedstock for biodiesel. Herbaceous crops, woody energy crops, mill residues, urban wood waste and forest residues are considered as feedstock for electricity generation. POLYSYS anchors its baseline to US Department of Agriculture's (USDA) published baseline projections for the agriculture sector. The current model is calibrated according to the USDA 2010/11 baseline. The model also estimates changes in emissions due to land use changes, and soil organic carbon (SOC) at the sub-county level (Hellwinckel et al., 2010).

2.5 MARKAL Model

MARKAL is a least cost linear optimization energy system modeling framework which computes an inter-temporal partial equilibrium on energy markets, i.e., it ensures that the supply meets the given demand of energy services at a given set of prices of all energy forms at each time period with an assumption of possessing complete foresight in a competitive market (Loulou, Goldstein and Noble, 2004). It contains the structure of the energy system from resource supplies, energy conversion technologies to end use demands; the structure is called the Reference Energy System (Figure 2.1). It is a data driven model which includes data that characterize each of the technologies and resources used, including fixed and variable costs, technology availability and performance, and pollutant emissions. Outputs of the model include the least cost technological mix, total system cost and energy services. It accounts energy flow from energy resources, processes, conversions and end-uses (e.g. resources -mining, oil-well; process –refinery, industrial process technology; conversion processes -electricity generation and end use sectors- agriculture, residential and commercial, industrial and transportation). This model was used in several studies on energy and CO_2 emission analysis at country and global levels (Shay et al., 2008; Shrestha and Pradhan, 2010; Shrestha and Pradhan, 2008; Strachan and Kannan, 2008; Shukla, Dhar and Mahapatra, 2008; Rajesh et al., 2003; Seebregts et al., 2005; Smekens, 2004; Remme and Blesl, 2008). More about the model is described in ETSAP (2007) and Loulou, Goldstein and Noble (2004).

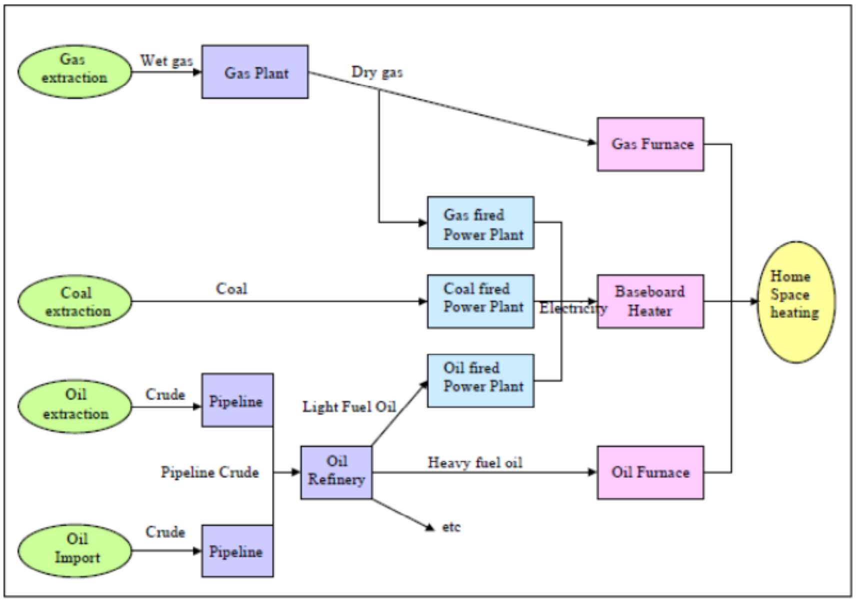

Figure 2.1 An example of a portion of simple Reference Energy System (RES)
(Source: Loulou et al., 2004)

2.6 Strengths and Weakness of Linking POLYSYS and MARKAL Models

In a modeling framework, partial equilibrium models like POLYSYS and MARKAL analyze biofuel issues by using a standalone modeling framework. POLYSYS analyzes biofuels based on the agricultural market where as MARKAL analyzes biofuels based on the energy market. These two models are stronger in evaluating the behavior on the corresponding markets as an underlining variable changes. However, being as how the agricultural sector shows a strong inter-linkage with the energy sector, the need to interlink these two models becomes important. It is also important in the aspect that it will give a meaningful exercise as the biofuels demanded in MARKAL model is not dynamically linked with the feed stock prices. The model treats the feedstock prices as an exogenous variable. POLYSYS considers the demand of biofuels as exogenous. Future technologies also have to compete with each other and these are governed by the competing technology costs and efficiencies, and the current framework in POLYSYS does not have such module. Thus, the integration is envisioned to have advantages from the two models in the analysis –characteristics of biofuel production considering agricultural systems and a least cost technology expansion plan of biofuel production considering the energy market. Therefore, such integration of the modeling framework to analyze biofuels in the agricultural and energy sectors appears to be promising since it will yield advantages greater than the two models separately.

CHAPTER 3

METHODOLOGY

3.1 Approach

This study envisions a link between two different sectoral models through a modeling framework that captures the benefit of each framework's strengths and lessens their weaknesses in an integrated environment. The two different sectoral models are POLYSYS and MARKAL. These are *soft-linked* in an integrated modeling framework in such a way that it captures the price dynamics of biofuels demand while competing for land use and food crop prices in POLYSYS and likewise, the least cost biofuel supply of biofuel production in MARKAL.

3.2 Model Description and Data Used in the Models

MARKAL Model

The objective function in the MARKAL is to minimize the total net present value of the system cost (discounted over the planning horizon). The annual costs include the following parameters:

a) Annualized investments in technologies;

b) Fixed and variable annual operation and maintenance (O&M) costs of technologies;

c) Cost of exogenous energy and material imports and domestic resource production (e.g., mining);

d) Revenue from exogenous energy and material exports;

e) Fuel and material delivery costs;

f) Welfare loss resulting from reduced end-use demands.

g) Taxes and subsidies associated with energy sources, technologies, and emissions.

Mathematically the objective function in the MARKAL is expressed as follows:

$$\begin{aligned} &Minimize\ NPV \\ &= \sum_{r=1}^{R} \sum_{t=1}^{t=NPER} (1+d)^{NYRS\cdot(1-t)} \cdot ANNCOST(r,t) \\ &\cdot (1 + (1+d)^{-1} + \cdots + (1+d)^{1-NYRS}) \end{aligned}$$

$$\text{s.t. } enduse\_dem(c,r,t) \quad \leq supply(c,r,t)$$

………………………… (3.1)

(Source: Loulou et al., 2004)

Where,

NPV is the net present value of the total cost of the system;

ANNCOST(r,t) is the annual cost in region ***r*** for period ***t***;

d is the general discount rate;

NPER is the number of periods in the planning horizon;

NYRS is the number of years in each period ***t***;

R is the number of regions;

Enduse_dem is the demand of each commodity '***c***' in end uses;

Supply is the total supply of each commodity '***c***'

c is the energy commodity;

The total annual cost ***ANNCOST(r,t)*** is the sum over all technologies ***k***, all demand segments ***d***, all pollutants ***p***, and all input fuels ***f***, of the various costs incurred, namely: annualized investments, annual operating costs (including fixed and variable technology costs, fuel delivery costs, costs of extracting and importing energy carriers), minus revenue from exported energy carriers, plus taxes on emissions. Mathematically, ***ANNCOST(r,t)*** is given as below:

$$
\begin{aligned}
&ANNCOST(r,t)\\
&\quad = \sum\nolimits_{k} \Big\{ Annualized\_Invcost(r,t,k) \cdot INV(r,t,k) + Fixom(r,t,k)\\
&\quad \cdot CAP(r,t,k) + Varom(r,t,k)\\
&\quad \cdot \sum\nolimits_{s,s} ACT + \sum\nolimits_{c} \Big[Delivcost(r,t,k,c) \cdot Input(r,t,k,c) \cdot \sum\nolimits_{s} ACT(r,t,k,s) \Big] \Big\}\\
&\quad + \sum\nolimits_{c,s} \Big\{ Miningcost(r,t,c,l) \cdot Mining(r,t,c,t) + Tradecost(r,t,c)\\
&\quad \cdot TRADE\left(r,t,c,s,\frac{i}{e}\right) + Importprice(r,t,c,l).Import(r,t,c,l)\\
&\quad - Exportprice(r,t,c,l) \cdot Export(r,t,c,l \Big\} + \sum\nolimits_{c} \{ Tax(r,t,p) \cdot ENV(r,t,p) \}
\end{aligned}
$$

…………………………. (3.2)

Where,

Annualized_Invcost(r,t,k) is the annual equivalent of the lump sum unit investment cost, obtained by replacing this lump sum by a stream of equal annual payments over the life of the equipment, in such a way that the present value of the stream is exactly equal to the lump sum unit investment cost, for technology ***k***, in period ***t***.

Fixom(r,t,k), Varom(r,t,k), are unit costs of fixed and operational maintenance of technology ***k***, in region ***r*** and period ***t***;

Delivcost(r,t,k,c) is the delivery cost per unit of commodity ***c*** to technology ***k***, in region ***r*** and period ***t***;

Input(r,t,k,c) is the amount of commodity ***c*** required to operate one unit of technology ***k***, in region ***r*** and period ***t***;

Miningcost(r,t,c,l) is the cost of mining commodity ***c*** at price level ***l***, in region ***r*** and period ***t***;

Tradecost(r,t,c) is the unit transport or transaction cost for commodity ***c*** exported or imported by region ***r*** in period ***t***;

Importprice(r,t,c,l) is the (exogenous) import price of commodity ***c***, in region ***r*** and period ***t***; this price is used only for exogenous trade, see below;

Exportprice(r,t,c,l) is the (exogenous) export price of commodity ***c***, in region ***r*** and period ***t***; this price is used only for exogenous trade, see below;

Tax(r,t,p) is the tax on emission ***p***, in region ***r*** and period ***t***; and

the decision variables in the MARKAL model are:

INV(r,t,k): New capacity addition for technology ***k***, in period ***t***, in region ***r***.

CAP(r,t,k): Installed capacity of technology ***k***, in period ***t***, in region ***r***.

ACT(r,t,k,s): Activity level of technology ***k***, in period ***t***, in region ***r***, during time-slice ***s***.

MINING(r,t,c,l): Quantity of commodity ***c*** (PJ per year) extracted in region ***r*** at price level ***l*** in period ***t***.

IMPORT(r,t,c,l), EXPORT(r,t,c,l): Quantity of commodity ***c***, price level ***l***, (PJ per year) exogenously imported or exported by region ***r*** in period ***t***.

TRADE(r,t,c,s,imp) and TRADE(r,t,c,s,exp): Quantity of commodity ***c*** (PJ per year) sold (exp) or purchased (imp) by region ***r*** to/from all other regions in period ***t***, for time-slice ***s*** (for electricity).

D(r,t,d): Demand for end-use ***d*** in region ***r***, in period ***t***.

ENV(r,t,p): Emission of pollutant ***p*** in period ***t*** in region ***r***.

Database and its Characteristics

In this study, the energy database- EPA US National Model Version 2.1 (USEPANMD) developed by the United States Environmental Protection Agency (USEPA) is used as the basic database that represents the nationwide energy economy of the US. The database was developed in the MARKAL modeling framework and comprehensively covers existing as well as a wide range of future technologies and energy commodities. Further, it is justifiable to use the model since it is developed by the USEPA for the purpose of developing a basic database that can be widely used by the academic and public sector.

The energy economy in the model is characterized by the resources used, conversion, process, electricity generation and demand technologies. There are six major energy resource commodities: crude oil, imported petroleum products, natural gas, coal, nuclear power and renewable sources which include biomass, wind, solar, hydro and geothermal. The resource supplies of the fossil fuels – crude oil, imported refined petroleum products, natural gas and coal are represented by stepped supply curves. The electricity generation is characterized by 16 existing electricity generation and 14 combined heat and power (CHP) technologies. There are 15 new electricity generation technologies including natural gas advanced combined cycle, geothermal, biomass integrated gasification, nuclear, pulverized coal steam, supercritical coal steam, integrated coal and gasification combined cycle, solar pv –centralized, -residential and commercial generation, solar thermal centralized generation technology and wind electricity generation technology. The end use sector (demand sector) is characterized by four sectors – residential, commercial, industrial and transportation.

The model contains biofuels such as ethanols and biodiesel. Ethanol is produced from corn and cellulosic feedstock (energy crops (switchgrass), corn stover, agriculture residues and wood) and biodiesel is produced from virgin soybean and waste soybean. The model considers woody energy crops, forest residues, urban wood waste and primary mill residues as feedstock for electricity generation. The base case result of the model is compared to the output of the base case result of Annual Energy Outlook (AEO) 2006 from the Department of Energy (DOE) (Shay et al., 2008).

POLYSYS Model

The POLYSYS modeling framework is conceptualized as a variant of an equilibrium displacement model (EDM) that simulates changes in economic policy, agricultural management, and natural resource conditions, and estimates the resulting impacts from these changes on the US agricultural sector (APAC, 2010). The model has interdependent modules which simulate (a) crop supply for the continental US, which is disaggregated into 3110 production regions; (b) national crop demands and prices; (c) national livestock supply and demand; and (d) agricultural income. These modules are driven by variables such as planted and harvested area, production inputs, yield, exports, cost of production, demand by use, farm price, government program outlays and net realized income. The model includes fourteen crops: corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, peanuts, sugar cane, sugar beets, dry beans, alfalfa hay, and other hay. Five livestock commodities are also endogenous to the system, including beef, pork, broilers, turkeys, and milk. At present, corn and herbaceous crops are considered as feedstock for ethanol production and soybean is considered feedstock for biodiesel. Herbaceous crops, woody energy crops, mill residues, urban wood waste and forest residues are considered as feedstock for electricity generation. POLYSYS anchors its baseline to US Department of Agriculture's (USDA) published baseline projections for the agriculture sector. The current model is calibrated according to the USDA 2010/11 baseline. The model also estimates changes in emissions due to land use changes, and soil organic carbon (SOC) at the sub-county level (Hellwinckel et al., 2010).

3.2.1 Descriptions of Data that Links the Models

As discussed earlier in the chapter, the soft linkage between the two modeling frameworks required a common flow of data in the following areas which are explained below:

a) Technology

The existing structure of POLYSYS has characterized the production of biofuels by two types of technologies a) Fermentation (existing corn based ethanol production) and b) Biochemical (future cellulosic based ethanol production). The feedstock used for the biochemical technologies are corn stover, wheat straw, switchgrass and wood (poplars, willows and wood residues).

The existing structure in the MARKAL has characterized the production of corn based ethanol by two existing and four future ethanol production technologies. The existing technologies for fermentation are dry mill and wet mill using natural gas and coal (USDA, 2002). The future technologies for corn based ethanol production are represented by dry mills using either natural gas or coal with or without combined heating power (USEPA, 2006). The ethanol yields of the future fermentation technologies are taken from the assumption in POLYSYS that ethanol yields will increase from 2.7 gal/bu in 2005 to 3.0 gal/bu in 2030. BCurtis (2008) states that the corn based technology is not likely to make much progress compared to the cellulosic based biofuels production technologies and thus, it is assumed that the ethanol yield from corn will reach to a saturation point by 2020 and it will continue to be 3.0 gal/bu till 2030 (Figure 3.1).

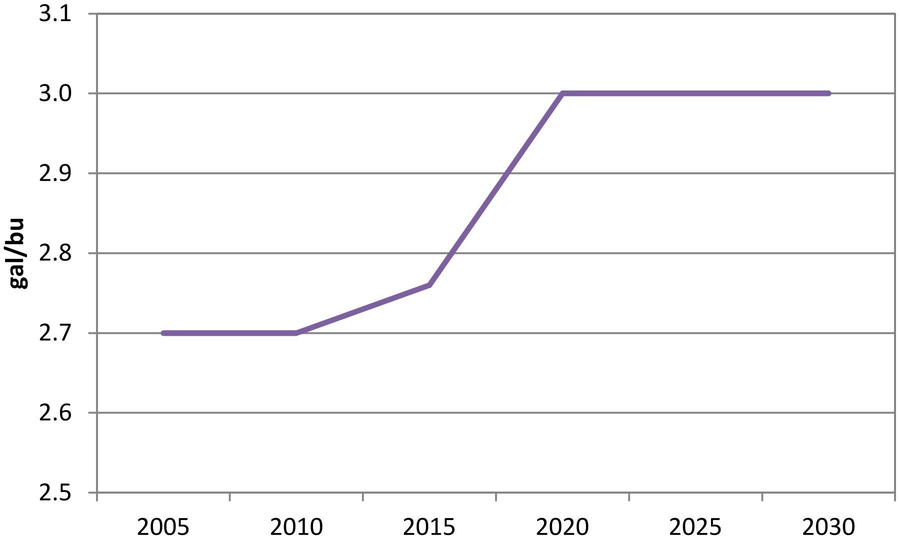

Figure 3.1 Corn ethanol yield during 2005 to 2030

The existing structure of the cellulosic ethanol production in MARKAL was characterized by two biochemical ethanol production technologies based on the National Renewable Energy Laboratory's reports -McAloon et al. (2000) and Aden et al. (2002). These two technologies were assumed to be introduced in year 2010 (based on NREL (2000)) and 2015 (based on NREL (2002)) respectively. These technologies are assumed to be capable of using the different biomass feedstocks (agriculture residues, corn stover, energy crops, wood residues, primary mills and urban wood waste). As there is higher potential for thermochemical based cellulosic ethanol production technologies (BCurtis, 2008), in order to capture the future potential, two thermochemical cellulosic ethanol technologies based on 100% wood residues are assumed to be introduced from 2015 and three thermochemical (biomass to liquid -BTL) cellulosic ethanol production technologies based on 100% switchgrass but also capable of co-firing with coal with biomass up to 40% are assumed to be introduced from 2020. The two thermochemical cellulosic technologies are a) Indirect gasification (Phillips et al., 2007) and b) Direct gasification technology (Dutta and Phillips, 2009). The three biomass to liquid (BTL) ethanol production technologies are a) 100% switchgrass BTL-RC-V, b) 29% biomass and 71% coal CBTL-OTA-V and c) 40% biomass and 60% coal (Liu et al., 2010). The ethanol yield of the cellulosic ethanol production via biochemical technology is assumed to increase until 2025 as assumed in POLYSYS (Figure 3.2). Following 2025, it is assumed that the yield will increase to 90 gal/ton, 85 gal/ton, 93 gal/ton and 95 gal/ton for ethanol production from corn stover, agricultural residues and dedicated energy crops by 2050.

b) Cellulosic Biomass Supply and Prices

Maximum biomass availability is characterized in MARKAL as biomass supply with respect to 14 step prices (Figure 3.3). They are: $100, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 40 and 37 per ton of biomass (2010 year price). The biomass quantity of supply with respect to the step prices are endogenously determined by using the exogenous biomass step prices in POLYSYS. Biomass equilibrium price levels for a specific cellulosic ethanol demand are determined in POLYSYS. In POLYSYS, at a given biomass price offer, the types of biomass (agriculture residue, wood residue, switchgrass, corn stover) are made available for ethanol production if the net revenue from the biomass is positive at the given price level (i.e. the cost of harvesting the feedstock is less than the revenue generated from ethanol). Thus, at each of the offered biomass price levels it determines the endogenous quantity of the biomass that can be supplied to the energy market and it is assumed that such quantify will be offered with a single price tag irrespective of different biomass types. Thus, it is justifiable to state that these different biomass

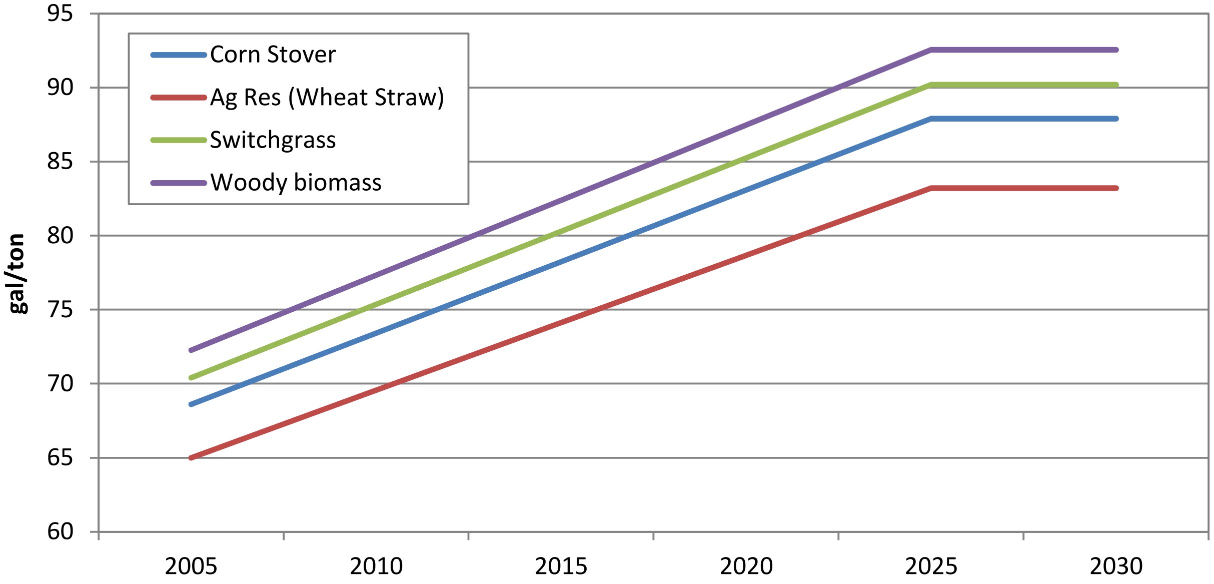

Figure 3.2 Ethanol yield from different cellulosic feedstock using biochemical technology in MARKAL during 2005-2030 (taken from POLYSYS)

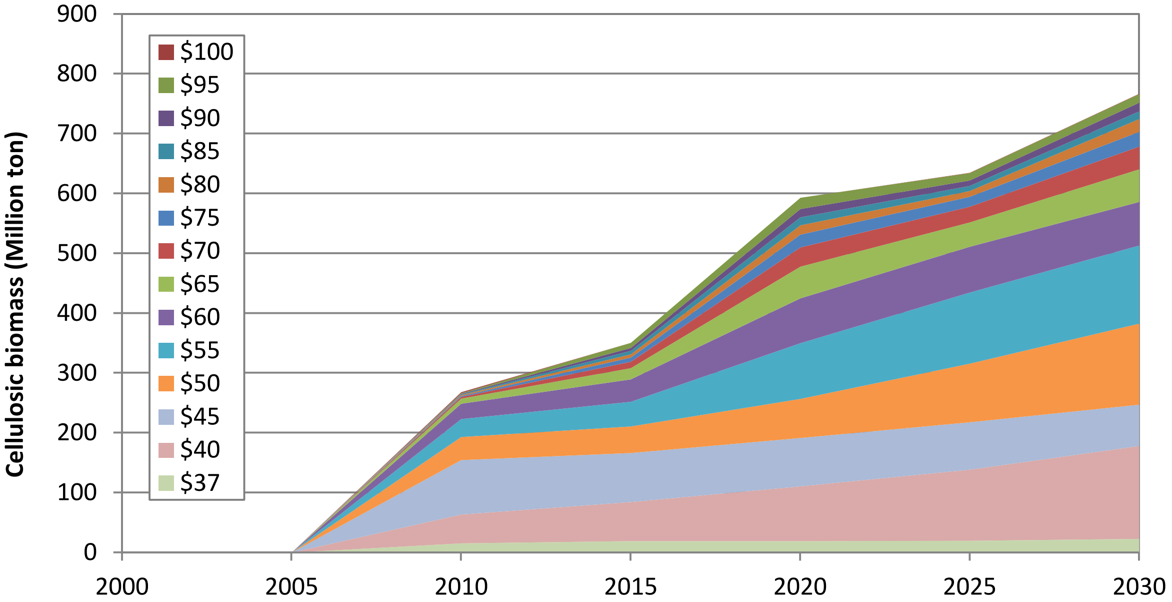

Figure 3.3 Availability of dedicated energy crops for cellulosic ethanol at the selected 14 exogenous biomass price levels during 2000-2030 in MARKAL (taken from POLYSYS).

feedstocks are treated as complimentary commodities in POLYSYS. In MARKAL, these feedstocks are treated as a perfect substitute in cellulosic ethanol production and these feedstocks have to compete with each other as per their cost and energy density. Thus, to simplify and realize the linkage, the selected cellulosic feedstocks are treated as a single biomass commodity. In other words, POLYSYS and MARKAL are soft linked via the single commodity (Figure 3.4). However, other than in the soft linkage, both models treat and compute these different cellulosic biomass commodities as separate commodities differentiated by cost of collection, energy content and technical feasibility. This approach conceptualizes two markets functioning separately according to their own characteristics.

c) Corn Grain Prices and Supply

Corn grain price is an endogenous variable in POLYSYS which is computed in equilibrium with other crops prices including dedicated energy crops. Not to further complicate the linkage, for MARKAL to behave within the boundary of POLYSYS's behavior, a set of equilibrium corn prices were computed for each of the fourteen exogenous biomass prices in POLYSYS. It is found that these prices vary by less than $15 per ton. Although premature enough, it shows that the corn grain prices are not highly sensitive to the selected exogenous biomass prices (Figure 3.5). Thus, these 14 sets of corn grain prices were given in MARKAL as a set of corn grain price curves such that these prices turn on and off according to the corresponding biomass supply. However, the in situ corn grain equilibrium price with POLYSYS linked with MARKAL is determined from POLYSYS after feeding in the biomass feedstock demand as a single commodity from MARKAL and this corn grain price is treated as the corn grain equilibrium price in the respective scenario.

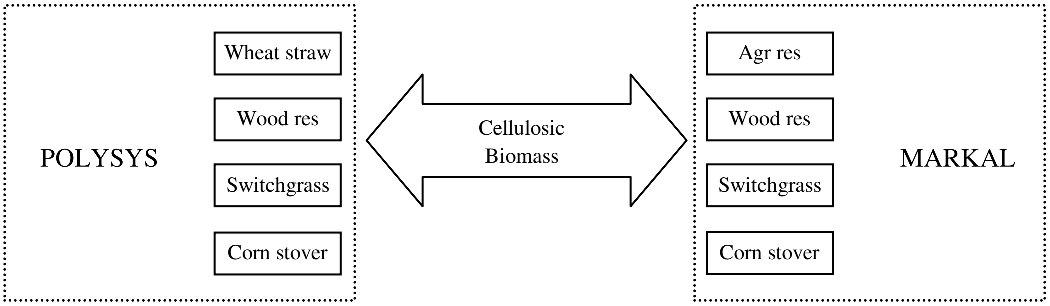

Figure 3.4 Concept of cellulosic biomass commodity linkage as a single commodity between POLYSYS and MARKAL modeling framework

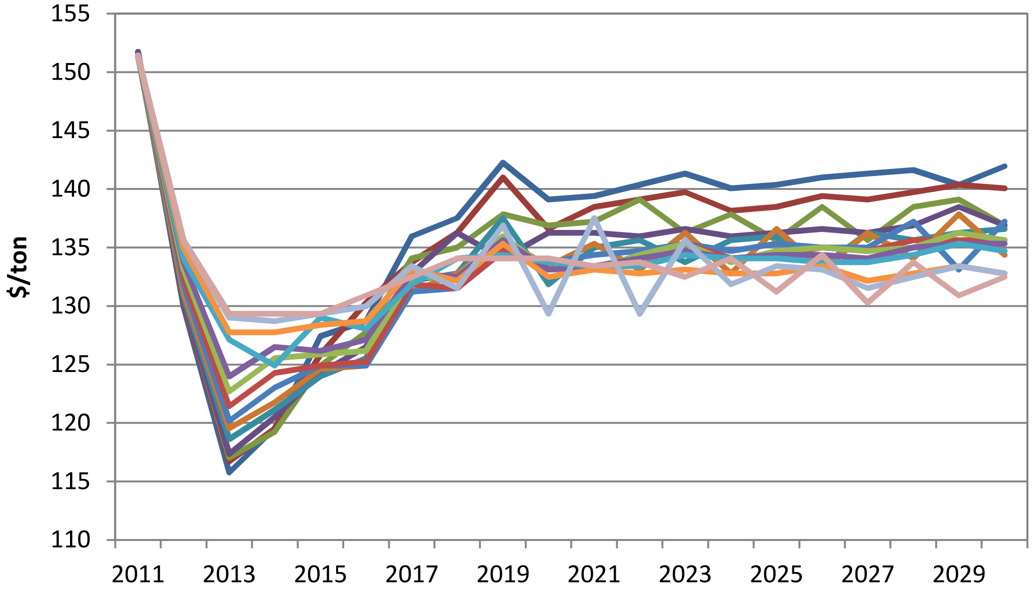

Figure 3.5 Corn grain prices for the selected exogenous biomass prices in POLYSYS during 2011-2030

The yearly maximum corn supply for each set of these corn grain prices is computed in POLYSYS as below:

$$MaxCS_t = Cornbc_t + StCorn_{t-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3.3)$$

Where,

$MaxCS$ = Yearly maximum available corn grain supply;

$Cornbc$ = Corn grain consumption to meet corn ethanol demand in the USDA base case in POLSYS;

$StCorn$ = Year end potential stock of total corn grain

t = year

$STCorn$ is estimated by remaining stock after estimating clearing the corn grain demand for separate demand functions. It is estimated as below:

$$STCorn_t = StCorn_{t-1} + Prod_t + Imp_t - Feed_t - Food_t - Seed_t - Exp_t \quad \ldots\ldots\ldots\ldots\ldots \ (3.4)$$

Where,

$Prod$ = Production of corn grain;

Imp = Imports of corn grain;

$Feed$ = Corn grain for feed use;

$Food$ = Corn grain for food use;

$Seed$ = Corn grain for seed use and

Exp = Exports of corn grain.

These maximum yearly corn supplies are linked to the corresponding corn prices as computed earlier. Thus, the maximum ceiling of corn grain supply for each year is computed from the estimation (Figure 3.6). It is imposed as a constraint in MARKAL for the maximum possible corn grain supply for corn based ethanol production during 2010 – 2030.

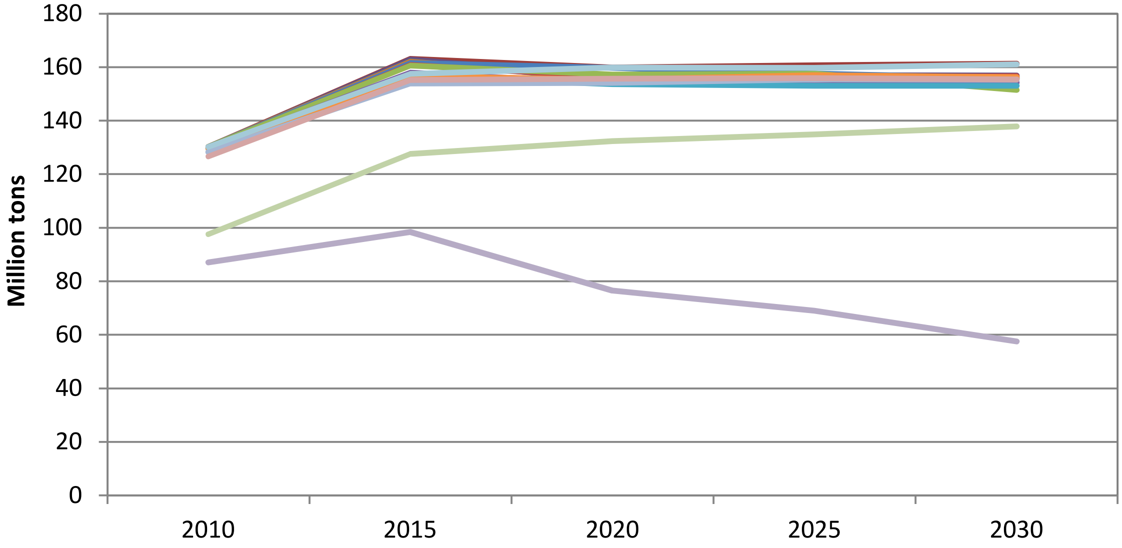

Figure 3.6 Maximum possible corn grain supply during 2010 – 2030 with respect to the selected 14 exogenous biomass price runs

3.2.2 Description of Scenarios

In this study, a reference and two alternative scenarios are constructed as below:

i) Base Case: Reference Scenario

This scenario reflects the renewable fuel standards as mandated in EISA until 2022 and follows the trend of biofuel supply according to the Annual Energy Outlook (AEO) 2010. POLYSYS has its basic database for agriculture inputs and outputs anchored to the projection of the United States Department of Agriculture (USDA). The USDA projection for ethanol supply shows corn ethanol supply, however, it projects no contribution from cellulosic ethanol till 2020 contrary to the EISA mandate. On the other hand, the Annual Energy Outlook projects cellulosic ethanol supply from 2015 onward and projects less (about 25.7 billion gallons) than the renewable fuel mandate (36 billion gallons). However, the corn ethanol demand in both projections are similar. So, it is wise to assume in the base case that there will only be corn ethanol supply till 2020 according to the USDA projection and after 2025, cellulosic ethanol and other advanced biofuels supply will follow to an extent close to the AEO projection (Figure 3.7).

Further, the reference scenario assumes that the current subsidy for corn ethanol and cellulosic ethanol will be continued until 2030. This scenario basically assesses the scenario where there is the least potential to have a diversion from the current scenario. In MARKAL, the planning horizon is 45 years from 2000 to 2050 with the base year 2000. The simulation in POLYSYS is until 2032. In this study, the issues are discussed for the period 2010-2030.

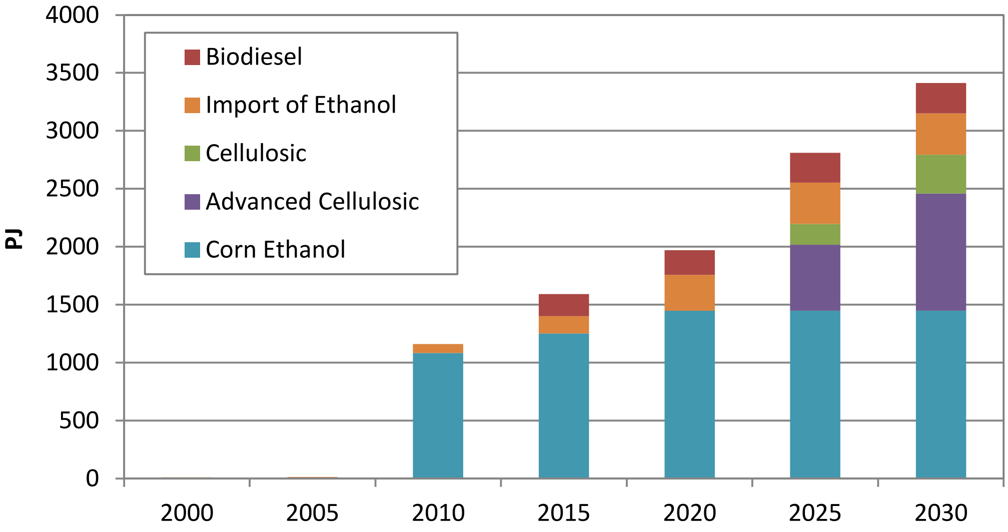

Figure 3.7 Biofuels production in the base case during 2000 – 2030

ii) Sub 1: Discontinued Subsidy for Corn Ethanol After 2013

This scenario basically analyzes the "what if" scenario. What if the subsidy for the corn ethanol be discontinued after 2013 while the subsidy for cellulosic ethanol be continued until 2030, all else equal.

iii) Sub 2: No Subsidy for Corn and Cellulosic Ethanol After 2013

This scenario analyzes the "what if" effect of phasing out of both corn and cellulosic subsidies. The scenario assumes that the subsidies will be phased out from 2013.

CHAPTER 4

BASE CASE SCENARIO ANALYSIS

4.1 Introduction

This chapter introduces and analyzes the base case scenario. The chapter provides information on *end-use demand* (service demand) in the transportation sector which is seen as a driving factor in the MARKAL model. These service demands are categorically and exogenously estimated into the model. The chapter also highlights technologies used in the model which explains the techno-economic characteristics of existing and future ethanol production technologies that are available in the base case. The biofuel requirement as a result from MARKAL is described in the chapter. Energy and agriculture issues: primary energy requirement, cost effective ethanol production technology, requirement of feedstocks for ethanol production, seasonal average prices of the selected crops and land use are analytically analyzed.

4.2 End-use Demand in the Transportation Sector

The transportation sector is characterized by nine end-use demands[3], 1129 end-use technologies and 12 energy carriers in MARKAL. The end-use demands are in Table 4.1 (for more details on demand estimation, please refer Shay et al., 2008):

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[3] These are service demands e.g., lighting, passenger miles etc. and these are exogenous parameters in the model.

Table 4.1 End-use demands in the transportation sector

End-Use Demands	**Units**	**2000**	**2010**	**2020**	**2030**
Domestic Air Transport	Billion passenger miles	541	612	729	814
Bus Transport	Billion vehicle miles travelled	10	11	11	12
Heavy Trucks*	Billion vehicle miles travelled	210	250	304	351
Personal Vehicles - Light Duty Vehicles	Billion vehicle miles travelled	2,462	2,815	3,372	4,066
Rail Freight Services	Billion ton miles	1,503	1,702	1,932	2,147
Rail Passenger Services	Billion vehicle miles travelled	1	2	2	2
Domestic Marine Freight Transport	Billion ton miles	591	643	701	721
Off-Highway Diesel	PJ	1,509	2,064	2,596	3,034
Off-Highway Gasoline	PJ	766	785	799	813

* greater than 10,000 lbs

(Source: Shay et. al., 2008)

Different types of the 1083 light duty vehicles (LDV), 16 heavy duty trucks, 16 buses, 5 air transport technologies, 4 public transport, 1 rail, 2 ship and 2 off-highway technologies are considered as end-use technologies. Likewise, the energy carriers are electricity, diesel, gasoline, compressed natural gas (CNG), 85% ethanol blend with gasoline (E85), hydrogen, jet fuel, liquefied petroleum gas (LPG) and residual fuel oil. Also separate flow of compressed natural gas (CNGX), 85% ethanol blend with gasoline (E85X) and liquefied petroleum gas (LPGX) are considered for flex-fuels.

4.3 Technology Selection

4.3.1 Existing Corn Based Ethanol Production Technology

USEPA (1998) surveyed ethanol cost of production in 1998 and reported two types of technology commonly known as dry milling and wet milling. Altogether the dry and wet milling technology produces corn based ethanol with an annual capacity of 80 PJ and 92 PJ respectively in year 2000. Since these technologies are already in operation, their variable operation and maintenance costs are only considered in this study. These costs are $ 2.96 million/PJ of ethanol production for dry milling and $ 3.55 million/PJ of ethanol production for wet milling. They are assumed to have a life of 20 years. It is assumed that once these are absolute, no such technology will be viable in future. The techno-economic characteristics of the technology are given in Table 4.2.

4.3.2 Future Corn Based Ethanol Production Technology

There are four types of future corn based ethanol production technology considered in the study. They are dry milling with natural gas or coal operated with or without a combined heating power (CHP). Ethanol yield in the future is assumed to increase from 2.7 gal/bu in 2005 to 3 gal/bu by 2030 (figures taken from POLYSYS). The techno-economic characteristics of these future technologies are given in Table 4.3.

Table 4.2 Existing corn based ethanol production technology characteristics

Input requirement	**Unit**	**Dry mills: existing**	**Wet mills: existing**
Corn	Mt/PJ	0.118	0.118
Electricity	PJ/PJ	0.043	0.030
Natural gas	PJ/PJ	0.403	0.173
Coal	PJ/PJ	0.052	0.128
Gasoline	PJ/PJ	0.074	0.074

(Source: Shapouri, Gallagher and Graboski, 2002; Shapouri and Gallagher, 2005)

Table 4.3 Future corn based ethanol production technology characteristics

Input requirement	**Unit**	**New Dry Mill**			
		NGas: no CHP	**NGas: CHP**	**Coal: no CHP**	**Coal: CHP**
Corn requirement	Mt/PJ	0.116	0.113	0.116	0.113
Electricity requirement	PJ/PJ	0.030	0.004	0.035	0.032
Natural gas requirement	PJ/PJ	0.384	0.412	-	-
Coal requirement	PJ/PJ	-	-	0.48	0.52
Gasoline requirement	PJ/PJ	0.074	0.074	0.074	0.074
Investment cost	M$/PJ	14.1	14.8	14.1	15.2
Variable O & M Cost	M$/PJ	1.84	1.84	1.84	1.84

(Source: USEPA, 2007; USEPA, 2005)

4.3.3 Cellulosic Based Ethanol Production Technology

Some ethanol production technologies using cellulosic feedstock are in early research phase whereas some technologies are in an advanced research phase. We have considered two types of cellulosic ethanol production technology. They are: a) Biochemical (fermentation) and b) Thermochemical (gasification – Fischer Tropsch Liquid (FT Liquid). Biochemical based technologies are in an advanced stage of research and deployment whereas thermochemical based technologies producing synthetic gas are in an early stage of research. The techno-economic characteristics of these technologies are given in Table 4.4 – 4.5.

4.4 Total Primary Energy Requirement

The total primary energy requirement (TPES) is shown in Figure 4.1. It shows that the TPES gradually increases by an annual average growth rate of 0.23% during 2010-2030. During the period, the share of crude oil which has the highest share in the total primary energy requirement will be reduced from 34.1% in 2010 to 30.2% by 2030. Likewise, the share of natural gas and coal will also decrease from 27.9% and 22.3% to 25.6% and 18.5% by 2030 respectively. However, the share of petroleum products will increase from 9.4% in 2010 to 11.2% in 2030. Biomass, which otherwise provides a nominal share (1.6%) in 2010, will provide a significant share (9.3%) in 2030 as the cellulosic based ethanol production technology is introduced in 2025.

Table 4.4 Selected cellulosic based ethanol production technology characteristics (which are assumed to be in advanced research phase)

Details	**Units**	**Biochemical**	**Indirect gasification**	**Direct gasification**
Ethanol Yield	gal/dry ton	69.56	80.1	65.3
Biomass Feedstock Use	MM dry ton	0.77	0.81	0.81
Coal used	MM dry ton	-	-	-
Ethanol Production	MM gal/yr	53.74	61.8	50.4
Denatured Ethanol Production	MM gal/yr	56.22	65.1	53.1
Total Installed Capital - Equipment Cost	MM $	113.7	137.2	182.7
Total Capital Investment	MM $	179.4	NA	NA
Total Project Investment	MM $	197.4	190.8	254.1
Total operating costs	$/gal eth	1.068	1.012	1.516
(a) Feedstock, incl. biomass to boiler	$/gal eth	0.334	0.437	0.536
(b) Non-feedstock Raw Materials	$/gal eth	0.184	0.026	0.010
(c) Waste disposal	$/gal eth	0.029	0.004	0.003
(d) Electricity	$/gal eth	-0.093	0	-0.003
(e) Fixed Costs	$/gal eth	0.109	0.195	0.289
(f) Capital depreciation, tax, ROI	$/gal eth	0.503	0.557	0.890
(g) DDG Credit	$/gal eth	-	-0.207	-0.208
Net operating cost (Total Op cost – a – d - g)	$/gal eth	-	0.38	0.695
Excess Electricity Generated	kWh/gal eth	4.28	-	0.611
	kWh/dry ton	311	-	40
Gasoline as denaturant	MM gal/yr	2.481	3.253	2.653
Year introduced		2010	2020	2020

(Source: Aden et al., 2002; Phillips et al., 2007; Dutta and Phillips, 2009)

Table 4.5 Selected cellulosic based ethanol production technology characteristic (assumed to be in early stage of research)

Details	**Units**	**100% switchgrass BTL-RC-V**	**29% biomass, 71% coal CBTL-OTA-V**	**40% biomass, 60% coal, CBTL-OT-V**
Coal Feedstock	MM dry ton		1.69	1.06
Switchgrass Feedstock	MM dry ton	1.18	1.18	1.18
Ethanol Production	MM gal/yr	23.08	55.55	41.02
Biodiesel Production	MM gal/yr	39.30	94.58	69.85
Total Installed Capital - Equipment Cost	$/GJ of FT	13.80	13.60	14.70
Total Operating Costs	$/GJ of FT	3.60	3.50	3.80
Excess Electricity Generated	kWh/yr	331.13	3216.67	2373.08
	kWh/dry ton	281.49	2734.43	2017.31
Year Introduced		2025	2025	2025

(Source: Liu et al., 2010)

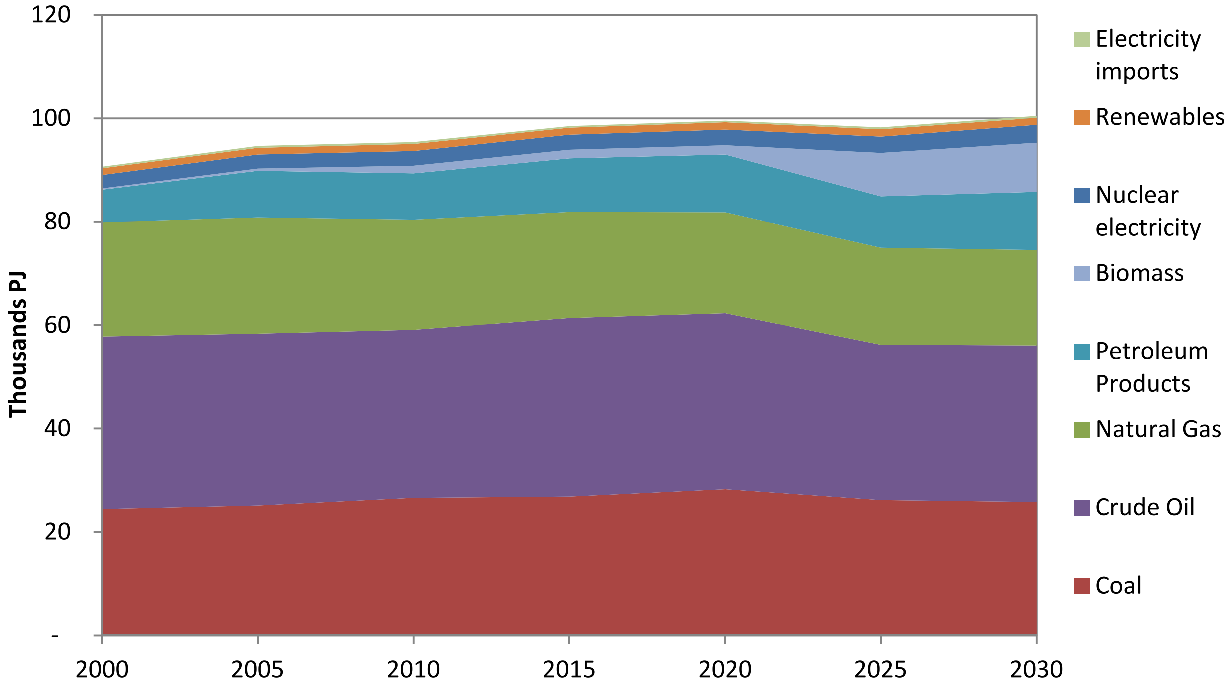

Figure 4.1 Total primary energy production during 2000 - 2030

4.5 Biofuel Demand and Feedstock Requirement

As discussed in the methodology, the biofuel production in the base case is estimated to follow the combination of the AEO 2010 for cellulosic ethanol and the USDA baseline for corn ethanol. So, there will be no cellulosic ethanol until 2020 in the base case according to the USDA baseline. The result of the least cost minimization from MARKAL is shown in Table 4.6. The results show that the biofuel production will gradually increase by 2030. The production of corn ethanol gradually increases to its maximum supply by 2030 and thus, the corn ethanol production meets the maximum supply by 2030. As cellulosic based ethanol comes into market, its production will increase from 2.3 billion gallons in 2025 to 4.1 billion gallons by 2030. Likewise, the production of advanced cellulosic ethanol will also increase from 4.5 billion gallons in 2025 to 8.7 billion gallons by 2030. There will be a small portion of the domestic ethanol demand and is constantly supplied by imports. Also, there will be a small increase in biodiesel production during the period (from 0.6 billion gallons in 2010 to 0.8 billion gallons by 2030) (Table 4.6).

The requirement of feedstocks for ethanol productions gradually increases as ethanol demand increases (Figure 4.2). The corn requirement gradually increases from 5,127 million bushels to about 5,900 million bushels by 2016, which is the maximum available corn feedstock for ethanol production. Likewise, the requirement of the dedicated energy crops (switchgrass, poplars and willows) will gradually increase from 0.1 million tons in 2014 to 482.7 million tons in 2030. Among the requirement of dedicated energy crops, switchgrass will have the highest share (89%) followed by poplars (9%) and willows (2%). The requirement of crop residues will gradually increase from 6.3 million tons in 2012 to 123 million tons in 2030. In a similar trend, wood residues, which gradually increase from 3.3 million tons in 2018 to 42 million tons in 2030.

There will be a small increment in the requirement of soybeans during the period (96 million bu in 2011 to 121 million bu in 2030).

Table 4.6 Biofuels productions during 2010-2030 (billion gallons)

Fuel Type	**2010**	**2015**	**2020**	**2025**	**2030**
Corn	11.7	13.9	15.1	15.1	15.3
Cellulosic	0.0	0.0	0.0	2.3	4.1
Advanced Cellulosic	0.0	0.0	0.0	4.5	8.7
Imports	0.8	1.6	3.3	3.7	3.7
Biodiesel	0.6	0.9	0.8	0.8	0.8

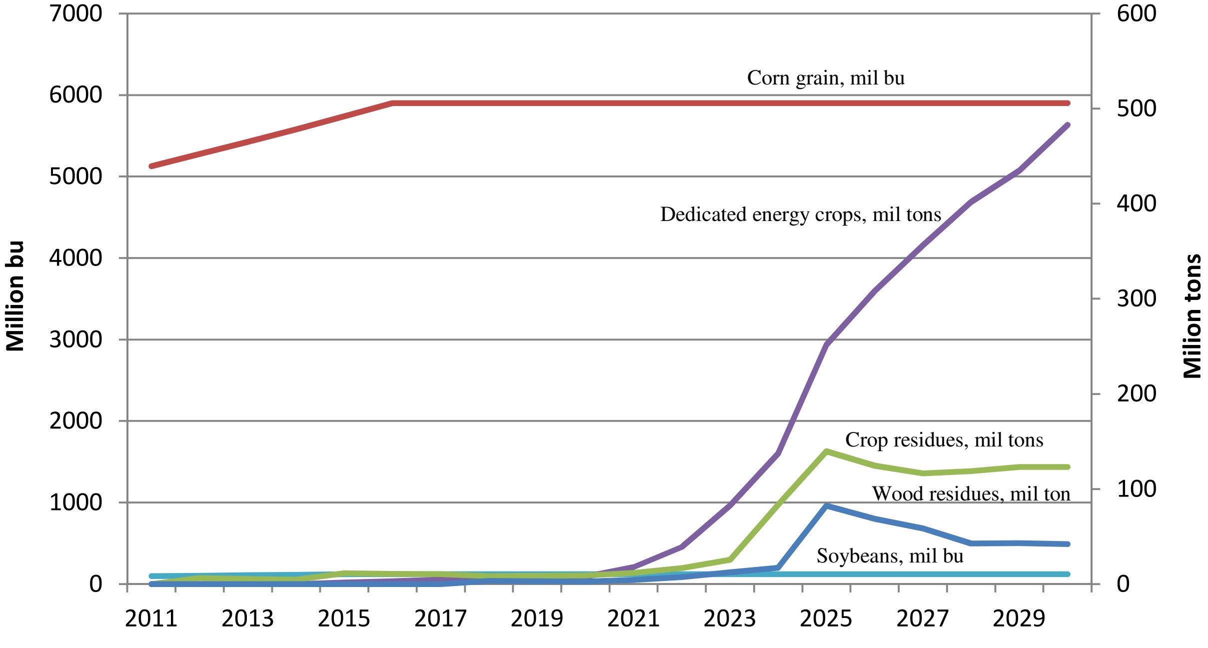

Figure 4.2 Biomass feedstock requirements for biofuels production during 2011-2032

4.6 Ethanol Production Technology

The cost effective technology path among the selected ethanol production technologies in the base case is shown in Figure 4.3. Among the selected corn based ethanol production technology, wet milling technology will cease ethanol production from 2010 onward whereas the existing dry milling without combined heat and power (CHP) will operate till 2025 in the base case. The dry milling with combined heat and power is the most cost effective technology among the corn ethanol production technology. As the cellulosic ethanol production technology is introduced in 2025 onward, the Fischer Tropsch liquid technology that synthesizes 29% biomass with 71% coal takes up the largest share of the ethanol production from 2025 onward. Although biochemical cellulosic ethanol production technologies are available from 2015 onward, these will be cost effective only from 2025 onward. The indirect gasification ethanol production technology using 100% biomass will gradually increase from 2025. The result shows that the dry milling with CHP (corn based) will have the largest share (54%) in total ethanol production by 2030 followed by thermochemical ethanol production technology (31%) and biochemical cellulosic based technology (15%). This shows that the thermochemical ethanol production technology using a large portion of coal demands a larger quantity of biomass as a feedstock by 2030 and as the result, the cellulosic based ethanol takes up most of the ethanol production in the future as it becomes available.

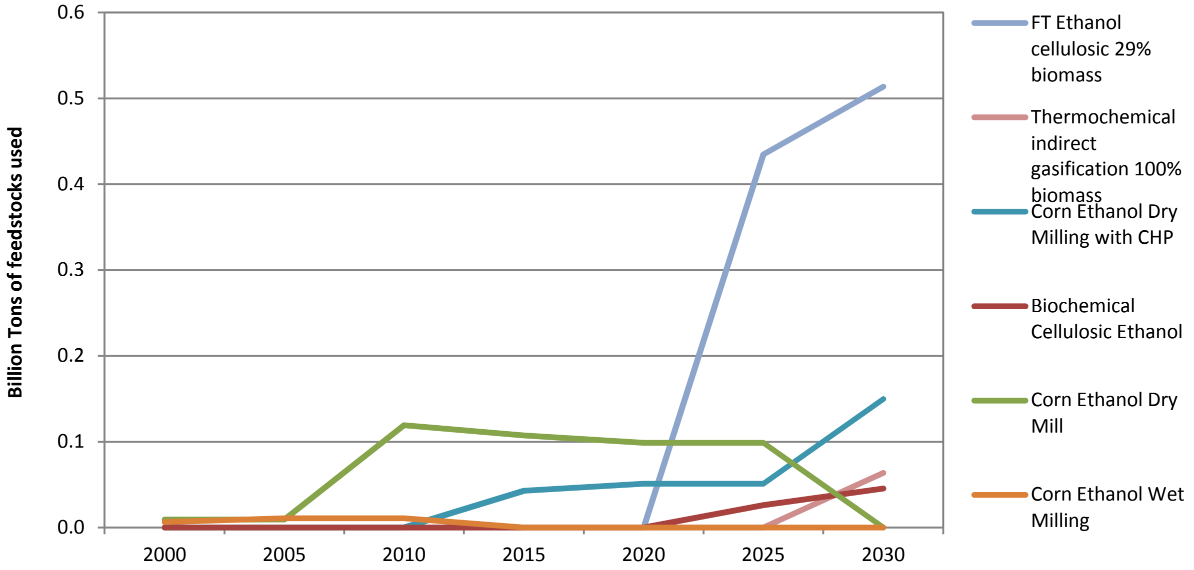

Figure 4.3 Requirement of feedstocks in the selected ethanol production technologies during 2000-2030

4.7 Seasonal Average Prices of the Selected Crops

As given in Figure 4.4, the prices of dedicated energy crops increase from $30/bu in 2011 to $39/bu in 2012 and it increases significantly to $77/bu in year 2030. The price of soybeans increases in 2025 onwards with a slight decline in 2026 in the base case and the price increases by about 15% during 2011-2030. The price of rice is steadily increased until 2030. There is over a 45% price increase in the price of rice noted during the period ($12.6/cwt in 2011 to $18.3/cwt in 2030). About a 29% price increase is noted in wheat ($6.5/bu in 2011 to $8.36/bu in 2030). The price of corn decreases during the years 2011 to 2024 going as low as $4.09/bu (in 2013) and sharply increases to $ 5.14/bu in 2026 and then declines a little during 2026 to 2030 ($4.86/bu in 2032). The final price of corn is found to have increased by 1% during 2011-2030.

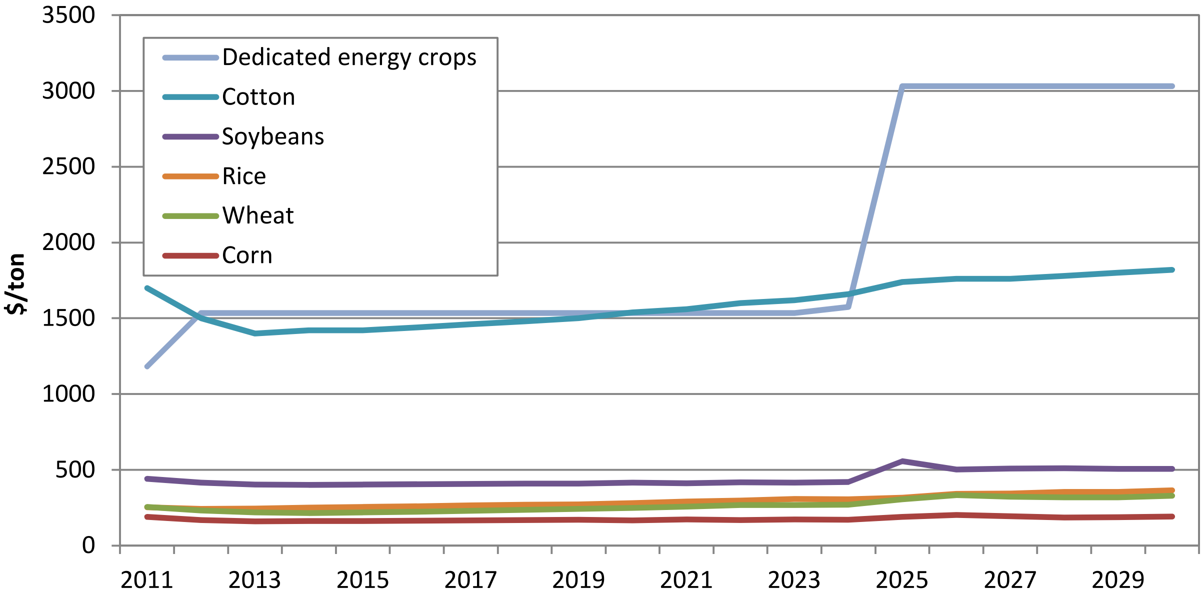

Figure 4.4 Seasonal average prices for the selected food and dedicated energy crops during 2011-2030

In the case of cotton, price increases by about 7% during the period. This shows that as the demand for ethanol increases, the prices of dedicated energy crops sharply increase and the price of rice is the most affected followed by wheat and soybean.

4.8 Land Use

The land uses for the selected crops in the base case are shown in Figure 4.5. The share of corn acreage declines from 29% in 2011 to 27.8% by 2030. Switchgrass acreage gradually increases from 2013 with a significant increase in 2025 and occupies 13.4% of the acreage by 2030. The share of wheat acreage significantly declines from 18% in 2011 to 13.4% by 2030 respectively.

Likewise, the share of cotton acreage slightly declines from 4% in 2011 to 2.4% in 2030. The shares of oats and rice acreage also slightly decline.

As seen in Figure 4.5, most changes take place from 2025 onward when cellulosic ethanol is introduced. As there is increase in cellulosic ethanol demand, switchgrass acreage is also increased. However, the increase in switchgrass acreage reduces the acreage of other crops. The most significant effect on the reduction of acreage is seen on wheat followed by corn.

There will be an increasing pressure on hay acreage in pasture land as the result of an increase in switchgrass, poplar and willow acreage in pasture lands. Thus, the available pasture land will gradually decrease from 461 million acres in 2011 to 393 million acres by 2030 (Figure 4.6).

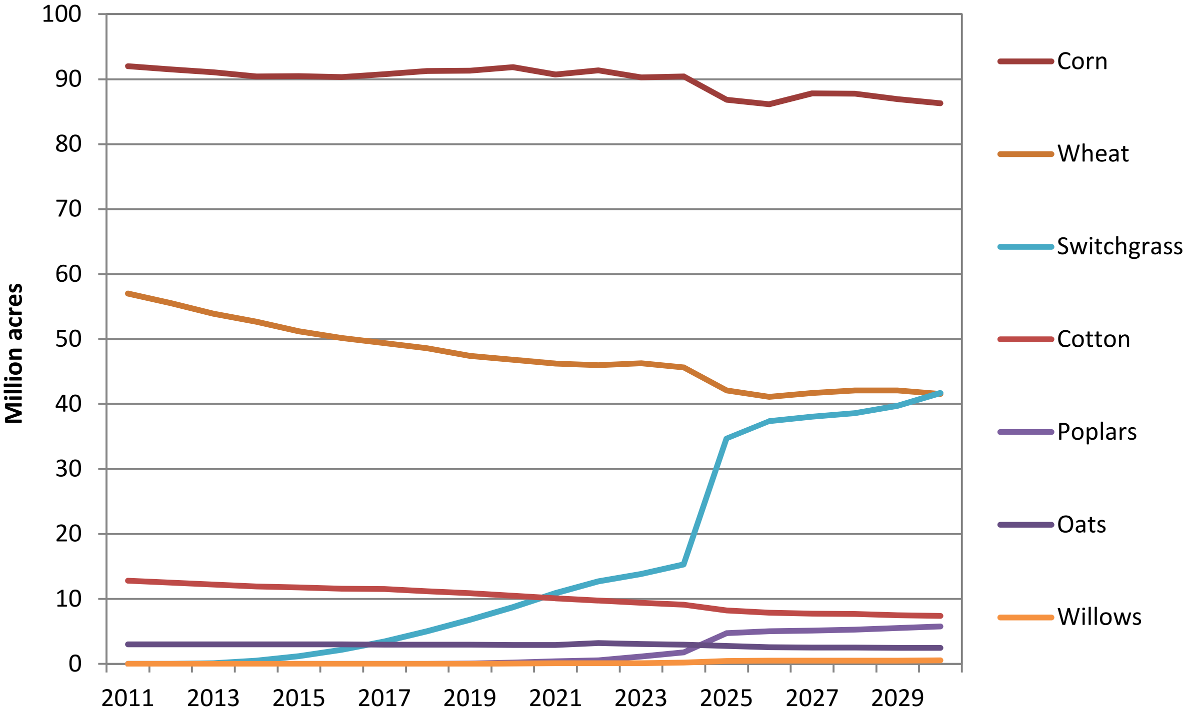

Figure 4.5 Acreage of the selected crops during 2011-2030

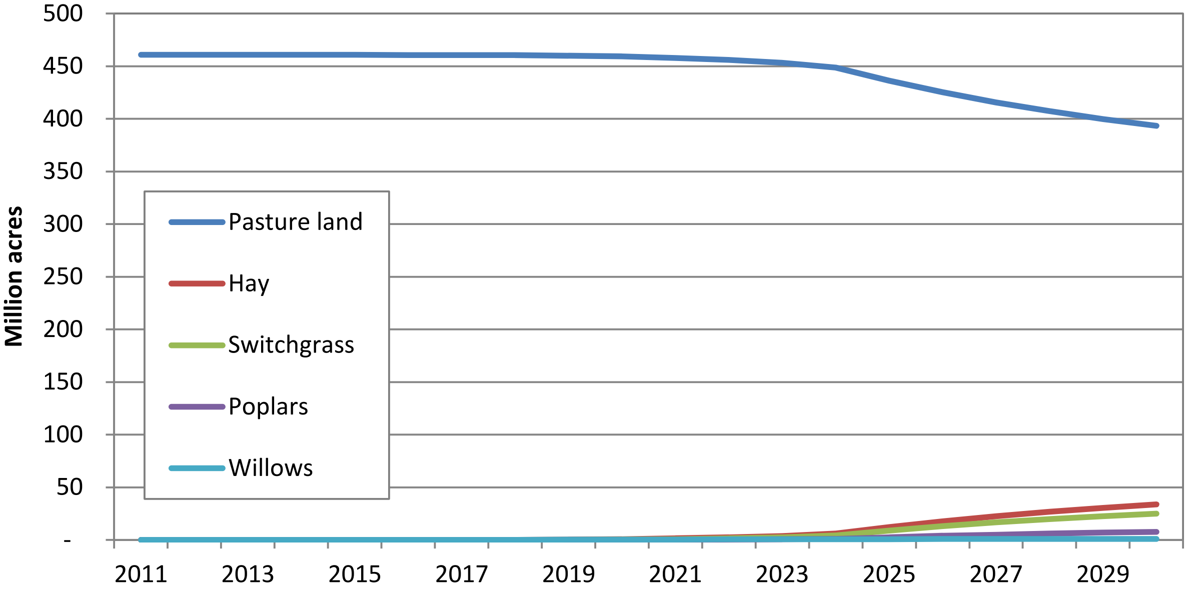

Figure 4.6 Acreage of the pasture land during 2011-2030

CHAPTER 5

ALTERNATIVE SCENARIO ANALYSIS

5.1 Introduction

This chapter compares and analyzes the issues in the alternative scenarios with respect to that in the base case which is discussed in the previous chapter. The alternative scenarios are the two subsidy scenarios. The first alternative scenario is the Sub1 scenario in which the current subsidy to the corn ethanol is assumed to be phased out from 2013 onward while the subsidy to the cellulosic ethanol will be continued until 2030. The second scenario is Sub2 scenario in which the current subsidy to the corn and cellulosic based ethanol is assumed to be completely phased out from 2013 onward, all else equal. The chapter basically highlights the effects of changes in the subsidies in the alternative scenarios. These effects are described as changes on the primary energy requirements, biofuel requirements, future ethanol production technologies, requirement of feedstocks for ethanol production, seasonal average prices of selected crops and land use.

5.2 Effects on Total Primary Energy Supply

The changes in the total primary energy supply (TPES) in an energy economy basically show the effect on service efficiency of the energy system while meeting the same service demands. Increases in the TPES basically mean declining service efficiencies and vice versa. In the two alternative scenarios even though both scenarios have removal of the subsidies, the effect on the total primary energy supply has been opposite during 2010-2030 (Table 5.1). In Sub1 scenario, there was a reduction in the TPES whereas in Sub2 it increased. This shows that the phasing out of subsidy to the corn ethanol improves the service efficiency of the energy sector from that in the base case scenario where as removing the subsidy to the cellulosic ethanol damages the service efficiency as it requires more energy than the base case to meet the same service demand. With the subsidy being phased out to the corn ethanol, the biggest effect is seen on the demand of corn which declines by an aggregate quantity of 1,821 PJ (shown as 'biomass' in Table 5.1) followed by coal (1,158 PJ) and natural gas (96 PJ) during 2010-2030. The reduction of coal and natural gas along with biomass is because the dry milling technology used for corn based ethanol production also uses coal and natural gas. Corn ethanol declines as the result of the subsidy being phased out and corresponding feedstock requirements are also reduced.

Table 5.1 Changes in total primary energy supply during 2010 – 2030 (PJ)

Fuel Types	**Base case**	**Change from the base case**	
		Sub1	**Sub2**
Coal	537,353	(1,158)	(1,728)
Natural Gas	393,806	(96)	93
Crude Oil	649,792	597	5,217
Petroleum Products	207,721	631	1,017
Renewables	28,340	-	-
Biomass	87,320	(1,821)	(3,187)
Nuclear electricity	60,697	-	-
Electricity imports	6,660	-	-
Total	1,971,688	(1,848)	1,411

Interestingly, there is an increase in the requirement of crude oil and the petroleum products by 1,007 PJ and 631 PJ respectively. Crude oil and petroleum products basically compete with ethanol to meet the service demands in the transportation sector and thus substitute reduction in corn ethanol. In total, there was a reduction of 1,848 PJ in TPES in the Sub1 scenario which is about a net reduction by about 0.1% from that in the base case.

In Sub2, removal of subsidy to cellulosic ethanol increases the total primary energy supply by 1,411 PJ (about 0.1% increase from that in the base case) which basically shows that the service efficiency of the system in Sub 2 declines from that in the base case during 2010-2030. The most significant effect is seen on biomass (reduction by 3,187 PJ followed by coal (reduction by 1,728 PJ). The requirement of crude oil, petroleum products and natural gas is increased by 5,217 PJ, 1,017 PJ and 93 PJ respectively during 2010-2030. This also shows that the removal of subsidies to cellulosic ethanol will decrease coal and increase natural gas and petroleum products in the economy. The increase crude oil, petroleum products and natural gas basically substitute the reduction in cellulosic ethanol as the subsidy was removed.

5.3 Effects on Biofuel Demand

In the Sub1 scenario, with the phasing out of subsidy for corn ethanol, the cumulative production for ethanol decreases by about 7% from that in the base case. Further, the result shows that it also has implications on cellulosic ethanol demand. The requirement of biochemical based cellulosic ethanol will be increased by 35% whereas the requirement of thermochemical cellulosic based ethanol will be decreased by 2%. In an aggregate, the total cellulosic ethanol requirement increases by 10% from that in the base case during 2010-2030. It implies that with the decrease in the corn demand as the subsidy is phased out, it will leverage the demand for cellulosic ethanol.

In the Sub 2 scenario, the phasing out of the subsidy to cellulosic ethanol will take the biochemical based cellulosic ethanol completely out of market whereas, thermochemical cellulosic ethanol will see a huge reduction in demand by 19% from that in the base case during 2010-2030. Also since this scenario also has a phasing out of subsidies to corn, corn ethanol will also see a reduction of 10% demand from that in the base case which is higher than the reduction in Sub1 scenario (Table 5.2).

5.4 Effects on Ethanol Production Technology Selection

As seen in Table 5.3, in the Sub1 scenario, corn ethanol from dry milling with CHP will decline by 19% from that in the base case. As discussed in the above section about changes in cellulosic ethanol as the result of phasing out subsidy to corn ethanol, there will be a reduction by over 12% in thermochemical indirect gasification based ethanol production whereas the biochemical based cellulosic ethanol production will see an increase by over 34% from that in the base case. In the absence of a corn ethanol subsidy, the biochemical based cellulosic ethanol production is marginally more cost effective than the indirect gasification based cellulosic ethanol while it does not make any difference to the Fischer Tropsch liquid technology based cellulosic ethanol.

In Sub2, there will be a significant reduction in cellulosic ethanol production from both biochemical (67%) and indirect gasification technology (50%) whereas there is no change in the cellulosic production from the Fischer Tropsch liquid technology. There will also be a reduction in the corn ethanol production from dry milling with CHP technology (26%). This simply shows that the Fischer Tropsch liquid technology based cellulosic ethanol production is the most cost effective technology followed by the indirect gasification and biochemical technology based cellulosic ethanol production in the scenario (Table 5.3).

Table 5.2 The percentage change in cumulative ethanol and biodiesel productions during 2010-2030

Fuel types	Base case in billion gallons	% change from the base case	
		Sub1	Sub2
Corn ethanol	288	(7)	(10)
Biochemical Cellulosic ethanol	22	35	(100)
Thermochemical Cellulosic ethanol	45	(2)	(19)
Biodiesel	16	0	0

Note: Figures in the parentheses are percentage reductions.

Table 5.3 The percentage change in cumulative ethanol production from the selected technology during 2010-2030

Biofuel Production Technology	Base case in PJ	% change from the base case	
		Sub1	Sub2
Biochemical Cellulosic Ethanol	244	34	(67)
Corn Ethanol Dry Mill	1,821	0	0
Corn Ethanol Dry Milling with CHP	1,100	(19)	(26)
Corn Ethanol Wet Milling	27	0	0
FT Ethanol Cellulosic 29% Biomass	3,456	0	0
Thermochemical Indirect Gasification 100% Biomass	160	(12)	(50)

Note: Figures in the parentheses are percentage reductions.

5.5 Effects on Seasonal Average Prices of the Selected Crops

As shown in Figure 5.1, there is no significant change in the seasonal average prices of the selected food crops and dedicated energy crops in the Sub1 scenario but it is noted that in the Sub2 scenario, phasing out of cellulosic ethanol have significant effects on the prices of these crops. In the Sub2 scenario, the prices of the selected food crops and dedicated energy crops are decreased from year 2025 (Figure 5.2). The prices of dedicated energy crops are decreases by about $11/bu from 2025 until 2030. This shows that the phasing out of subsidy of corn basically has no effect on food crops and dedicated energy crop prices whereas the phasing out of the subsidy to cellulosic ethanol significantly reduces the prices of food crop and dedicated energy crops.

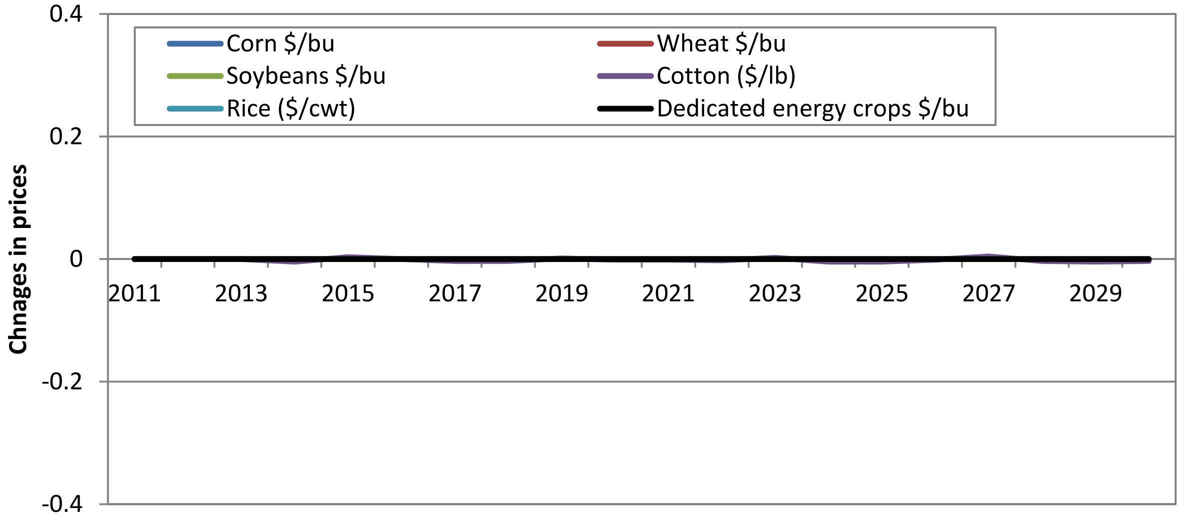

Figure 5.1 Changes from the base case in seasonal average prices of the food crops and dedicated energy crops in the Sub1 scenario during 2011-2030

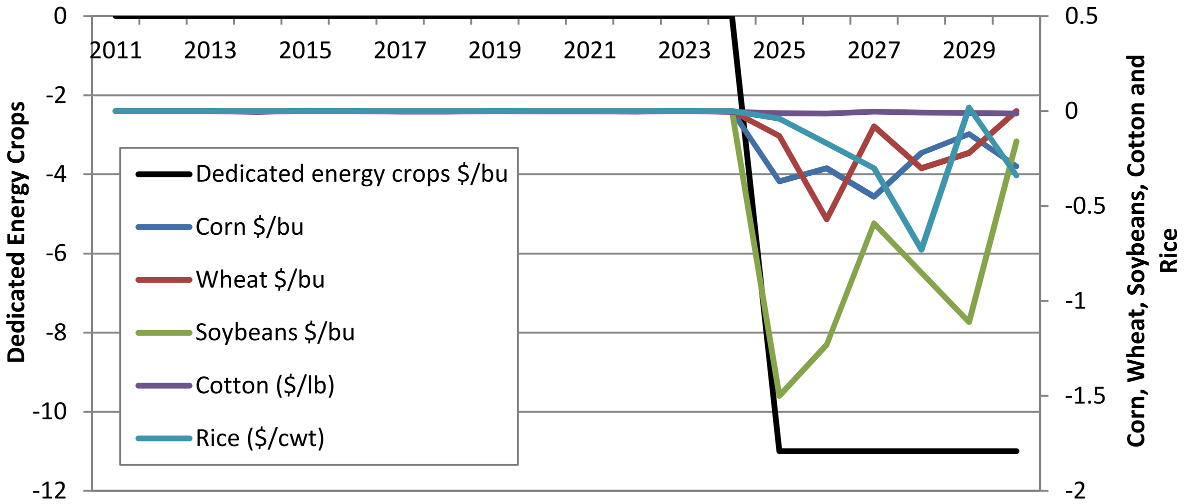

Figure 5.2 Changes from the base case in seasonal average prices of the food crops and dedicated energy crops in the Sub2 scenario during 2011-2030

5.6 Effects on Land Use Changes

The effect on land use for the selected food crops and dedicated energy crops in the two alternative scenarios are shown in Figure 5.3 and 5.4. In the Sub1 scenario, the results show that there is no significant difference in land used for the selected food and dedicated energy crops from that in the base case. However, in the Sub2 scenario, the acreages of the selected food crops are increased and the acreages for the dedicated energy crops are decreased. Among the dedicated energy crops, while the acreage of willows slightly increases during the period of 2025 – 2030, the acreages of switchgrass and poplar significantly decrease. These changes in the land use are observed effectively from year 2025. Among the food crops, the acreages of soybeans and corn significantly increases while the acreage of oats, cotton and rice are slightly increased. The acreage of grain sorghum is slightly decreased. The acreages of barley and wheat are not significantly affected.

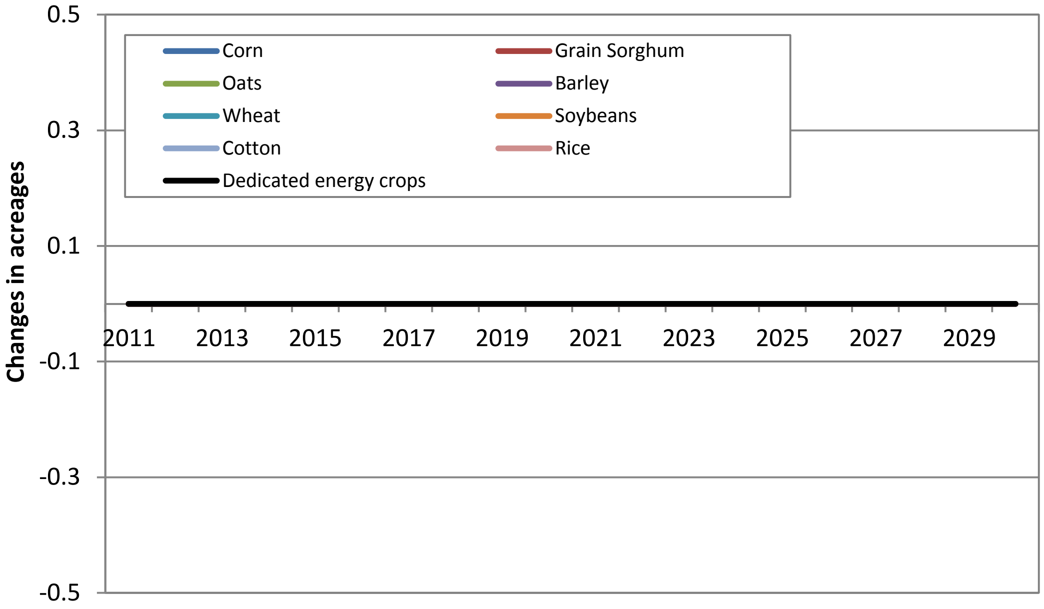

Figure 5.3 Changes in crop acreage from the base case in Sub1 scenario during 2011-2030

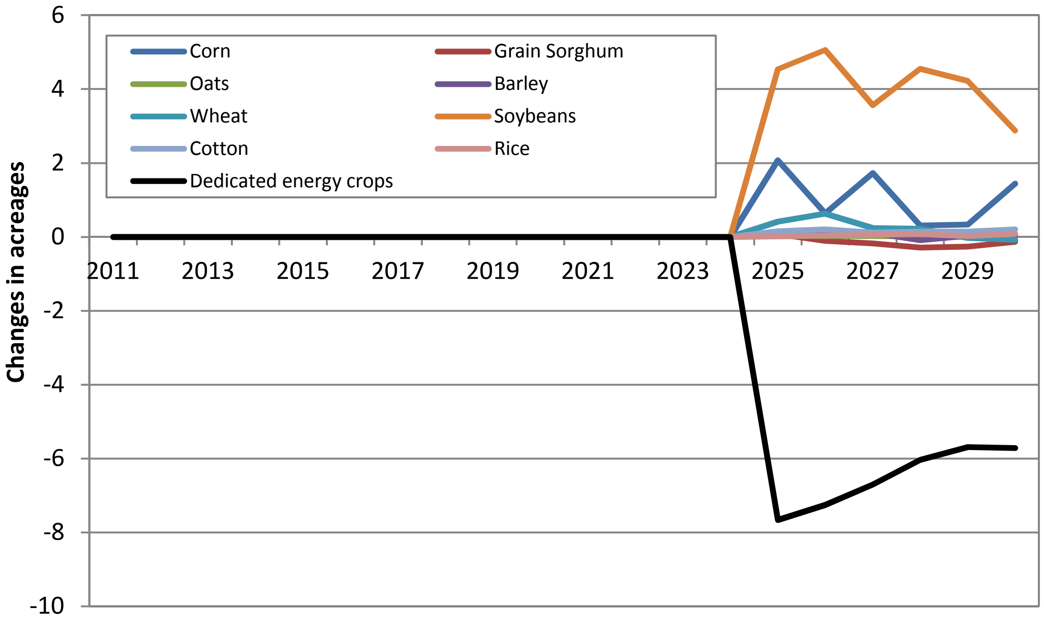

Figure 5.4 Changes in crop acreage from the base case in Sub2 scenario during 2011-2030

CHAPTER 6

SUMMARY AND CONCLUSIONS

The study is successful in linking two different sectoral models through a modeling framework in a pragmatic approach. The two different sectoral models: POLYSYS (agriculture sectoral model) and MARKAL (energy sectoral model) are soft-linked in an integrated framework in such a way that it captures the strength of price dynamics of biofuels demand in POLYSYS and the strength of least cost biofuel supply in MARKAL. As the result, the framework can now evaluate biofuel policy implications in an integrated modeling environment that evaluates the policy implications in the agricultural and energy sectors simultaneously. Since the strength of one model is a weakness for the other model, the assessment through the linkage is able to nullify the weaknesses of the two models and benefit their strengths. In a standalone model, MARKAL used to evaluate energy policy and likewise, POLYSYS used to evaluate agricultural policy. The evaluation conducted in a standalone framework used to ignore the possible effect on the other sector. This modeling framework in the study is now effective in evaluating the effects in both agricultural and energy sectors.

In the study, the modeling framework is also utilized to evaluate the subsidy policies provided to ethanol blenders. Three scenarios were constructed in both models: a) Base case, b) Phasing out of corn ethanol subsidy from 2013 onward and c) Phasing out of corn and cellulosic ethanol subsidy from 2013. In the base case scenario, it is noted that thermochemical technology takes up much of the cellulosic production from 2025 and the seasonal average price of dedicated energy crops significantly increases along with an increase the price of rice, wheat and cotton. The results show that the price of rice is the most affected because of the increase in cellulosic ethanol demand. The price of rice increases by over 45% during 2011-2030, whereas the price of corn increases by a small amount during the period (about 1%). The switchgrass acreage increases significantly and thus significantly displaces wheat followed by corn.

In the alternative scenario Sub1, the primary energy supply decreases by over 1,848 PJ whereas in the Sub2 scenario, it increases by over 1,411 PJ from that in the base case during 2010-2030. This basically shows that the service efficiency of the energy sector improves in Sub1 while the same declines in the Sub2 scenario. The most significant effect noted as the subsidies are removed is the increase in crude oil and petroleum products and a reduction in biomass and coal. Also noted that the phasing out the subsidy to corn ethanol will increase cellulosic ethanol productions but phasing out subsidy to cellulosic ethanol will reduce both corn and cellulosic ethanol productions. The results also show that advanced cellulosic ethanol productions will be cost effective even if subsidies are phased out. Such subsidies will significantly affect biochemical based ethanol production followed by indirect gasification technologies. Further, the results show that the phasing out the subsidy to corn ethanol has no significant effect on seasonal average prices of the selected food and dedicated energy crops; and also, no significant changes in the land uses of these crops. However, the phasing out of the subsidy to cellulosic ethanol, the prices significantly decrease from year 2025; the prices of dedicated energy crops decline by about $11/bu. Also, the acreages of the food crops such as corn, soybeans, cotton, rice increase while the acreages of dedicated energy crops decrease.

Thus, the modeling framework has effectively evaluated the implications of the subsidy policies linking both models. However, there are some limitations which should be considered while utilizing the linkage:

a) The linkage is an attempt to link two models with different philosophy of functioning. MARKAL optimizes with complete foresight in a planning horizon whereas POLYSYS optimizes yearly and thus use the optimized figures for the simulation in the next year. In addition, the MARKAL model has 5 year interval periods and the results are, thus, indicative of a trend rather than a point estimate. Since POLYSYS simulates year by year basis, its results are capable of yearly indications. During the linkages, data have been interpolated for the years in between its five year interval period while feeding the common information from the MARKAL. Thus, the results should be evaluated for a plausible scenario rather than a particular year.
b) The base case results from the linkage are based on the baselines from AEO 2010 and USDA 2011. The results in the base case in MARKAL are from the energy sector equilibrium after using some shadow prices in biofuels to achieve the given baselines. So, any changes in these baselines also require changes in the shadow prices and thus may change the equilibrium results.

Future Work

Some further works that can be carried out in this study:

a) Since this model linkage is a first attempt and due to several limitations, hard linkage of the model could not be carried out. It is plausible that a hard linkage within a module while simultaneously simulating the two models is desirable. Further, in such a linkage, the cost of production of fossil fuels can be linked to fuel inputs in POLYSYS which is not carried out in this study.

b) This study is an attempt where it has tried to address the need of evaluating effects of policy on two different sectors but further such evaluation cannot neglect the interactions with rest of the sectors in the economy and thus a general equilibrium framework may be needed. The estimates from the general equilibrium framework while linking these two models may provide an insight on the results due to macroeconomic factors in the economy.

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APPENDICES

Appendix A.1

Maximum Availability of Biomass Feedstocks and Corn Grain at the Selected 14 Exogenous Biomass Prices During 2010 – 2030 (Million Tons)

Switchgrass

Price ($/ton)	2010	2015	2020	2025	2030
100	0.0	25.6	199.1	290.3	330.2
95	0.0	52.1	222.7	287.0	340.4
90	0.0	49.4	214.5	280.5	334.8
85	0.0	46.8	207.3	274.3	325.0
80	0.0	43.6	198.4	267.8	317.0
75	0.0	40.8	190.8	261.7	309.4
70	0.0	37.7	180.5	254.0	300.6
65	0.0	33.4	166.3	243.8	290.4
60	0.0	27.9	146.8	226.4	273.6
55	0.0	19.4	109.2	185.8	235.2
50	0.0	10.7	62.0	106.9	148.6
45	0.0	5.6	37.5	62.4	74.8
40	0.0	0.0	2.5	19.2	46.4
37	0.0	0.0	0.0	0.3	3.2

Corn Stover

Price ($/ton)	2010	2015	2020	2025	2030
100	109.7	137.8	152.5	160.5	109.7
95	114.6	141.4	152.2	160.3	114.6
90	113.8	139.6	150.7	159.6	113.8
85	112.7	137.7	148.8	157.9	112.7
80	111.8	137.6	147.3	155.9	111.8
75	110.5	135.5	144.2	153.7	110.5
70	109.4	133.5	141.5	147.2	109.4
65	106.4	127.8	135.3	141.3	106.4
60	102.7	121.9	128.5	135.3	102.7
55	99.9	118.2	125.5	132.7	99.9
50	94.7	113.1	121.1	128.8	94.7
45	90.1	109.1	117.2	125.0	90.1
40	59.4	82.1	91.7	102.8	59.4
37	0.0	0.0	0.0	0.2	0.0

Appendix A.1 (Contd.)

Maximum Availability of Biomass Feedstocks and Corn Grain at the Selected 14 Exogenous Biomass Prices During 2010 – 2030 (Million Tons)

Agricultural Residue (Wheat Straw)

Price ($/ton)	2010	2015	2020	2025	2030
100	18.6	27.4	30.7	33.3	35.1
95	18.6	28.7	30.5	33.3	34.8
90	18.2	27.9	29.9	32.7	34.3
85	18.2	27.4	29.6	32.3	34.3
80	18.2	27.0	29.1	31.9	33.8
75	18.2	26.4	28.3	31.4	33.0
70	17.6	24.9	27.3	30.7	32.5
65	17.6	24.0	26.6	30.3	32.1
60	17.0	22.7	25.0	28.7	30.8
55	16.4	20.4	23.2	26.8	29.1
50	13.3	17.0	19.5	23.0	25.0
45	10.0	12.9	15.0	17.1	19.3
40	4.7	5.5	6.5	7.9	9.4
37	0.0	0.0	0.0	0.0	0.0

Poplar, Willows and Wood Residues

Price ($/ton)	2010	2015	2020	2025	2030
100	165.6	129.9	99.4	149.5	179.5
95	164.7	155.1	198.3	161.1	231.0
90	163.6	151.1	190.2	157.2	223.2
85	162.6	150.1	186.0	156.7	220.5
80	161.5	149.1	181.9	156.3	218.0
75	160.4	148.1	177.0	157.1	207.2
70	159.4	147.1	168.9	151.9	198.4
65	156.9	144.2	157.0	142.4	177.0
60	149.6	136.0	131.5	127.4	146.2
55	125.4	112.5	99.5	96.4	116.5
50	100.3	88.2	62.1	64.5	80.5
45	68.8	58.0	29.8	21.1	28.1
40	15.8	19.7	19.7	19.7	19.7
37	15.7	19.4	19.4	19.4	19.4

Appendix A.1 (Contd.)

Maximum Availability of Biomass Feedstocks and Corn Grain at the Selected 14 Exogenous Biomass Prices During 2010 – 2030 (Million Tons)

Corn Grain

Price ($/ton)	2010	2015	2020	2025	2030
100	130.23	162.82	156.47	157.23	157.03
95	130.23	162.97	156.98	157.99	156.95
90	130.23	163.10	158.27	158.25	157.49
85	130.23	162.46	159.87	159.06	157.79
80	130.23	162.11	158.43	159.09	158.78
75	130.23	161.68	159.24	160.30	158.04
70	130.23	160.94	159.54	159.49	160.15
65	130.23	160.20	159.54	159.80	159.03
60	130.23	159.47	159.06	160.00	158.86
55	130.23	159.09	159.16	159.87	159.24
50	130.23	159.80	159.64	159.85	159.24
45	130.23	158.30	159.34	160.36	160.10
40	130.23	157.77	158.68	160.71	160.10
37	130.23	157.41	159.82	159.80	161.24

Appendix A.2
Total Primary Energy Supply in Base Case during 2000 – 2030 (PJ)

Fuel Types	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Biodiesel	45	47	101	129	119	115	115
Natural Gas	22,113	22,507	21,292	20,492	19,532	18,834	18,516
Asphalt	144	218	218	223	228	233	238
Coal	24,271	24,873	26,370	26,652	28,032	25,913	25,550
Heating Oil	120	0	1180	1219	1310	1249	1217
Diesel	2,026	1,802	328	390	470	328	402
Imported Electricity	333	333	333	333	333	333	333
Imported Ethanol	10	13	78	149	311	356	356
Gasoline	2,163	3,404	1,038	988	935	1,007	1,079
Jet Fuel	251	555	842	857	689	873	933
Kerosene	58	431	532	389	90	158	81
LPG	810	992	1,220	719	793	876	967
LNG	208	0	1,458	3,966	5,035	3,966	5,035
Petrochemical Feedstocks	0	0	15	0	0	0	0
Residual Fuel Oil	632	898	1,395	892	820	402	387
Black Liquor	0	915	948	982	1,016	1,052	1,090
Crude Oil	33,392	33,246	32,519	34,489	34,041	30,036	30,266
Biomass	190	404	1,336	1,421	1,416	7,908	9,093
Municipal Solid Waste	0	0	43	55	93	109	127
Nuclear electricity	2,635	2,689	2,802	2,871	2,982	3,161	3,448
Renewables (solar, wind, geothermal, hydro electricity)	1,275	1,349	1,371	1,330	1,332	1,350	1,255
Total (PJ)	90,674	94,678	95,420	98,547	99,577	98,259	100,489

Appendix A.3
Total Primary Energy Supply in Sub1 Scenario during 2000 – 2030 (PJ)

Fuel Types	2000	2005	2010	2015	2020	2025	2030
Biodiesel	45	47	101	129	119	115	115
Natural Gas	22,113	22,507	21,292	20,516	19,530	18,807	18,485
Asphalt	144	218	218	223	228	233	238
Coal	24,271	24,873	26,370	26,501	28,013	25,953	25,348
Heating Oil	120	0	1,180	1,219	1,310	1,249	1,217
Diesel	2,026	1,802	328	390	470	328	402
Imported Electricity	333	333	333	333	333	333	333
Imported Ethanol	10	13	78	149	311	356	356
Gasoline	2,163	3,404	1,038	1,044	935	1,007	1,079
Jet Fuel	251	555	842	857	718	873	933
Kerosene	58	431	532	389	90	200	81
LPG	810	992	1,220	719	793	876	967
LNG	208	0	1,458	3,966	5,035	3,966	5,035
Petrochemical Feedstocks	0	0	15	0	0	0	0
Residual Fuel Oil	632	898	1395	892	820	402	387
Black Liquor	0	915	948	982	1,016	1,052	1,090
Crude Oil	33,392	33,246	32,519	34,662	34,038	30,012	30,214
Biomass	190	404	1,336	1,201	1,390	7,908	8,857
Municipal Solid Waste	0	0	43	55	93	109	127
Nuclear electricity	2,635	2,689	2,802	2,871	2,982	3,161	3,448
Renewables (solar, wind, geothermal, hydro electricity)	1,275	1,349	1,371	1,330	1,332	1,350	1,255
Total (PJ)	90,674	94,678	95,420	98,427	99,557	98,290	99,967

Appendix A.4
Total Primary Energy Supply in Sub2 Scenario during 2000 – 2030 (PJ)

Fuel Types	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Biodiesel	45	47	101	129	119	115	115
Natural Gas	22,113	22,507	21,292	20,457	19,516	18,878	18,565
Asphalt	144	218	218	223	228	233	238
Coal	24,271	24,873	26,370	26,513	27,869	25,854	25,580
Heating Oil	120	0	1,180	1,219	1,310	1,249	1,217
Diesel	2,026	1,802	328	390	470	339	402
Imported Electricity	333	333	333	333	333	333	333
Imported Ethanol	10	13	78	149	311	356	356
Gasoline	2,163	3,404	1,038	1,044	935	1,007	1,079
Jet Fuel	251	555	842	857	947	873	739
Kerosene	58	431	532	389	90	135	81
LPG	810	992	1,220	719	793	876	967
LNG	208	0	1,458	3,966	5,035	3,966	5,035
Petrochemical Feedstocks	0	0	15	0	0	0	0
Residual Fuel Oil	632	898	1,395	892	820	402	387
Black Liquor	0	915	948	982	1,016	1,052	1,090
Crude Oil	33,392	33,246	32,519	34,649	34,012	30,425	31,314
Biomass	190	404	1,336	1,219	1,188	7,758	8,978
Municipal Solid Waste	0	0	43	55	93	109	127
Nuclear electricity	2,635	2,689	2,802	2,871	2,982	3,161	3,448
Renewables (solar, wind, geothermal, hydro electricity)	1,275	1,349	1,371	1,330	1,332	1,350	1,255
Total (PJ)	90,674	94,678	95,420	98,387	99,399	98,471	101,307

Appendix A.5
Feedstock by Technology Types During 2010 – 2030 (Million Tons)

Base Case

Technology Type	Feedstock	2010	2015	2020	2025	2030
Biochemical Cellulosic Ethanol	Cellulosic	0.0	0.0	0.0	25.9	45.6
Corn Ethanol Dry Mill	Corn	119.3	107.2	98.7	98.7	0.0
Corn Ethanol Dry Milling with CHP	Corn	0.0	42.7	51.2	51.2	149.9
Corn Ethanol Wet Milling	Corn	10.9	0.0	0.0	0.0	0.0
FT Ethanol cellulosic 29% biomass	Cellulosic	0.0	0.0	0.0	434.5	513.5
Thermochemical indirect gasification 100% biomass	Cellulosic	0.0	0.0	0.0	0.0	63.9

Sub1 Scenario

Technology Type	Feedstock	2010	2015	2020	2025	2030
Biochemical Cellulosic Ethanol	Cellulosic	0.0	0.0	0.0	21.0	88.9
Corn Ethanol Dry Mill	Corn	119.3	107.2	98.7	98.7	0.0
Corn Ethanol Dry Milling with CHP	Corn	0.0	16.8	48.1	51.2	122.2
Corn Ethanol Wet Milling	Corn	10.9	0.0	0.0	0.0	0.0
FT Ethanol cellulosic 29% biomass	Cellulosic	0.0	0.0	0.0	434.5	513.5
Thermochemical indirect gasification 100% biomass	Cellulosic	0.0	0.0	0.0	4.9	46.1

Sub2 Scenario

Technology Type	Feedstock	2010	2015	2020	2025	2030
Biochemical Cellulosic Ethanol	Cellulosic	2.0	3.0	4.0	5.0	6.0
Corn Ethanol Dry Mill	Corn	119.3	107.2	98.7	98.7	0.0
Corn Ethanol Dry Milling with CHP	Corn	0.0	18.9	24.4	44.5	149.9
Corn Ethanol Wet Milling	Corn	10.91	0	0	0	0
FT Ethanol cellulosic 29% biomass	Cellulosic	0.0	0.0	0.0	434.5	513.5
Thermochemical indirect gasification 100% biomass	Cellulosic	2.0	3.0	4.0	5.0	6.0

Appendix A.6
Planted Acreage by Crop Types During 2011 – 2030 (Million Acres)

Base Case

Crop Types	2011	2015	2020	2025	2030
Corn	92	90.48	91.84	86.83	86.26
Grain Sorghum	6	5.93	5.43	3.8	3.2
Oats	3	3	2.93	2.74	2.46
Barley	3.2	3.2	3.13	2.68	2.76
Wheat	57	51.17	46.83	42.11	41.57
Soybeans	78	78.94	78.29	64.37	62.86
Cotton	12.8	11.78	10.47	8.23	7.37
Rice	3.3	3.29	3.24	2.99	2.72
Hay	61.7	61.28	59.68	57.36	53.66
Switchgrass	0	1.21	8.71	34.71	41.67
Poplars	0	0	0.19	4.74	5.77
Willows	0	0	0.06	0.45	0.54
Total Eight Crops	317	310.31	312.37	335.62	378.24

Sub1 Scenario

Crop Types	2011	2015	2020	2025	2030
Corn	92	90.48	91.84	86.83	86.26
Grain Sorghum	6	5.93	5.43	3.8	3.2
Oats	3	3	2.93	2.74	2.46
Barley	3.2	3.2	3.13	2.68	2.76
Wheat	57	51.17	46.83	42.11	41.57
Soybeans	78	78.94	78.29	64.37	62.86
Cotton	12.8	11.78	10.47	8.23	7.37
Rice	3.3	3.29	3.24	2.99	2.72
Hay	61.7	61.28	59.68	57.36	53.66
Switchgrass	0	1.21	8.71	34.71	41.67
Poplars	0	0	0.19	4.74	5.77
Willows	0	0	0.06	0.45	0.54
Total Eight Crops	317	310.31	312.37	335.62	378.24

Appendix A.6 (Contd.)
Planted Acreage by Crop Types During 2011 – 2030 (Million Acres)

Sub2 Scenario

Crop Types	2011	2015	2020	2025	2030
Corn	92	90.48	91.84	88.9	87.7
Grain Sorghum	6	5.93	5.43	3.87	3.07
Oats	3	3	2.93	2.76	2.46
Barley	3.2	3.2	3.13	2.76	2.8
Wheat	57	51.17	46.83	42.52	41.49
Soybeans	78	78.94	78.29	68.91	65.74
Cotton	12.8	11.78	10.47	8.38	7.57
Rice	3.3	3.29	3.24	3	2.8
Hay	61.7	61.28	59.68	57.67	54.99
Switchgrass	0	1.21	8.71	27.94	36.42
Poplars	0	0	0.19	3.86	5.29
Willows	0	0	0.06	0.44	0.55
Total Eight Crops	317	310.31	312.37	335.62	378.24

Appendix A.7
Seasonal Average Prices During 2011 – 2030

Base Case

Product Type	Unit	2011	2015	2020	2025	2030
Corn	$/bu	4.8	4.1	4.24	4.81	4.86
Wheat	$/bu	6.5	5.55	6.31	7.75	8.36
Soybeans	$/bu	11.2	10.26	10.56	14.16	12.85
Cotton	$/lb	0.85	0.71	0.77	0.87	0.91
Rice	$/cwt	12.6	12.72	14.05	15.85	18.3
Dedicated energy crops	$/bu	30	39	39	77	77

Sub1 Scenario

Product Type	Unit	2011	2015	2020	2025	2030
Corn	$/bu	4.8	4.1	4.24	4.81	4.86
Wheat	$/bu	6.5	5.55	6.31	7.75	8.36
Soybeans	$/bu	11.2	10.26	10.56	14.16	12.85
Cotton	$/lb	0.85	0.713	0.769	0.866	0.907
Rice	$/cwt	12.6	12.72	14.05	15.85	18.3
Dedicated energy crops	$/bu	30	39	39	77	77

Sub2 Scenario

Product Type	Unit	2011	2015	2020	2025	2030
Corn	$/bu	4.8	4.1	4.24	4.44	4.57
Wheat	$/bu	6.5	5.55	6.31	7.62	8.36
Soybeans	$/bu	11.2	10.26	10.56	12.66	12.69
Cotton	$/lb	0.85	0.713	0.769	0.859	0.897
Rice	$/cwt	12.6	12.72	14.05	15.81	17.96
Dedicated energy crops	$/bu	30	39	39	66	66

Appendix A.8
Feedstock Requirement for Biofuel Production During 2011 – 2030

Base Case

Feedstock Type	Unit	2011	2015	2020	2025	2030
corn grain	Mil bu	5127.8	5737.7	5901.1	5901.1	5901.1
crop residues	Mil tons	0.0	11.4	9.1	139.6	123.0
dedicated energy crops	Mil tons	0.0	1.7	7.9	251.8	482.7
wood residues	Mil tons	0.0	0.0	2.7	82.4	42.0
Soybean	Mil bu	96.6	122.0	122.0	122.0	121.6

Sub1 Scenario

Feedstock Type	Unit	2011	2015	2020	2025	2030
corn grain	Mil bu	5077	4880	5782	5901	4811
crop residues	Mil tons	0.0	8.9	4.6	139.6	117.8
dedicated energy crops	Mil tons	0.0	1.6	7.9	251.8	502.0
wood residues	Mil tons	0.0	0.0	2.7	82.4	43.7
Soybean	Mil bu	96.6	122.0	122.0	122.0	121.6

Sub2 Scenario

Feedstock Type	Unit	2011	2015	2020	2025	2030
corn grain	Mil bu	5095	4965	4847	5637	5901
crop residues	Mil tons	0.0	9.0	4.3	140.8	98.8
dedicated energy crops	Mil tons	0.0	1.6	7.4	229.2	394.9
wood residues	Mil tons	0.0	0.0	2.5	77.9	34.8
Soybean	Mil bu	96.6	122.0	122.0	122.0	121.6

VITA

Shreekar Pradhan, a resident of Kathmandu, Nepal had an undergraduate degree in Mechanical Engineering from the Tribhuvan University, Nepal and Master of Science in Renewable Energy Engineering from the Tribhuvan University, Nepal. He worked in the Tribhuvan University for more than 3 years in teaching and conducting research in energy. He also worked in the Energy, Economics and Planning unit in the Asian Institute of Technology (AIT), Thailand for more than 2 years. He is interested in assessing emerging environmental issues related to energy use and its effect in the economy. He is keen to assess these issues using computable economic modeling tools. He is currently pursuing his PhD in the Department of Economics, the University of Tennessee, Knoxville.