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MODELING OF U.S. CORN ETHANOL INDUSTRIAL GROWTH

Deogratias Kibira and Guodong Shao
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, MD 20899, U.S.A.

ABSTRACT

The production capacity of corn ethanol as a transportation fuel is experiencing rapid growth in the United States. The demand is driven by increased prices of gasoline, government mandates, incentives, desire for cleaner fuels, and the need to be more self-reliant in energy sources. Continued strong growth of the corn ethanol industry will depend on profitability by both suppliers and producers. This in turn will be influenced by several factors such as demand, government incentives, feedstock availability and prices, processing plant capacity, and efficient farm and ethanol processing technologies. How and to what extent will the projected growth of the corn ethanol industry in the United States be influenced by some or all of these factors? We use system dynamics modeling to construct a causal-loop structure of the corn ethanol industry and stock and flow diagrams to explore how possible changes in projected factors and growth indicators will affect the industry. Currently, planners and researchers explore various energy supply options by the year 2030. Using system dynamics modeling, this paper explores different possible growth scenarios of the industry for the next twenty years.

Keywords: Renewable energy; energy independence; corn ethanol production; system dynamics.

INTRODUCTION

Fossil fuels such as coal, oil, and natural gas are the major sources of world energy, accounting for more than 80 % of the total energy produced [1]. Petroleum oil is the preeminent source of transportation energy. During the year 2009 the U.S. consumed about 20 million barrels of oil per day, 60 % of which is imported [2]. The price of oil has been escalating such that whereas the average price of oil during the 1990s was $20 per barrel, it rose to an average of $59 during 2006. The highest price of oil exceeded $140 per barrel during 2008 [2]. Although the credit crunch later in the year 2008 saw a fall to $30 per barrel, the price started going up again to more than $90 later in the year 2010. In addition to the high expenditure associated with costly imported oil, the U.S. wants to develop cleaner and renewable energy to reduce greenhouse gas emissions. Ethanol is one such energy source. Ethanol for transportation can be used to oxygenate gasoline as alternative to methyl tertiary butyl ether (MTBE) and as an extender. MTBE, even in minute concentrations, contaminates water causing unpleasant taste and therefore, a call for reduction in its use. This paper uses growth projections of the industry as a base to explore factors that are relevant to the future of ethanol demand and its production/supply system.

In 2006 former President George Bush outlined the Advanced Energy Initiative, which among other objectives, aims to reduce reliance on foreign energy sources [3]. A study by the Department of Energy/United States Department of Agriculture (DOE/USDA) suggests that with aggressive technology developments, bio fuels could potentially supply 60 billion gallons[1] (238 billion liters) of ethanol by the year 2030, which is 30% of the nation's current use of gasoline [3]. The plan to promote ethanol is continued in the current administration. The process of ethanol production requires electricity and direct thermal energy that can be produced using coal, natural gas, nuclear, and other sources that are domestically available. Thus, overall, ethanol contributes to energy independence regardless of its requirements for production. The price of gasoline is estimated to be less by between $0.19 and $0.40 per gallon because of the effect of the presence of ethanol [4]. This reduction in price benefits motorists directly. Ethanol use in automotive transportation is expected to continue to rise. About 70% of gasoline sold in the U.S. is blended with ethanol in various proportions. As of September 2010, ten states mandate a 10 % ethanol mixed with gasoline (E10). The federal government wants to increase this blending level to 15 % (E15) [5].

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[1] 1 gallon = 3.79 liters

This paper describes a model to investigate the industry so as to understand the challenges such as the effect of i) ethanol production on the availability of corn for food, ii) removing the government subsidy on ethanol profits, and iii) ethanol production on price of gasoline. Additional issues include:

- the necessary reserves of corn and ethanol
- the processing capacity investment needed, and
- the costs/benefits of investments in improved processing technology

Given that this is a complex problem, this paper uses a systems view of the industry. We construct a system dynamics model to better understand the effect of various factors on the growing ethanol industry and to elucidate the dynamics associated with those factors. The model uses existing forecasts to determine future corn availability, production capacity, ethanol blend demand, and cost and revenue elements. The model can be run using different scenarios of demand, production capacity, corn availability, and buffers stocks for corn and ethanol. Such a model could improve analysis of the industry and be used by planners and businesses to explore how best to respond to any changes that may occur on a number of given factors.

In the following sections, we give a background and review previous research that has used systems modeling of the industry. Next, we describe the structure of the industry using a casual loop diagram showing the relationships and feedback dynamics that are playing and will continue to play a major role in the future of the industry. After that the flow diagram for the supply chain of ethanol is provided, describing the boundaries of the problem modeled in the paper. This is followed by the stock and flow diagram. Finally the results of running the model using alternative scenarios are discussed.

RELATED WORK

One of the earliest applications of system dynamics in policy oriented modeling was the construction of the World3 model, first published in 1972 [6]. A new version of the model called World3-03 has been developed and published in “Limits to Growth – The 30 Year Update” [7]. Both models show that the current unprecedented growth in world population, food production, resource consumption, and industrial production cannot be sustained in the long run without exceeding the earth’s limits. Early energy models such as those developed by Naill [8] and Sterman [9] were used to model fossil fuel usage. An investigation and modeling framework for transition to bio fuels has been developed [10]. The outcome of such models can be used to determine and direct energy policy to help alleviate potential economic and social problems.

System dynamics modeling has been used in a number of bio fuel analysis situations. Sample examples follow. The Noblis corporate energy initiative investigates alternative energy supply-chain scenarios to manage the transition to a more sustainable energy future [11]. Bush et al. [12] use system dynamics to explore potential market penetration scenarios for bio fuels in the U.S. The investigation into bioenergy and land use to understand the interaction between economic conditions and land competition between different crops is done by Scheffran et al. [13]. While Franco et al. [14] use system dynamics to understand the difficulties in fulfilling government requirements for biofuels blending and to evaluate the effect of different government policies in the production of ethanol and biodiesel. The U.S. Department of Energy modeling of the biomass program is described in Riley et al. [15].

Regarding ethanol, West [16] along with other researchers at Sandia National Laboratories and General Motors describe a system dynamics model to investigate the feasibility, economics and environmental impact of producing 90 billion gallons (341 billion liters) of ethanol per year by 2030. There is also a system dynamics model for forecasting the future of bio diesel production growth in the U.S. [17]. This latter model has conducted sensitivity analysis to determine the parameters that most affect the feasibility and cost competitiveness of large scale bio diesel production. This model investigates the effect of key factors such as market growth, government incentives, and stock prices on the viability and sustained growth of the industry. Our motivation for corn ethanol industry modeling is similar to that of this bio diesel research.

MODEL CONCEPTUALIZATION

This section presents the causal loop diagram and the stock and flow diagrams of the corn ethanol system. We used the modeling tool Vensim, which allows the analyst to connect variables to form causal relationships. The stock and flow diagram of the ethanol system in Vensim is made up of variables, auxiliaries, constants, and stocks/accumulations [18].

We first determine the boundaries of the system and the factors that are important. Also to note are the inputs and outputs variables. The factors relevant to the model are ethanol demand, ethanol production capacity, availability of corn for ethanol production and the policy for how much of total corn harvest to allocate to ethanol, and the total corn production. Others are the required amount of corn, pure ethanol, and ethanol blend in order to absorb unanticipated surge in demand or sudden decline in production and supply. These factors are represented in the causal loop diagram in the next section.

The Causal Loop Diagram

The system dynamics methodology uses causal loop diagrams to illustrate (positive or negative) feedback mechanisms in systems [19]. Figure 1 shows the causal loop diagram of the corn ethanol industry system. This is a higher level representation of the dynamics of the industry. It shows the interactions and relationships between the corn ethanol industry and the overall transportation energy, corn production, and food systems. The diagram comprises of multiple loops indicating how corn production, corn price, level of ethanol production, government tax incentives and oil price influence the industry. We examine the loop labeled L1 (shown in bold red) that starts with the *Corn ethanol production* factor, as an example. An increase in *Corn ethanol production* influences a reduction in *Ethanol price*. But an increase in *Ethanol price* decreases *Ethanol demand*, hence, the negative polarity of the connecting arrow. Since we have a decrease in *Ethanol price* there will be an increase of *Ethanol demand* followed by the *Gap between ethanol demand and supply*. This would call for both increased *Ethanol production investment* and demand for more *Allocation of corn to ethanol production*. An arrow closes the loop with positive polarity since an increase in *Allocation of corn to ethanol production* that *Corn ethanol production* would also increase. This loop represents an example of positive feedback self-reinforcing process. However, the loop would be prevented from increasing the levels of each factor indefinitely because other factors outside the loop such as *Total production costs* actually influence the *Ethanol price*. *Gasoline price* also influences *Ethanol demand*. Another example starts with *Profitability*, which when it increases will positively affect further *Ethanol production investment* and *Allocation of corn to ethanol production*. The effect of this is to increase *Corn ethanol production* and decrease the *Ethanol price* by the forces of supply and demand. A lower *Ethanol price* would mean reduced *Profitability*. This is an example of a self balancing loop, where growth is attenuated and checked from within the loop. Such a subsystem would tend to be innately stable.

The key factors relevant to the level of ethanol production are *Ethanol production investment* (in terms of plant) and the *Allocation of corn to ethanol production*. The profitability depends on *Total production costs, Ethanol price, Revenue from animal feeds,* and government *Incentives*. *Corn price* plays a role in total production costs. The diagram also shows the relationship between factors that influence the amount of corn produced, farmland, water usage, environmental pollution, allocation between competing demands, and the corn price.

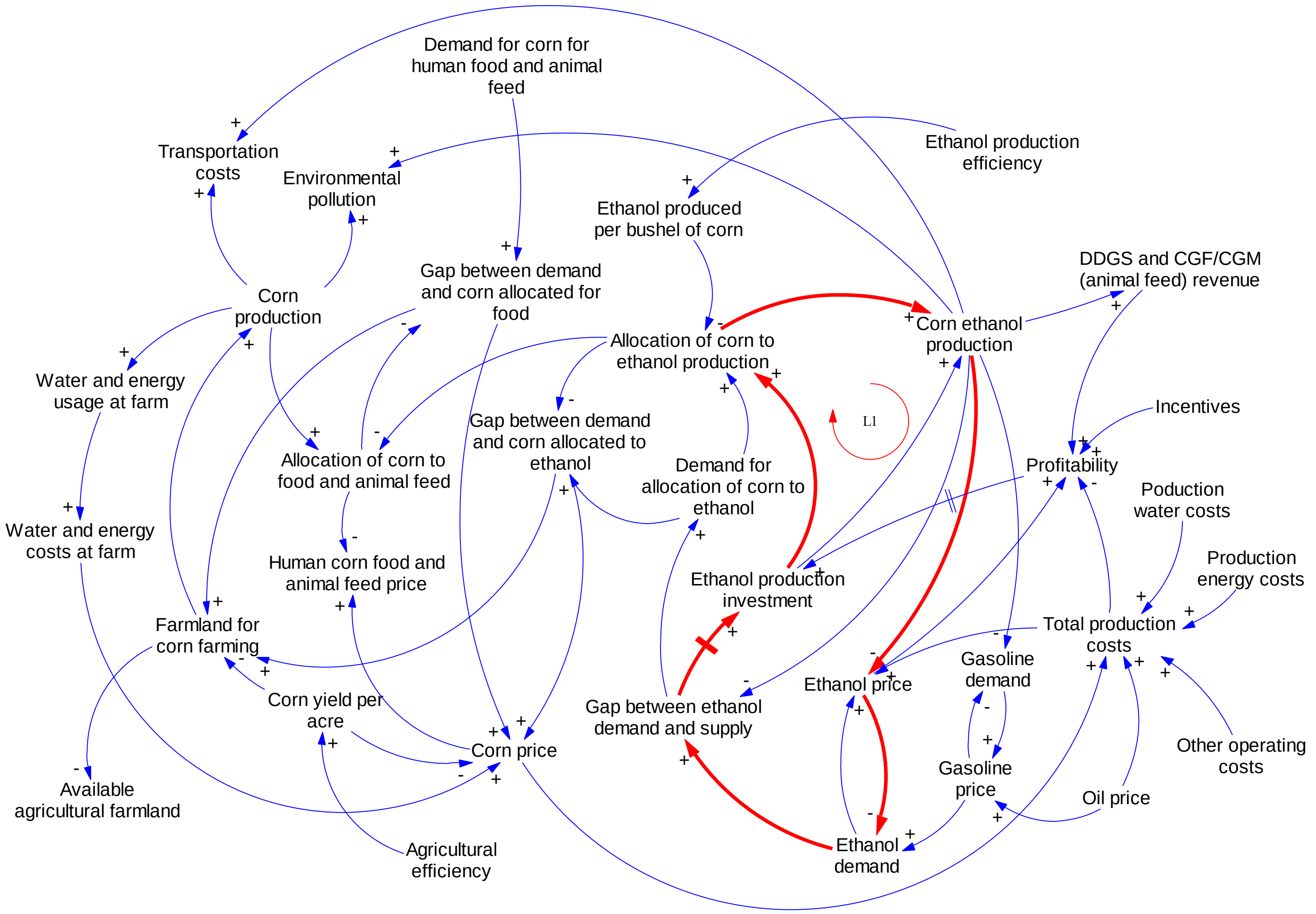


Figure 1: Causal loop diagram of the dynamics of corn ethanol

Model Overview

Figure 2 shows the various inputs into the system; from corn farming and harvest to ethanol production. For example, energy is required by farm equipment to cultivate the land, plant, grow, and harvest the corn. The farmers use fertilizers that release nitrous oxide into the atmosphere. Farming also uses water for irrigation. Corn transportation to plants and ethanol production activities use fossil fuels contributing to demand of these fuels and also increasing carbon emissions. The boundary shows the core part of the system that is included the stock and flow diagram model [20].

Stock and Flow Diagrams

The model is a representation of a system of storages, production and usage rates, distribution and all factors relevant to the industry. It starts with the forecast of corn harvest over the planning/model horizon. The total corn production in 2009 was 13.1 billion bushels (333 million metric tons) and projected to be 24.6 billion (625 million metric tons) in 2030. Of this, ethanol production used 4 billion bushels (102 million metric tons) in 2009 and projected to use 12 billion bushels (305 million metric tons) in 2030. The U.S. produced 10.6 billion gallons (40.2 billion liters) during 2009 and 13.2 billion gallons (50 billion liters) in 2010. The ethanol production is projected to increase linearly as shown in Figure 3, subsequent to expected corresponding increase in processing installation capacity. The data and relationship between factors was based on projected corn availability and investment in the industry, as published in reference [21]. There are four sectors in the model. The first sector is the main corn ethanol production sector that depicts the supply and demand dynamics of corn and ethanol (Figure 4).

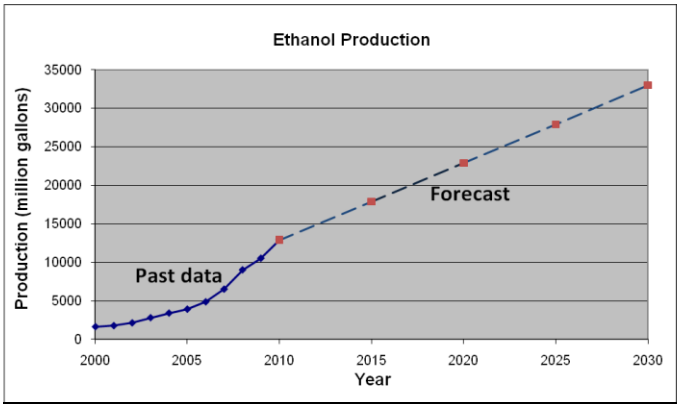


Figure 3: Past and growth trend of ethanol production

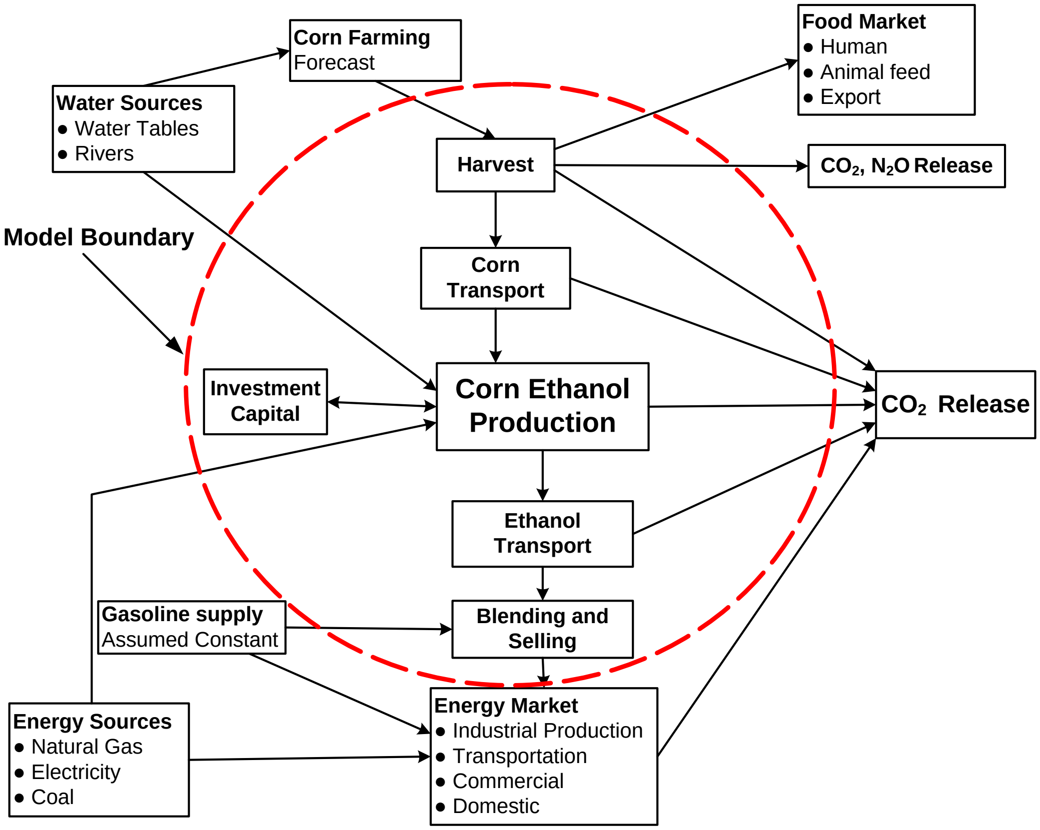


Figure 2: Overview of the corn ethanol production and distribution system

The second, called secondary production, models animal feeds production as a byproduct of corn ethanol production. The third sector models the energy used during production. The fourth sector models the capital flows, i.e., the incomes and expenditures. Because of space limitations, only the first sector will be detailed in the paper. The modeling period runs from 2009 to 2030. We use a month as time unit making the modeling period 252 months. The “TIME STEP” for computations in the model is $1/8^{th}$ of a month.

An examination of the model in Figure 4 shows that the sale of ethanol depends on the demand. This is a “pull” system whereby the blending for ethanol is in proportion to the demand or to fulfill the reserve requirement. But this is constrained by the available ethanol, both in reserve and what can be produced by the mills during the period. The demand for production of ethanol is dependent on the desired production (to keep up with the demand and stock coverage). The production is limited by the current production capacity. The rate of ethanol production “pulls” the requirement for corn purchase for ethanol. A reserve for corn is maintained for stock for some period in the future. The corn harvest system, on the other hand, is modeled as a “push” system where corn is harvested as projected and stored. If the demand for corn should be less than what is produced, the surplus would accumulate in the reserve. On the other hand, if demand is higher and the production plant capacity is available, there would be no corn left in reserve as it will all be consumed. In this case, corn availability would be the factor constraining the amount of ethanol produced. The factors relevant to any variable in the model are used to determine the expressions used in the modeling.

For example:

The corn demand =
MAX(MAX(0,(Required corn reserve for ethanol-Corn stock for ethanol)/Stock adjustment time),Corn consumption)

The corn consumption for ethanol =
*MIN(Ethanol production/(0.3*Wet mills conversion rate+0.7*Dry mills conversion rate),Corn stock for ethanol/TIME STEP)*

The ethanol production =
MIN(MIN(Capacity dry mills+Capacity wet mills, Corn stock for ethanol(0.7*Dry mills conversion rate+0.3*Wet mills conversion rate)/TIME STEP),Desired production)*

The adjustment for blend stock =
*((E10 RESERVE TO MAINTAIN-E10 stock)*0.1+(E85 RESERVE TO MAINTAIN-E85 stock)*0.85+(E10 RESERVE TO MAINTAIN+E85 RESERVE TO MAINTAIN)*0.25-Ethanol stock)/Stock adjustment time*

The rate of ethanol blending into E10 =
*MIN(0.32*Ethanol stock/TIME STEP, (MAX (0, (E10 RESERVE TO MAINTAIN-E10 stock)/Stock adjustment time)+ Selling and using E10 *0.1))*

The ethanol stock at any time t, ES(t)

$$ES(t) = \int_0^t [EP(s) - EBE10(s) - EBE85(s)]\,ds + stock(0)$$

Where EP is the ethanol production, EBE10 is the ethanol blending into E10, EBE85 is the ethanol blending into E85 and stock(0) is the initial stock of ethanol.

We can also show how various factors such as production capacity and corn availability constrain the ethanol production rate. The demand for ethanol and production plant installation capacity is modeled to increase in the same proportion as the amount of corn harvested. The model uses current proportion of production from the two types of mills, i.e., 70 % by dry milling and 30 % by wet milling. However, in a given period, not all orders for ethanol may be satisfied since the ethanol delivered will depend on stock level and that quantity that can be produced during the considered period. The price of ethanol blend also depends on the demand.

Corn is purchased for ethanol production according to demand, price, and corn availability. This stock level of corn to maintain, in turn, depends on the desired ethanol production, buffer stock coverage, and production rate of the mills. We model the supply and demand of two blends of ethanol, E10 and E85, to constitute 80 % and 20 % respectively of the total demand.

RUNNING THE MODEL

After checking for validity and dimensional consistency, the model was executed. As previously indicated, the unit of time used is one month and the model is run for a period of 21 years (252 months). The “base” run of the model is set at forecast levels of ethanol demand, ethanol prices, corn production, and plant production capacity. After the base run, the model is executed using a new set of scenarios to investigate the behavior. Figures 5 and 6 show the variation of different factors when there is a change from the projected levels. In the first scenario, it is assumed that half way through the 252 months simulation, the demand changes while the other factors remain as previously projected. In the second, the production plant capacity and demand change while the other factors remain unchanged.

Change in Demand

Figure 5 graphs show how some factors would vary if demand were to be increased by 20% in month 126. The factors are represented by the variables E85 stock, Desired production, Ethanol stock, Selling and using E85, and Total corn stock available. An initial stock of 4 billion gallons (15.2 billion liter) of E85 blend is assumed to be in the system. There is also a starting level of other stocks.

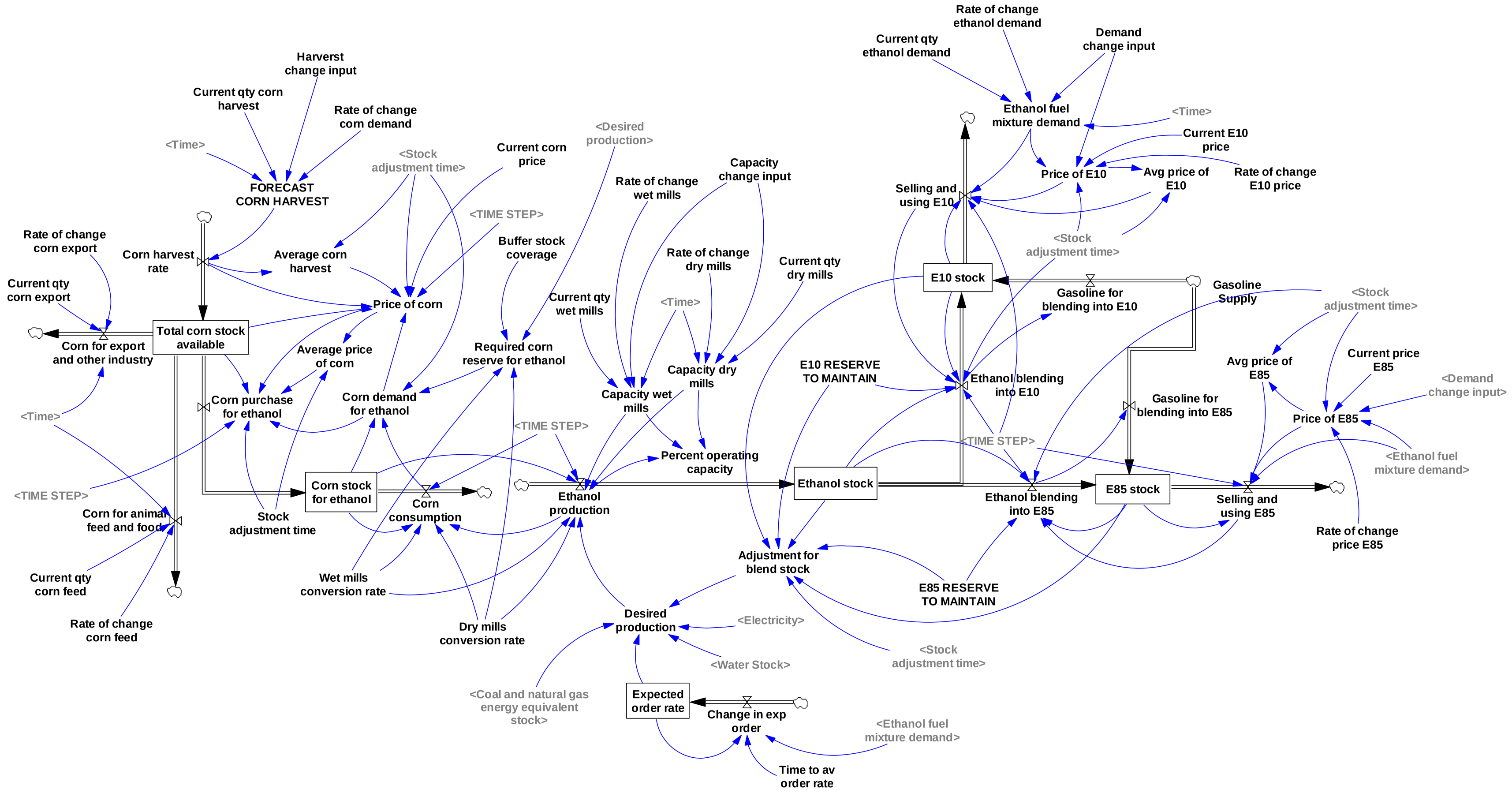
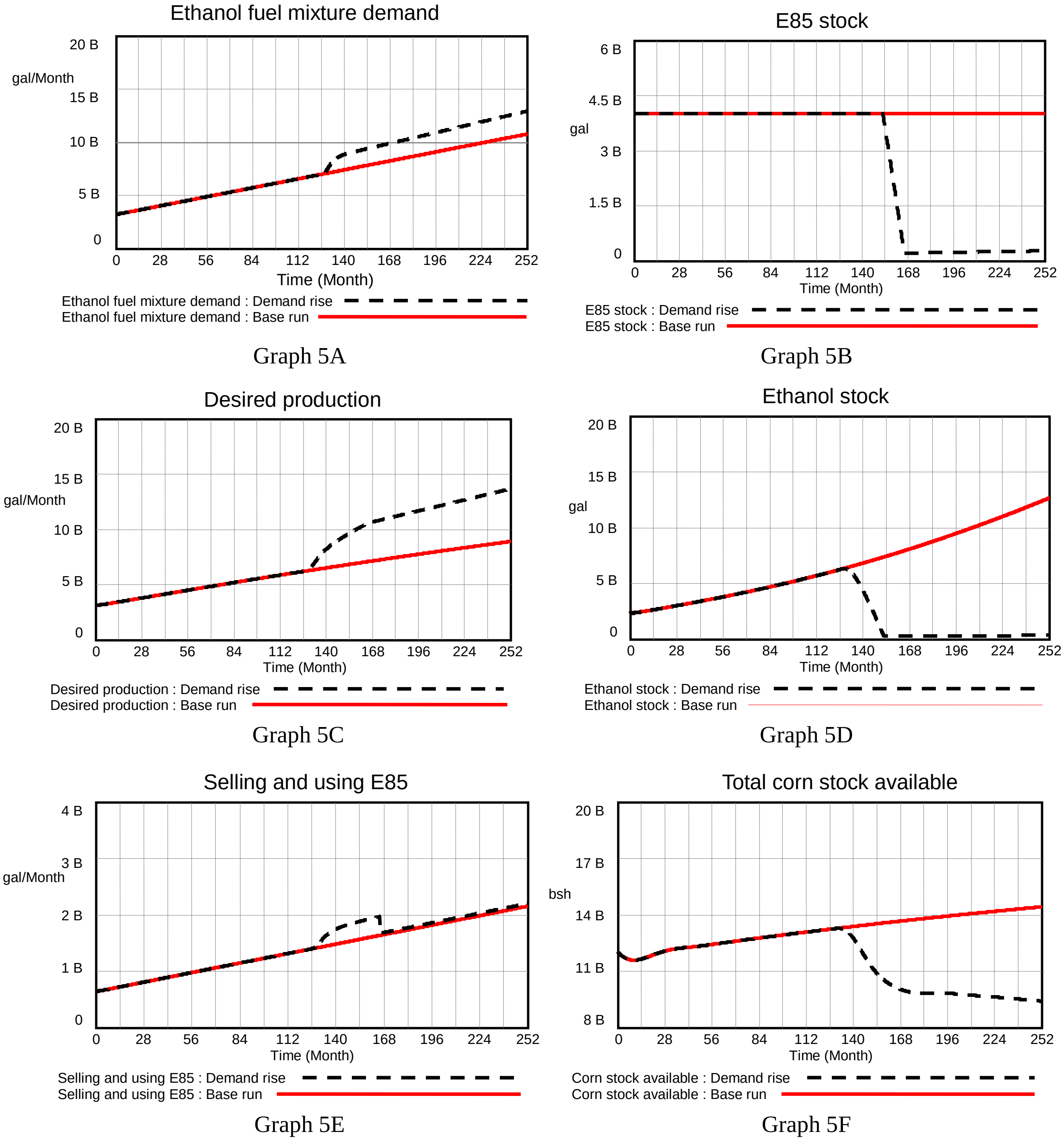


Figure 4: Stock and flow diagram of the corn ethanol production system

Graph 5A shows the 20 % change in projected demand juxtaposed with the base run. Correspondingly, the sales (for both E10 and E85) increase as shown in Graph 5E, but for about a 30 month period before falling. This is because the additional demand is satisfied from stock. The blend and ethanol stocks also drop, as shown in Graph 5B and Graph 5D. When this stock is depleted the sales reduce to a level commensurate with the rate of production of ethanol, which is constrained by the capacity of the mills and corn availability. The Graphs 5C and 5F show the increase for the factor Desired production and depletion of total corn stock. The issue for investigation is this instance is how much reserve is needed to cushion a surge in demand.



Graph 5A

Graph 5B

Graph 5C

Graph 5D

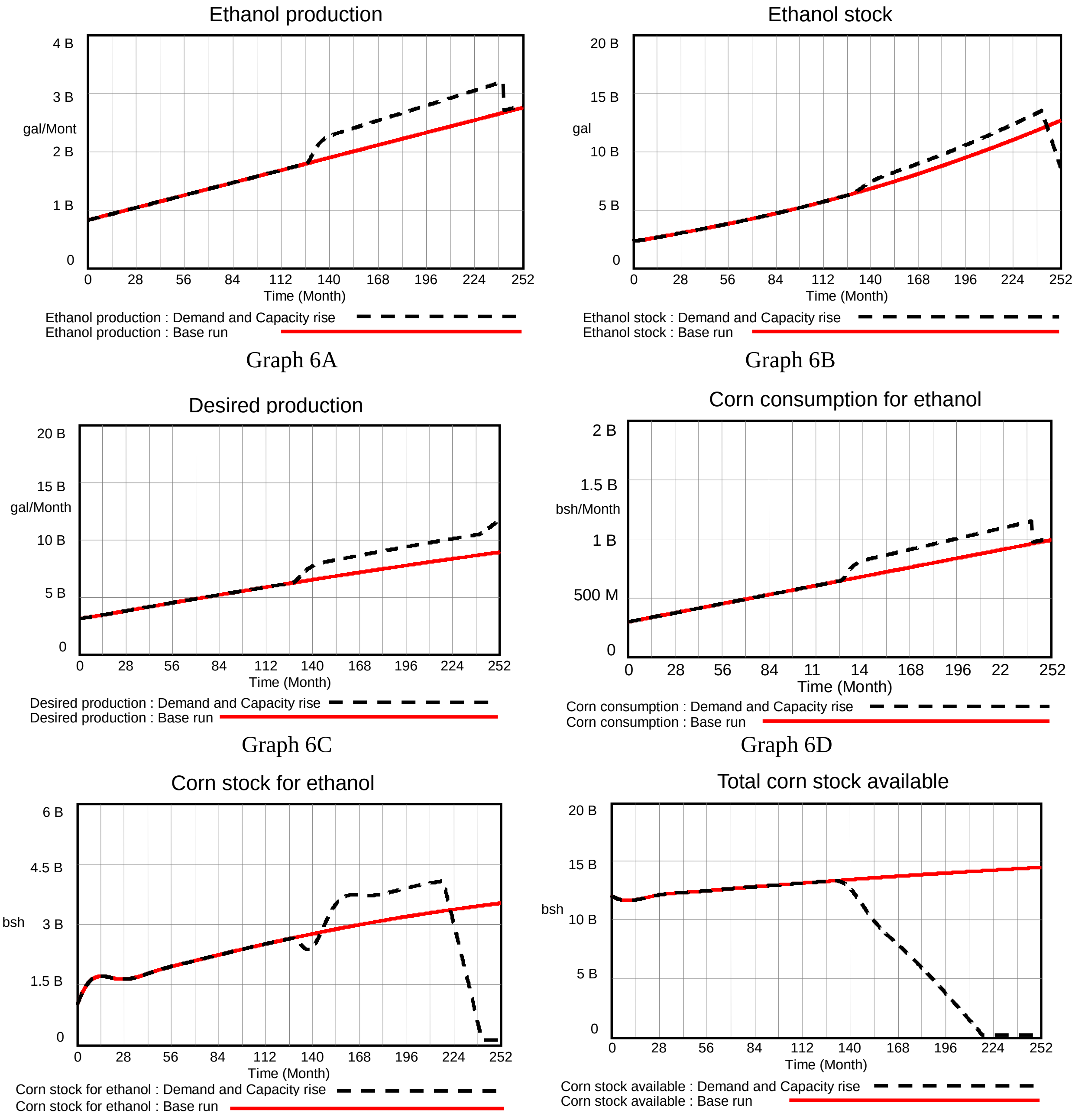
Graph 5E

Graph 5F

Figure 5: Comparison between base run and surge in ethanol demand

Change in Demand and Plant Capacity

The graphs in Figure 6 result from running a scenario where the demand and production are increased simultaneously by 20 % during the month 126. The graphs in the Figure show the factors: The Ethanol stock, Ethanol production, Desired production, Corn consumption for ethanol, Corn stock for ethanol, and Total corn stock available. The production and sales would increase in accordance with the 20% rise. But without corresponding increase in corn production, all corn stocks would be consumed by around month 220 (Graph 6F). The demand would then begin to deplete the ethanol stock to drop as shown in Graph 6A. The ethanol production would afterwards only be commensurate with the corn production.



Ethanol production

Graph 6A

Ethanol stock

Graph 6B

Desired production

Graph 6C

Corn consumption for ethanol

Graph 6D

Corn stock for ethanol

Graph 6E

Total corn stock available

Graph 6F

Figure 6: Comparison between base run and simultaneous increase in plant capacity and demand

Model Results

These simulation runs show model behavior and factor variations that would not be apparent without the model. For example, the relatively short period of time for which a surge in demand can be satisfied before production capacity and/or corn availability force the sales to drop to base values. Additional experiments can be performed to determine the behavior using alternative inputs or if there is a reduction in inputs rather than an increase.

DISCUSSION AND CONCLUSIONS

The search for alternative sources of energy continues as petroleum reserves dwindle, demand increases and prices escalate. Ethanol from corn is one of the fuels promoted and its production has increased in recent years. The U.S. is now the world's largest producer of ethanol. However, continued expansion of its production will need continued research in more efficient processing technologies to increase yield and to reduce energy consumption. Because of the concern for further clearing of land to grow the corn and use of chemical fertilizers, increased yield of corn per acre would be needed. Storage facilities would be built as well as investment in processing plant. The uncertainties in current projections of the future growth must also be planned for.

The paper has described a system dynamics model that can be used to study the state of corn ethanol fuel industry in the U.S., and the effect of uncertainties in forecast on the future of the industry. This holistic view can yield a better insight into the current and future growth as well as effects on demand, corn harvest, and ethanol processing capacity on the industry. The experiments have explored alternative scenarios and analyzed key relevant factors. Corn ethanol production will continue to expand along with improvements in yield per acre of corn and ethanol yield per bushel. This will reduce the effect of using such a food source as an energy source. Corn ethanol production from also produces useful animal feeds that can improve livestock production.

The model would be useful to guide on policy formulation and on issues such as storage capacity, processing technology, processing capacity, and corn farming investment.

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DISCLAIMER

A number of software products are identified in context in this paper. This does not imply a recommendation or endorsement of the software products by the authors or NIST, nor does it imply that such software products are necessarily the best available for the purpose.

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