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Technology uncertainty and learning by doing in the cellulosic biofuel investment

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Abstract: This study investigates the impacts of technology uncertainties and learning curve on investment decisions in the cellulosic biofuel industry. We find the future success of cellulosic biofuel may depend on the learning by doing effects rather than expected advances in conversion technology. The anticipated technology breakthroughs may even further delay investment decisions because the firm has incentives to wait until the breakthrough is realized. If the government wants to trigger commercialized production through the promotion of learning effects, an enforced mandate level of at least 500 million gallons may be needed.

Key words: cellulosic biofuel, technology uncertainties, real options analysis, learning curve

JEL classification: Q42, Q48, Q55

1. Introduction

The Energy Independence and Security Act of 2007 modified the Renewable Fuel Standard (RFS2) in the U.S., expanding the renewable fuel mandates which require the specific amounts of renewable fuel to be blended into the domestic fuel supply. These mandated volumes increase from 9 billion gallons in 2008 to 36 billion gallons by 2022. Cellulosic biofuels, defined as those derived from cellulose, hemicellulose or lignin, which achieve at least a 60% reduction in greenhouse gas (GHG) emissions, comprise a significant component of the overall mandate. These cellulosic biofuels can be produced from various feedstocks, such as crop and forest residues or switchgrass and miscanthus, that have the potential to be grown on marginal soils, generate high fuel yields per unit of land, and achieve significant environmental benefits as compared to conventional crops and biofuels. However, despite the promise of these fuels, they have yet to be produced in substantial volumes. According to the Federal Register (2013), Environmental Protection Agency (EPA) estimates that the expected production capacity of cellulosic biofuel will be less than 50 million gallons in 2014, coming from only two existing plants and an additional two plants currently under construction.

There exists a large and growing body of previous research with optimistic views about the future success of cellulosic ethanol based on advancements made in the industry over the past two decades (Kaylen et.al, 1999; National Renewable Energy Laboratory , 2010; Wallace, 2003). However, even with the high subsidy to the cellulosic ethanol (\$1.02/gallon) and the booming ethanol market (ethanol price never below \$2.2/gallon) since 2011, the predicted success has not been achieved. In 2012, the actual volume of cellulosic ethanol produced was just 20,000 gallons (EIA, 2013), far behind the initial target of 500 million gallons imposed by The Clean Air Act (EPA, 2012).

Key barriers to investment in cellulosic biorefineries include various sources of risk and huge irreversible sunk costs. These uncertainties and irreversible costs make it difficult to attract investors to build cellulosic refining capacity, and even more difficult for those investors to procure financing from both debt and equity sources to fund the investment. Most previous studies predicting the success of cellulosic ethanol totally or partly ignore these uncertainties and risks using the net present value (NPV) method. The failure to consider these substantial uncertainties and risks makes these studies underestimate the investment threshold in terms of conversion efficiency in this emerging industry.

Recently a “battle” between the EPA and the American Petroleum Institute (API) has been raised to the federal court. The API, an oil lobby, argues that the EPA is unreasonably optimistic and sets an unrealistic goal for cellulosic biofuel production because no commercial scale plants currently exist in the U.S. (Moreno & Dertke, 2012). Meanwhile, EPA insists that the mandate is reasonable and it tries to “set an applicable volume that promotes growth in the cellulosic industry as envisioned by Congress” (Moreno & Dertke, 2012).

This study provides a potential explanation for the current failure of the cellulosic ethanol biofuel and for the different understandings of this industry between the government and oil companies. The EPA and many researchers may underestimate the private investment threshold in this industry if they overlook or underrate the high risks and uncertainties associated with the cellulosic biofuel investment decision. The threshold is further underestimated when EPA takes into account the learning by doing effects obtained through the production. Our results show that even with the numerous

government-funded research programs and the federal loan guarantee program to support the development of the cellulosic biofuel industry, the profitable level of refinery technology in this industry is still yet to be achieved.

This analysis adopts a more appropriate framework, real options analysis (ROA), to analyze the cellulosic refinery investment decision. ROA explicitly includes the uncertainties and the option value of delaying the investment decision. Characteristics of the cellulosic biofuel industry suggest that the waiting option plays a key role in the investment decision. First, uncertainties and risks are significant in this industry. Uncertainties about the refinery technology, biomass supply and cost, prices of ethanol and oil, government policies and establishment cost make the return of this investment very unpredictable. Second, since the refinery industry of cellulosic ethanol is highly specialized, the initial investment expenditures are sunk costs and thereby are at least partly irreversible. Third, the potential investors have the option to delay their investment. Even if the mandate is enforced, the potential investor from the oil industry can purchase the credits directly from EPA to meet the requirement. Furthermore, this method can account for the learning by doing effects by incorporating the industry output as a dynamic variable. ROA has been widely used in the environmental investment decision literature (Slade, 2001; Insley, 2002; Schatzki, 2003). In this model, the state variable is stochastic and the investors may delay their investment decisions if the current state is not favored. A firm will invest only if the expected project value exceeds both the investment cost and the real option value of delaying the decision to future periods.

This is consistent with the real firm's action in the cellulosic biofuel industry. In 2012, British Petroleum (BP) canceled its proposed cellulosic biofuel plant with a 36 million gallon annual capacity in Florida, while still funding the research and development of cellulosic

processing. Meanwhile, two cellulosic biofuel plants are currently under construction in Kansas and Oregon. We show that the heterogeneous investment behaviors may be explained by firm's different waiting opportunity cost.

2. Literature Review

A few studies based on ROA have been devoted to the biofuel investment in the consideration of different uncertainties. In the early studies, ethanol or energy prices were considered as the primary source of uncertainty. For example, Murto and Nese (2003) present a model to examine the impact of the uncertainty of fossil fuel prices on investment choices between fossil fuel and biofuel plants.

With ethanol prices increasing since 2006, the focus has shifted to stochastic profit margins and the production costs. Schmit, Luo and Tauer (2009) estimate that the entry threshold in terms of the profit margin for the corn ethanol industry is \$1.33/gallon. Based on this result, Schmit et al. (2011) further expand their model to capture both revenue and cost uncertainty.

More recent studies have explored the impacts of other uncertainties. Song, Zhao and Swinton (2011) study the uncertainty in the supply of feedstock for cellulosic biofuels by analyzing the farmers' planting decision between traditional crops and energy crops. Miao, Hennessy and Babcock (2012) investigate the effects of policy uncertainty related to EPA's ability to waive the RFS mandates on investment behavior in the cellulosic industry.

However, these studies do not provide an explanation for the continuing lack of investment in cellulosic processing capacity. First, ethanol prices have remained in the profitable range of \$2.30 to \$3.00 per gallon since 2011. This implies that the ethanol price should not be an obstacle to enter the cellulosic biofuel market. Second, operating costs have dropped significantly since 2008, reported by a survey of 11 leading cellulosic ethanol producers

(Bloomberg new energy finance, 2013). For instance, the enzyme cost decreased by 72% between 2008 and 2012. Third, the risk related to the availability and reliability of feedstock supplies has been reduced. For example, BP has established a 20,000 acre farm to grow energy crops in Florida, but still cancelled their proposed cellulosic refinery while continuing to do research. Finally, there is still a gap between the EPA minimum requirement and the supply of cellulosic biofuel even if the EPA waives most mandates. The adjusted mandate in 2012 changes from 500 million gallons to 10.45 million gallons, but only 20,000 gallons cellulosic ethanol are produced. Thus, the waived mandate only affects the investment decision in a very limited way.

3. Industry Background

The current critical obstructions to entering the cellulosic biofuel industry are the processing technology, high capital cost requirements, and the ethanol “blend wall”. First, although the long-run production cost of cellulosic biofuel is expected to decrease, the refinery technology determines the basic production cost and profits in the beginning several years. If current technology is not profitable enough or not mature enough for large commercial production facilities, the refinery plant may incur substantial losses and go bankrupt in this period. The first demonstration-scale cellulosic biofuel plant in the U.S, Western Biomass Energy LLC, filed for bankruptcy in 2013. For this reason, most potential investors may delay their investments until more profitable and mature technologies become available. A major step forward to commercializing cellulosic biofuel production is enhancing the ethanol yield to more than 100 gallons per ton of dry biomass from the current 65-70 gallons per ton (Wyman, 2007).

Second, the establishment cost of such a plant is huge, usually in the range of \$200 million to \$500 million contingent on the capacity (National Renewable Energy Laboratory , 2010). Most firms cannot make this investment using equity funds and have to obtain outside

money from the financial market. However, financial institutions do not perceive the return of this investment to be high enough to compensate for the associated high risk (Keller & Plath, 1999). As a result, the credit constraints in terms of a high loan rate may hinder investment in this new industry. This is particularly important after the financial crisis of 2008.

Finally, the “blend wall” imposes a barrier when domestic ethanol production meets the maximum market demand for E10 blended gasoline. Without expanding the production and adoption of more flexible-fuel vehicles and building additional infrastructure which can handle higher ethanol blends (i.e. E15 or E85), there is no additional market demand for the new produced cellulosic ethanol. Thus, potential investors may choose to wait for the significant change in the car consumption and in the gasoline distribution infrastructure.

These factors are vital to the debate between EPA and the oil companies. EPA argues that the mandate spurs commercialized production of the cellulosic biofuel and this commercialization in turn makes the production profitable, but the current refinery technology and the credit constraints make the process of commercialization almost impossible. In other words, EPA emphasizes the benefits after the large-scale production while the private firms stress the obstacles to this production.

The U.S government does recognize these obstacles. For the refinery technology, the U.S Department of Agriculture (USDA), Department of Energy (DOE) and EPA support numerous studies on cellulosic biofuel. For example, DOE developed five biofuel research centers in 2008 with a total cost of more than \$300 million and provided \$480 million to support the improvement of biofuel energy efficiency in 2009 (Babcock, Marette, & Treguer, 2011). But Wyman (2007), a leading scientist in the cellulosic biofuel field, argues that “government research funds are not well spent on incremental

technical advances because these have little effect on commercialization and would better result from the commercial learning curve”. As Wyman points out, the technological change can be induced through both R&D spending and learning by doing (Goulder & Mathai, 2000). Specifically, R&D spending induces a technology jump while learning by doing improves the knowledge accumulation through production experience.

Besides R&D spending, the learning curve is also particularly considerable in bioethanol industries at the industry level and is well examined by several studies. The learning by doing effect is usually described by the progress ratio (PR), which means the cost will decrease by one minus PR with each doubling in cumulative outputs in unit of a million cubic meters (m³). In the corn ethanol industry, Hettinga et al. (2009) find a PR of 0.87 in the processing cost and Chen and Khanna (2012) show that the PR is 0.75 from 1983 to 2005. In the sugarcane ethanol industry, van den Wall Bake et al. (2009) estimate that the PR of feedstock costs and industry cost are 0.68 and 0.81, respectively. Again, the learning by doing effect can only function after commercialized production and this effect thereby is probably ignored when private firms make the investment decision.

To overcome firms’ credit constraints, loan guarantee programs, historically offered for agricultural producers and for electric utilities, have recently been extended to the biofuels sector through the Section 1703 from DOE and the advanced biofuel payment program operated by USDA. Two loan guarantees, each with amount of \$132.4 million and \$235 million, are provided to support the development of commercial-scale cellulosic ethanol plants located in Hugoton, Kansas and Boardman, Oregon in the past two years. But POET, the largest ethanol producer in the U.S, has rejected a \$105 million federal loan guarantee that would have supported the establishment of a cellulosic ethanol plant in 2012, due to the program’s complicated review

process and expensive annual facility and maintenance fee. This refusal implies a necessary modification to the current loan guarantee programs to guarantee its effectiveness on spurring the investment.

Considering the uncertainties about the refinery technology, the credit constraint in terms of interest rate, and the learning curve, this study gives both analytical and numerical investment thresholds for cellulosic biofuel refineries. Moving towards commercialization of cellulosic fuel production will require providing the necessary economic, legal, and/or political incentives for fuel producers to make significant capital investments in building processing facilities. Besides analyzing the refineries' investment decisions, another focus of this research will be on the efficient design of incentives to develop next-generation biofuels through providing solutions to the financial problems currently faced in launching commercial scale production of cellulosic biofuel. We analyze the design of government programs to accelerate investment in cellulosic biorefineries, and provide recommendations for modifications of existing programs based on the results from this research's economic modeling efforts.

The remainder of this article is organized as follows. Section 4 and Section 5 describe the theoretical ROA model developed in this study, and present the analytical solutions of optimal investment threshold. In section 6, we present the data sources used to calibrate the numerical model which quantifies the investment threshold across a range of scenarios in section 7. Section 8 provides some conclusions.

4. Modeling the option to enter the cellulosic biofuel industry

The decision of entry into cellulosic biofuel refineries for a risk-neutral agent is modeled from the perspective of a representative firm. The potential investor faces an uncertain technological

conversion rate from cellulosic biomass to ethanol, denoted by A . Suppose A follows some known stochastic motion that is expressed by:

$$dA = a(A, t)dt + g(A, t)dz + h(A, t)dq \quad (1)$$

$$s. t. \quad A \leq \bar{A}$$

where $a(A, t)$ is the drift parameter, $g(A, t)$ is the variance term and $h(A, t)$ is the jump size. dz represents the increment of a Wiener process and dq denotes a Poisson process with the mean arrival rate λ , given as

$$dz = \epsilon_t \sqrt{\Delta t} \quad \epsilon_t \text{ is a standard normal distribution variable}$$

$$dq = \begin{cases} 0 & \text{with probability } 1 - \lambda dt \\ \theta & \text{with probability } \lambda dt \end{cases}$$

In addition, dq and dz are independent. \bar{A} is the technology ceiling due to the chemical structure of biomass. Equation (1) means that the conversion rate is determined by three factors. First, there will be an expected improvement (at the rate of a) on the current refinery technology. Second, the conversion rate fluctuates stochastically by the rate of g . The reason is that the conversion rate heavily depends on the biomass quality, which is further determined by stochastic weather conditions, the unknown quality of agricultural management, and the age of the biomass. Third, if a technology breakthrough occurs at the frequency of λdt , the current conversion rate increases by some fixed percentage θ .

Besides the uncertain conversion rate, another dynamic variable is the industry cumulative output. Due to learning by doing effects, operating costs decrease as the industry grows. Thus, current production has two benefits. It not only generates profits from selling the output, but also reduces the future production cost with the learning curve. A part of the operating cost is thus like an investment and results in lower production costs in the future.

The investment behavior is modeled as an entry problem using real option analysis (Dixit & Pindyck, 1993) and dynamic programming methods. The choice problem for a potential investor is given by the following Bellman equation:

$$V_t^0(A, Q, t) = \max\{F_t(A, Q, t); \pi_t(A, Q, t) + e^{-\rho dt} E[V(A + dA, Q + dQ, t + dt)] - I(1 + \omega)\} \quad (2)$$

where Q is the industry cumulative output, V^0 is the value of the idle firm, F is the option value of waiting, π is the one-period profit from the refinery plant if investing, ρ is the discount rate, I is the initial investment, ω is the average financing cost, $E[\cdot]$ means the expected value, and t represents the time period. For convenience, denote $V_t^1(A, Q, t)$ as

$$V_t^1(A, Q, t) = \pi_t(A, Q, t) + e^{-\rho dt} E[V(A + dA, Q + dQ, t + dt)] \quad (3)$$

V^1 is the sum of current period profit and the future capital gain, representing the expected value of the refinery plant. The first term on the right-hand side of equation (2) reflects the option value of waiting and the second term describes the total expected net return from investing in the current period. The firm only invests in the current period when this net return exceeds the option value.

Following the technique developed by Dixit and Pindyck (1993), at each level of Q , there exists an investment threshold A^* such that the investor will enter the market if he observes that $A > A^*$. To find this critical value, several boundary conditions are imposed:

$$V^1(0, Q, t) = 0 \quad (4)$$

$$F(0, Q, t) = 0 \quad (5)$$

$$F(A^*, Q, t) = V^1(A^*, Q, t) - I(1 + \omega) \quad (6)$$

$$F_A(A^*, Q, t) = V_A^1(A^*, Q, t) + V_Q^1(A^*, Q, t) \quad (7)$$

F_A , V_A^1 , and V_Q^1 are first derivatives with respect to A and Q , respectively. Equation (4) says that if the conversion rate is zero, the value of this plant is zero. Furthermore, holding the option of establishing such a plant is also worthless, which is equation (5). Equation (6) says the investor is

indifferent between keeping the option and entering the market at the critical level of A^* .

Equation (7) is a typical smooth-pasting condition in real options analysis and states that the marginal benefits of waiting and investing should be equal at the critical value. It is worth noting that the current production produces a marginal benefit $V_Q^1(A^*, Q, t)$ with learning curve besides the profit and capital gain.

5. The entry decision under a combined Geometric Brownian Motion (GBM) and Jump process

5.1 The benefits from producing the cellulosic biofuel

We assume that the refinery plant has a simple Leontief production function:

$$q = Am \quad (8)$$

where q is the quantity of output in the current year and m is the input of biomass feedstock. The plant's processing ability of the feedstock determines the initial investment, giving

$$I = Bm \quad (9)$$

where I is the total initial establishment cost of a refinery plant and B is the unit capital cost per feedstock ton. The total cost function C and the industry progress ratio is characterized by

$$C = cmQ^b \quad (10)$$

$$PR = 2^b \quad (11)$$

In equation (10), c is the unit production cost, containing not only the feedstock cost but also the other operating cost. The experience index b captures the learning curve with progress ratio PR .

Given the ethanol price P , the profits from the production are written as

$$\pi = Pq - C = \frac{PAI}{B} - \frac{cQ^b I}{B} = \frac{I}{B} [PA - cQ^b] \quad (12)$$

5.2 The stochastic process

Suppose the conversion rate follows a mixed GBM and Poisson process, then equation (1) is rewritten as

$$dA = \alpha_A A dt + \sigma_A A dz + A dq \quad (13)$$

s. t. $A \leq \bar{A}^1$

Expanding equation (3) by Ito's lemma, equation (12) and equation (13) become

$$\begin{aligned} & \frac{1}{2} \sigma_A^2 A^2 V_{AA}^1(A, Q) + \alpha_A A V_A^1(A, Q) - (\rho + \lambda) V^1(A, Q) + \lambda V^1[(1 + \theta)A, Q] + q V_Q^1 + \frac{I}{B} [PA - cQ^b] \\ & = 0 \quad (14) \end{aligned}$$

5.3 A special case with an analytical solution

In equation (14), learning by doing affects the value of the refinery plant in two ways. First, the previous cumulative output reduces the current production cost, which is reflected by cQ^b .

Second, the current production contributes to the reduction in the future cost, which is qV_Q^1 in the equation. If we assume $qV_Q = 0$, then there is an analytical solution for this model. This assumption is reasonable when the industry is small. The learning curve only functions at huge amounts of production (Q is in the unit of a million m³, approximately equivalent to 264 million gallons but the expected produced volume q in 2013 is only 6 million gallons (EIA, 2013)). This implies that qV_Q is very close to 0. But when the refinery industry grows sufficiently large, the model cannot ignore qV_Q and the solution must be obtained numerically. Suppose $qV_Q = 0$ and use the condition (4), then the solution for equation (14) is:

$$V^1(A, Q) = J_1 A^{\gamma_1} + \frac{I[PA - cQ^b]}{B(\rho - \alpha_A - \lambda\theta)} \quad (15)$$

Where J_1 is an unknown parameter and γ_1 is the positive root of equation (16)².

¹ Dixit & Pindyck (1993) proves that the critical value is independent of the variable ceiling, so we overlook this constraint in the rest part of this paper.

² γ_1 only takes one positive value in most cases. Assuming $\theta = -1$, then equation (16) is a quadratic equation of γ and there will be only one positive root.

$$\frac{1}{2}\sigma_A^2\gamma(\gamma-1) + \alpha_A\gamma - (\rho + \lambda) + \lambda(1 + \theta)\gamma = 0 \quad (16)$$

Ruling out the speculative bubble (Dixit & Pindyck, 1993), equation (17) shows the final solution for the plant value.

$$V^1(A, Q) = \frac{I[PA - cQ^b]}{B(\rho - \alpha_A - \lambda\theta)} \quad (17)$$

By similar arguments³ and condition (5), the solution for the option value is

$$F = DA^{\gamma_1} \quad (18)$$

By equation (17) and (18), we obtain the critical value A^* using condition (6) and (7).

$$A^* = \frac{[cQ^b + (1 + \omega)B(\rho - \alpha - \lambda\theta)]}{P} \left(\frac{\gamma_1}{\gamma_1 - 1} \right) \quad (19)$$

Equation (19) gives some useful economic intuition about the critical value A^* . First, the learning effects Q^b (b is negative) lower the technology threshold. As cumulative output increases, the investment threshold will also decline. Thus, the learning effects promote investment decisions. Second, the financing cost ω increases the technology threshold and thus, delays investment. A larger ω makes the investor more likely to give up the investment. Third, the greater the per unit capital cost B the larger the investment threshold, implying that high capital costs are barriers to industry growth. Finally, the high ethanol price reduces the technology threshold and attracts more investors. For other parameters such as ρ, α, λ and θ , they affect the critical value A^* through both themselves and γ_1 . We will discuss and illustrate their effects in the numerical results section of this paper.

6. Data

6.1 The cellulosic biofuel refinery industry

³ $\frac{1}{2}\sigma_A^2 A^2 F_{AA}(A, Q) + \alpha_A A F_A(A, Q) - (\rho + \lambda)F(A, Q) + \lambda F[(1 + \theta)A, Q] + qF_Q = 0$. Here $qF_Q=0$ because there is no production.

The production and investment costs for a refinery plant are taken from several sources. Previous studies report a farm-gate price in the range of \$23/dry ton to \$114/dry ton (Congressional Research Service, 2010) for feedstocks such as switchgrass. This substantial variation depends on the local land rent, crop yields and the farmer's conversion and establishment costs incurred through switching from conventional crops to energy crops. To calculate the average industry investment threshold, we use \$80/dry ton as the benchmark level.

Operating and investment costs vary among different refinery technologies adopted by plants. The most popular four refinery technologies are gasification and fermentation (GF), enzymatic hydrolysis (EH), simultaneous saccharification and fermentation (SSF), and dilute acid hydrolysis (DCH) (Dwivedia, Alavalapath, & Lala, 2009). Table 1 summarizes the costs of these technologies reported in various reports (National Renewable Energy Laboratory, 2010; Laser, Jin, Jayawardhana, & Lynd, 2009; Piccolo & Bezzo, 2009; Haquea & Epplinb, 2012). DCH and SSF are the two most efficient technologies but they only represent a small part of the market due to their immaturity.

The majority of proposed plants have chosen to adopt technologies of EH and GF, which are two relatively mature technologies but with lower efficiency. The first commercialized-scale cellulosic ethanol plant (just certified by DOE in July 2013) in Vero Beach, Florida uses the technology of GF to produce 8 million gallons ethanol annually. Using the weighted average method, the conversion rate at the industry level is 63.89 gallons/dry ton; the capital cost is \$525.39/ton and the operating cost is \$53.19/ton.

The ethanol price used is from the Nebraska energy office and the average rack price in 2012 is \$2.36/gallon.

Table 1: Refinery costs of the cellulosic biofuel by different technologies

Technology	conversion rate (gallons/dry ton)	capital cost (\$ per feedstock ton) ⁶	operating cost ⁴ (\$ per feedstock ton)	proposed capacity million gallons	market share ⁵
DCH	76.30	522.08	85.91	37.40	12.33%
EH	66.00	536.11	67.12	104.90	34.58%
SSF	84.00	524.29	43.26	31.31	10.32%
GF	53.75	517.93	34.89	129.75	42.77%
Weighted Average	63.89	525.39	53.19		

6.2 Stochastic parameters

Since the cellulosic ethanol industry is at the beginning of commercialization, we lack a historical series of data about the path of the conversion rate in this industry. To simulate this path, we use the historical data from the sugarcane ethanol industry in Brazil and the corn ethanol industry in the U.S and estimate the path of conversion rates in these two relatively mature bioethanol industries. Then we assume that the conversion rate in the cellulosic ethanol may follow either one or a mixture of both.

The conversion rate of the sugarcane ethanol in Brazil from 1976 to 2004 is reported by van den Wall Bake (2006) and the conversion rate in the U.S corn ethanol from 1986 to 2012 is calculated based on the data provided by the Renewable Fuel Association and USDA. Figure 1 and Figure 2 show the conversion rate path in these two ethanol industries. The conversion rate fluctuates rather stochastically and fit the GBM path well⁷. To estimate the GBM part of the path,

⁴ The operating cost does not include the feedstock cost.

⁵ The market share is calculated based on installed and under construction cellulosic ethanol production capacity disaggregated by adopted conversion technologies in the United States from the results by Dwivedia, Alavalapatib, & Lala (2009).

⁶ The operating and investment costs are calculated based on the plant capacity of processing the feedstock instead of the ethanol yield because the ethanol yield changes as the conversion rate changes in the future.

⁷ This stochastic path may be significant at the industry level. For each specific firm, its conversion efficiency may be less stochastic. This is similar as the production function used in Microeconomics. For each firm, its production function may be a Leontief function but at an industry level Cobb-Douglas or CES functions may fit better. In addition, the reason of strong fluctuation in both industries is not well documented in previous studies. The change of conversion rate in sugarcane ethanol and corn ethanol may be due to the age of sugarcane and the starch content of corn, respectively.

we drop some parts of these paths which are most possibly brought by a technology breakthrough. For the sugarcane ethanol, we consider that the increase in conversion rate from 1975 to 1979 is caused by a jump process. For the corn ethanol, the recent rising conversion rate from 2010 is due to a technology breakthrough in the corn fiber conversion and high fermentable starch hybrids (National Corn Growers Association, 2012).

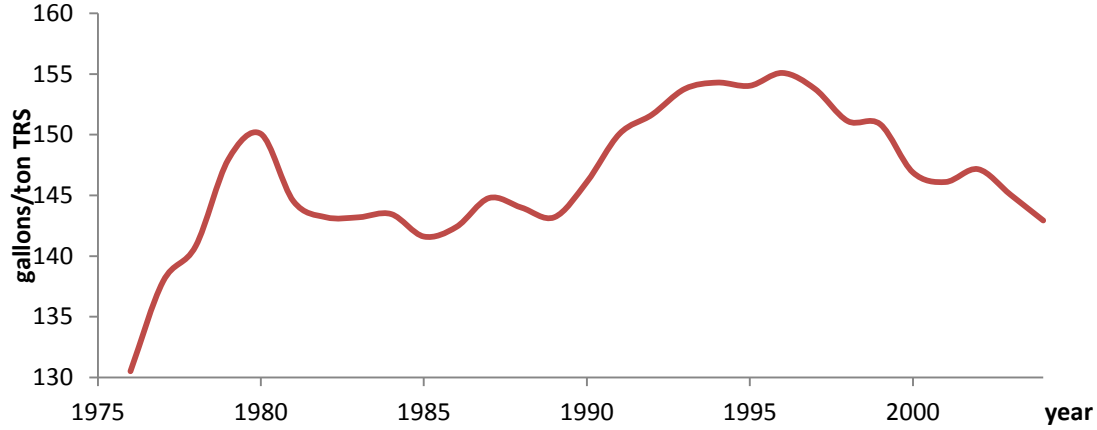


Figure 1: Conversion rate (gallons per ton of total reducible sugars) in the Brazil sugarcane ethanol

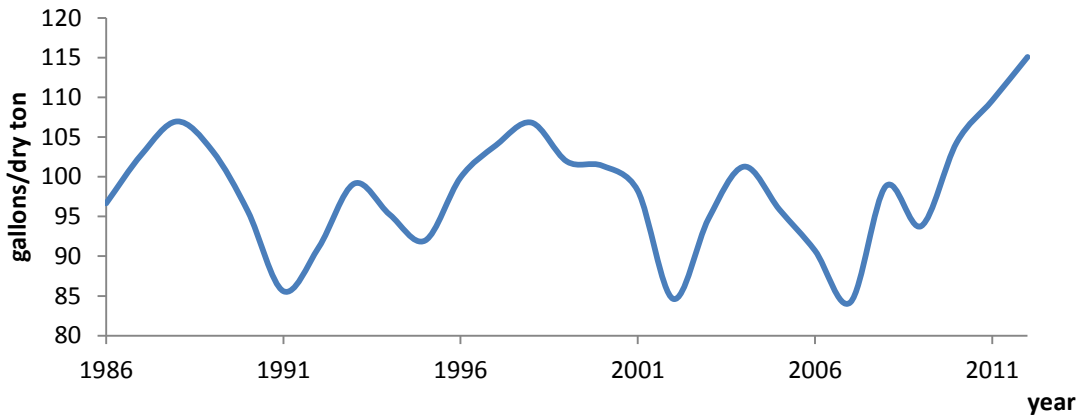


Figure 2: Conversion rate (gallons per dry ton of feedstock) in the US corn ethanol

The GBM part is estimated through equation (20).

$$\ln A_t - \ln A_{t-1} = c + \beta_1 \ln A_{t-1} + \sum_{j=1}^{n-1} \beta_j \Delta \ln A_{t-j} + \varepsilon_t \quad (20)$$

A Dickey-Fuller test is conducted and the results show that the null hypothesis of unit root is rejected at the significance level of 1%. By the maximum-likelihood method, the stochastic parameters are estimated through the distribution of annual change (Table 2). Besides the scenario of sugarcane and corn ethanol, the third scenario calculates the stochastic parameters assuming that the expected path in cellulosic biofuels is an equal mixture of the first two scenarios. For the jump process, we assume that the jump size is 10% and the mean arrival rate is 4% based on the technology breakthrough occurring in the corn/sugarcane ethanol.

Table 2: Stochastic parameters from different scenarios

Scenario	drift	standard deviation
Sugarcane	0.34%	2.01%
Corn	1.00%	8.06%
Mixture	0.67%	5.87%

6.3 Discount rates, financing cost, and learning effects

The discount rate varies for different investors. We assume that the baseline discount rate is 6%. Investors from the oil industry have higher opportunity costs than other investors. Their profit margins are reported in the range of 6.78% to 15.73% according to Yahoo finance.

The effective interest rate for a new or small business is 12.7% (Gale, 1991). If the investor has to borrow 90% of the total investment and self funds other parts with a discount rate 6%, the average financing cost of this investment is 11.44%. For learning effects, we use the progress ratio of 0.75 from corn ethanol industry (Chen & Khanna, 2012).

7 Simulation results

7.1 Baseline results

In this section, we calculate a private refinery technology threshold to entering the cellulosic biofuel market. A representative private firm makes the investment decision facing the uncertain conversion rate, without considering any government policies.

7.11 Technology uncertainties

The uncertainties about the conversion rate are composed of two parts. First, the GBM part fluctuates stochastically, which is measured by the variance term. Second, the potential technology breakthrough may bring a jump process, described by the jump size and the jump frequency. Figure 3 shows the technology thresholds calculated by both the NPV and ROA methods. The NPV method significantly underestimates the technology threshold by at least 25% compared to the ROA threshold at a standard deviation of 5%. This may explain why previous studies based on the NPV method have been overly optimistic on the cellulosic biofuel industry. The increasing variance raises the technology threshold substantially because the waiting option is more valuable to the investors, leading them to delay investments while waiting for a more profitable technology to compensate for increasing risks.

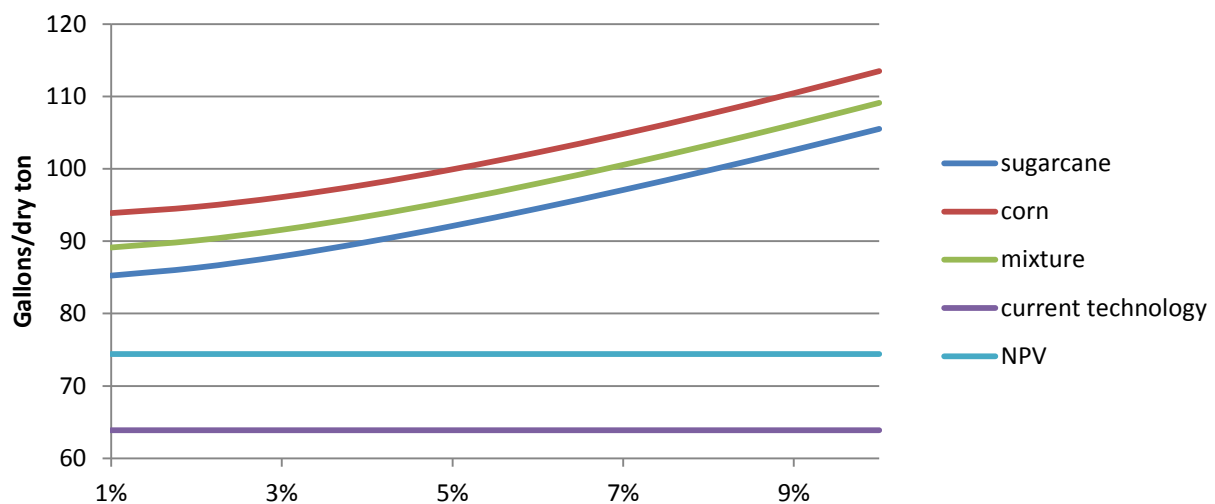


Figure 3: The technology thresholds with different standard deviation of the conversion rate

Although numerous studies argue that refinery technology breakthrough of the cellulosic ethanol will occur in the short-term, this optimistic prediction may delay investment. The reason is that investors may choose to wait for the new technology to build a more profitable refinery plant if such a technology is expected to be achieved in the near future. Figure 4 demonstrates this investment behavior. If firms expect that the breakthrough of refinery technology occurs more frequently, their technology thresholds grow higher, further delaying investment decisions. Furthermore, comparing Figure 4 to Figure 3, the uncertainties caused by the future technology advance have a stronger effect on raising the investment threshold than the uncertainties brought by the stochastic GBM. This suggests that the basic incentive for investors to wait is the breakthrough of refinery technology. The expectation for large technology advances may be an important factor to explain the current failure of investments in the cellulosic refineries. Although the technology jump may accelerate investment after it occurs, it increases the technology uncertainties and thereby makes the waiting option more valuable before it happens.

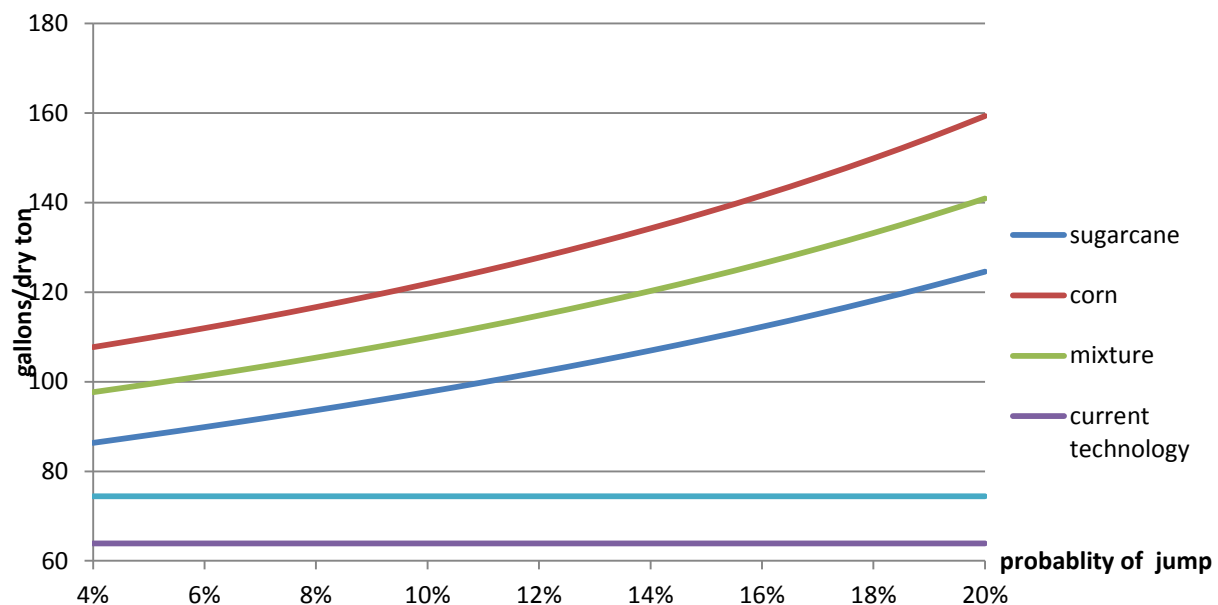


Figure 4: The technology thresholds with different probabilities of the technology breakthrough occurring annually

7.12 Feedstock costs

The feedstock cost plays an important role in the profitability of cellulosic ethanol production (NREL, 2010) but there is no consensus about the level of this cost by previous studies. A sensitivity analysis (Figure 5) shows that the feedstock cost has a strong impact on the investment decision. When this cost is approximately \$20/dry ton, a firm can build a profitable refinery plant even using the current technology. In other words, the low input cost compensates for the relatively high processing cost and thereby reduces the total production cost significantly. When the feedstock is as high as \$120/dry ton, the technology gap is at least 50 gallons/ton, implying that no firm can afford such a high input cost and remain profitable given current technology. Even an average feedstock cost between \$60 and \$80, the current range cited in many studies, is not low enough to result in profitable cellulosic production using the current technology and so prevents the firm from entering the market.

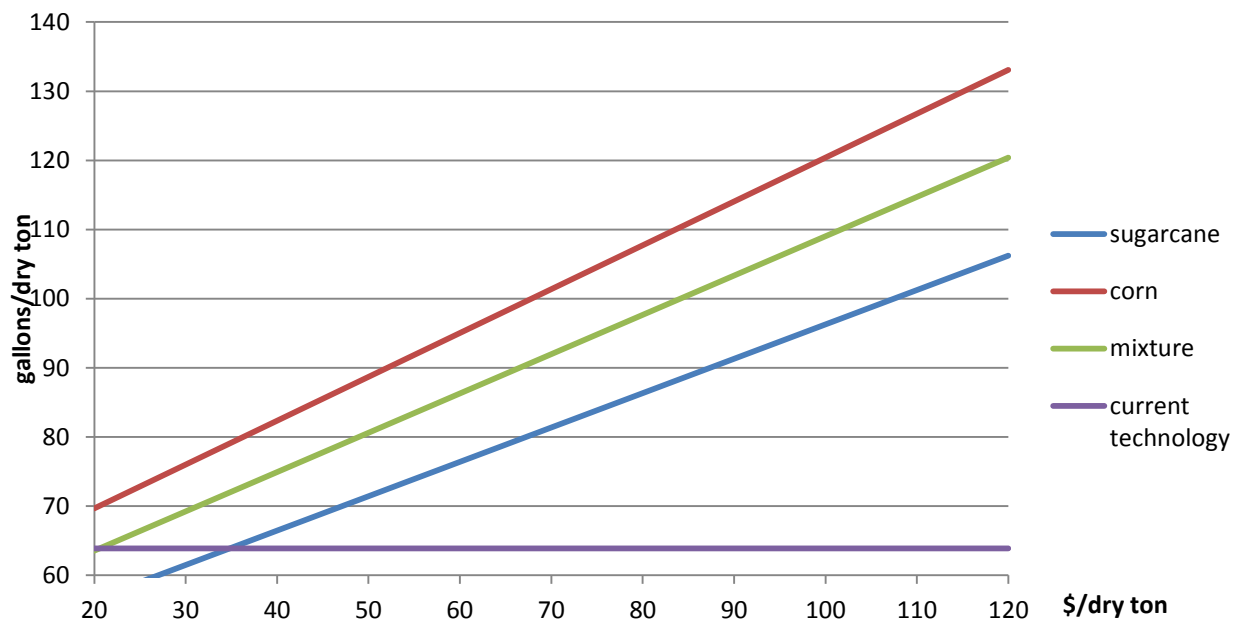


Figure 5: The technology thresholds with different feedstock costs

7.13 Discount rates

In contrast to the NPV method where increasing the discount rate will reduce the present value of a risky project, the increase in discount rate has two opposing effects within the ROA method (Dixit & Pindyck, 1993). First, a higher discount rate makes the total project less valuable because the future profits are discounted at a larger rate. This effect requires a more advanced technology and raises the technology threshold. Second, the larger discount rate makes the waiting opportunity cost more expensive, which encourages investors to exercise their option, reducing the investment threshold. In Figure 6, the second effect dominates when the discount rate is small, so the technology threshold decreases. Investors from a low-profit industry have high thresholds because their waiting opportunity cost is so low. As the discount rate grows, the first effect dominates and the threshold begins to increase. This implies that the investors from a high-profit industry such as the oil industry may prefer to stay at their current business. The most likely investors are firms with the discount rate in the range of 5% to 7%, whose profit margins are not high enough to keep them staying at their current industry or not low enough to make them wait for a more profitable technology.

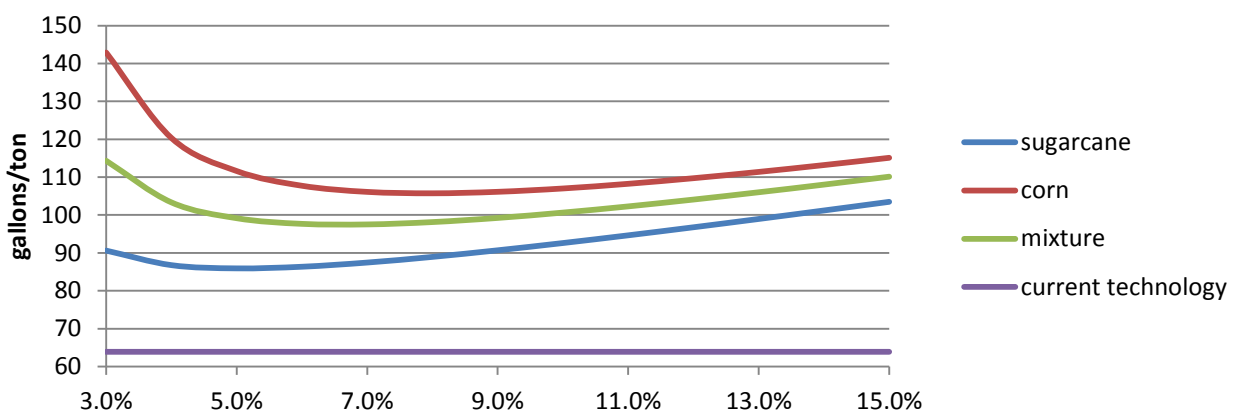


Figure 6: The technology thresholds with different discount rates

7.2 Policy Analysis

In this part, we focus on the impacts of some existing U.S. government policies on the cellulosic investment decision. Specifically, we analyze the effects of biofuel mandates and loan guarantee programs.

7.2.1 *The mandate and learning curve*

Figure 7 shows the different technology thresholds corresponding to different levels of industry outputs in three scenarios. Currently the cumulative output of the cellulosic ethanol industry is almost zero in the U.S. At this production level the technology threshold is at least 88 gallons/ton, far above the current technology of approximately 63 gallons/ton. This suggests that no investors will establish refinery plants using the current technology. When the learning by doing effect is incorporated as the industry grows, the firm's technology threshold moves down significantly. If the initial RFS target is achieved, the technology is no longer a main obstacle to enter this industry. But if EPA continues to waive the cellulosic mandate, the industry is not big enough to support the effects of the learning curve on reducing the production cost and thus, the low conversion rates achievable with current technology will continue to delay investment in this industry. In addition, the learning effects reduce the production cost and further lower the technology threshold. However, this occurs at a decreasing rate, meaning that the learning curve plays a more important role when the industry is relatively small. This suggests the importance of implementing and enforcing the biofuel mandate now when the industry is still very small. For example, if the initial mandate target of producing 500 million gallons cellulosic ethanol in 2012 were achieved, the private technology threshold would be estimated to approach what is feasible with current technology. If this happens, in the next year a few leading firms in the energy production may enter the market even without the mandate.

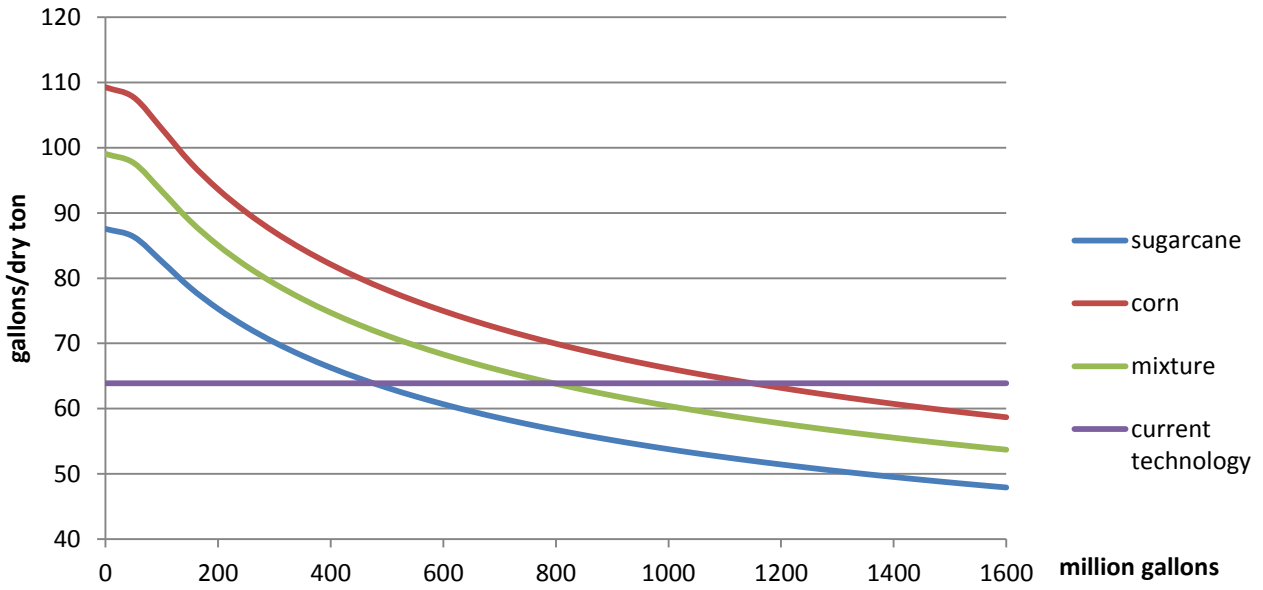


Figure 7: The technology thresholds with different industry cumulative outputs

7.2.2 The loan guarantee program

Higher interest rates increase the technology threshold because this makes building a refinery plant more expensive. For example, an increase in the interest rate from the benchmark level of 11.4% to 15% raises the threshold by 8% (Figure 8). Gale (1991) estimates that federal loan guarantee programs (LGP) may reduce the effective interest rate by 25% for small businesses. Using his estimation, the technology threshold decreases to 92 gallons/ton from the initial 97 gallons/ton in the mixture scenario as the interest rate decreases from 11.4% to 8.55%. However, the reduced technology threshold is still far above the current technology level, suggesting a necessary modification of the LGP to support the development of cellulosic biofuel refinery industry.

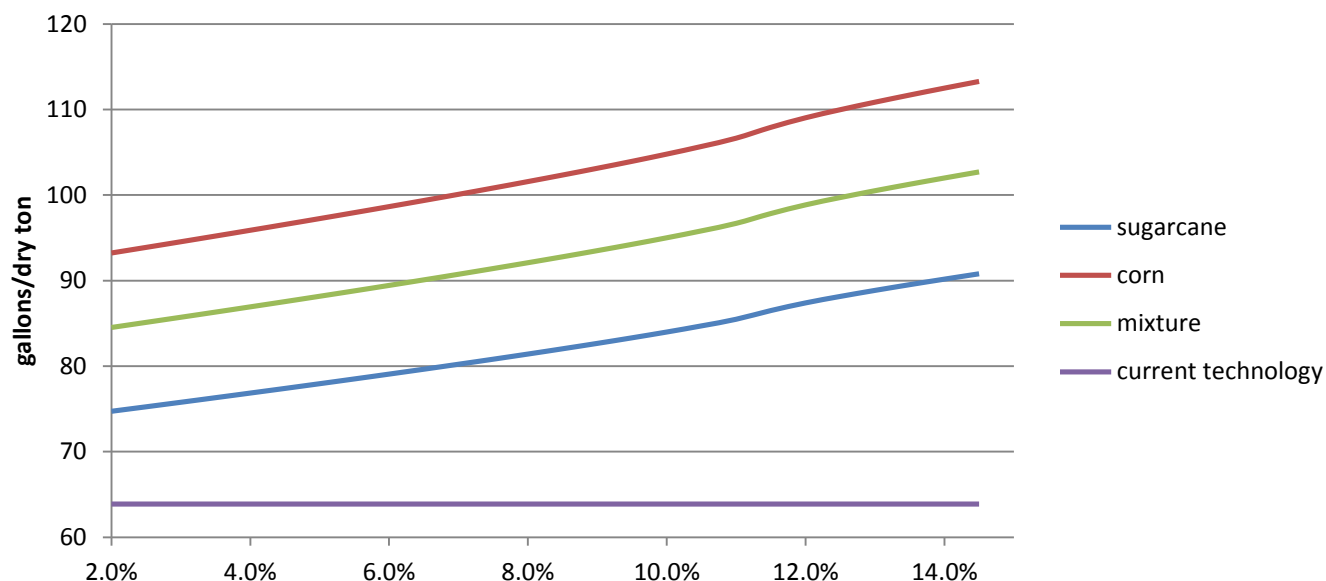


Figure 8: The technology thresholds with different interest rates

8. Conclusion

The lack of cellulosic production capacity in the U.S. is not well explained by previous studies, most of which are relatively optimistic with regards to the potential profitability of facilities in this new and emerging industry. A recent debate between the EPA and the oil companies shows that while the government still insists on a promising future for cellulosic ethanol the oil industry does not. This research provides a potential explanation for the lack of investment in cellulosic production capacity as well as for the different understandings of this industry between the government and oil companies. We find that the uncertainties about refinery technology may play a critical role in hindering investments in cellulosic ethanol refineries. Overly optimistic expectations for the technology breakthrough may further delay the investment because the investors choose to build a more profitable plant after the breakthrough occurs. The sooner they believe the breakthrough comes, the more likely they choose to wait.

The debate between the government and oil industry may be explained by and attributed to the learning effects. If even the initial mandate levels of cellulosic ethanol can be achieved, the

learning effects exhibited in the corn and sugar cane ethanol industries suggest that technology will no longer be an obstacle to commercialized production. The learning curve significantly reduces the production cost at a commercialized scale, which can compensate for relatively low conversion rates achievable with current technology. But before the mandate is really implemented, the current technology level still falls far behind the profitable technology threshold, suggesting no private investors will enter the market without additional policy support.

Besides the technology uncertainties and learning effects, the feedstock cost, discount rate, and interest rate also impact the investment decision. Low feedstock costs decrease the investment threshold significantly, implying the importance of feedstock supply to the refinery industry. The investors from oil industries may have more patience to wait because of the historically high profit margins they have earned, suggesting higher discount rates used to analyze investment opportunities. A more likely pool of investors in cellulosic biofuels may be corn ethanol producers who have seen their profit margins fall to 5% to 7% as that industry has matured.

Higher interest rates increase the firm's financing costs, resulting in a more costly investment. This causes the firm to wait for a more profitable technology and thereby delays the industry development. Although the government provides several loan guarantee programs to reduce this cost, these programs only play a very limited role in spurring the investment in the cellulosic ethanol refineries. This is shown by the relative insensitivity of the investment threshold to reduced interest rates and the relatively small impact that loan guarantee programs have had in reducing market interest rates for investors (Gale 1991).

In sum, the future success of cellulosic biofuel may depend on the learning by doing effects rather than expected advances in conversion technology. The anticipated technology

breakthroughs may even further delay investment decisions because the firm has incentives to wait until the breakthrough is realized. Thus, the government or researchers should be cautious about their predictions of the technology innovation in this field. If the government wants to trigger commercialized production through the promotion of learning effects, an enforced mandate level of at least 500 million gallons may be needed. Besides the learning curve, efforts to reduce the feedstock costs and production risk are other effective ways to overcome the current technology obstacles in this industry.

The model presented in this research can be extended to analyze the impacts of the ethanol “blend wall” and other policy factors on investment decisions in cellulosic biofuel refineries. In such an extended model, the blend wall or other government policies could be considered as additional dynamic variables. For example, with an ethanol blend wall that is a function of total fuel demand, potential investors in cellulosic biorefineries may require an even more advanced technology to make the production cost competitive with other potential sources of biofuel such as the corn ethanol industry. As a result, the blend wall imposes a higher investment threshold and further delays investments in this industry.

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