The Effects of Government Subsidies on Investment: A Dynamic Model of the Ethanol Industry

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Abstract

This paper analyses the effects of government subsidies and the Renewable Fuel Standard (RFS) on the U.S. ethanol industry. Analyses that ignore the dynamic implications of these policies, including their effects on incumbent ethanol firms' investment, production, and exit decisions and on potential entrants' entry behavior, may generate incomplete estimates of the impact of the policies and misleading predictions of the future evolution of the ethanol industry. In this paper, we first develop a stylized theory model of subsidies in which we examine which types of subsidies are more cost-effective for inducing investment in firm capacity. We then empirically analyze how government subsidies and the Renewable Fuel Standard affect ethanol production, investment, entry, and exit by estimating a structural econometric model of a dynamic game that enables us to recover the entire cost structure of the industry, including the distributions of investment costs, entry costs, and exit scrap values. We use the estimated parameters to evaluate three different types of subsidy: a volumetric production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. Results show that investment subsidies and entry subsidies are more cost-effective than production subsidies.

Keywords: ethanol, subsidy, renewable fuel standard, structural model, dynamic game
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1 Introduction

International attention has emerged in support of the development and use of renewable fuels such as ethanol. The motivating factors for this attention and support include high oil prices, security concerns from relying on foreign energy sources, support for economic growth in the agricultural community, the use of surplus grains, environmental goals related to criteria pollutants, and climate change emissions (Si et al., 2016).

In the United States, where the transportation sector is estimated to be responsible for over a quarter of the greenhouse gas emissions (Auffhammer et al., 2016), ethanol policies have been a politically sensitive topic. Politicians have pushed for support for ethanol production as an environmentally friendly alternative to imported oil, as well as a way to boost farm profits and improve rural livelihoods (Thome and Lin Lawell, 2016).

The development of the ethanol industry in the U.S. has historically been accompanied by government subsidies and, more recently, by the federal Renewable Fuel Standard (RFS). Ethanol production subsidies were implemented by the federal government in order to promote ethanol as a way to reduce dependence on imported oil (Pear, 2012). The launch of the ethanol industry was initiated in part by a volumetric production subsidy of 40 cents per gallon provided in the Energy Policy Act of 1978. Since then, the level of the subsidy has been modified a couple of times (Tyner, 2007). Most recently, the federal volumetric ethanol production subsidy was reduced from 51 cents per gallon to 45 cents per gallon in the 2008 Farm Bill, and subsequently eliminated on December 31, 2011. Such changes may have affected ethanol plant investment and ethanol production. Indeed, the rate of expansion in ethanol production capacity has decreased from a 4.6% growth rate over the period 2005-2008 to a growth rate of 0.6% per month in 2009, after the production subsidy was reduced (O'Brien and Woolverton, 2010).

In addition to volumetric production subsidies, the ethanol industry has also been supported by the federal Renewable Fuel Standard (RFS). The Renewable Fuel Standard was created under the Energy Policy Act of 2005 with the goal of accelerating the use of fuels derived from renewable sources (EPA, 2013a). This initial RFS (referred to as RFS1) mandated that a minimum of 4 billion gallons be used in 2006, rising to 7.5 billion gallons by 2012. Two years later, the Energy Independence and Security Act of 2007 greatly expanded the biofuel mandate volumes and extended the date through 2022. The expanded RFS (referred to as RFS2) required the annual use of 9 billion gallons of biofuels in 2008, rising to 36 billion gallons in 2022, of which 15 billion gallons can come from corn ethanol.[1] The industry production capacity for corn ethanol reached its targeted volume of 15 billion gallons at the end of 2012.[2]

This paper analyses the effects of government subsidies and the Renewable Fuel Standard on the U.S. ethanol industry. Analyses that ignore the dynamic implications of these policies, including their effects on incumbent ethanol firms' investment, production, and exit decisions and on potential entrants' entry behavior, may generate incomplete estimates of the impact of the policies and misleading predictions of the future evolution of the ethanol industry. In this paper, we first develop a stylized theory model of subsidies in which we examine which types of subsidies are more cost-effective for inducing investment in firm capacity. We then empirically analyze how government subsidies and the Renewable Fuel Standard affect ethanol production, investment, entry, and exit by estimating a structural econometric model of a dynamic game that enables us to recover the entire cost structure of the industry, including the distributions of investment costs, entry costs, and exit scrap values. We use the estimated parameters to evaluate three different types of subsidy: a volumetric production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS.

[1]In addition to the expanded volumes and extended date, the RFS2 also builds upon the RFS1 in three other ways. First, the total renewable fuel requirement is divided into four separate, but nested categories—total renewable fuels, advanced biofuels, biomass-based diesel, and cellulosic biofuels—each with its own volume requirement. Second, biofuels qualifying under each category must achieve certain minimum thresholds of lifecycle greenhouse gas emission reductions, with certain exceptions applicable to existing facilities. Third, all renewable fuel must be made from feedstocks that meet an amended definition of renewable biomass, including certain land use restrictions (Schnepf and Yacobucci, 2012; EPA, 2013c; Lade, Lin Lawell and Smith, 2016).

[2]Cellulosic ethanol production is still negligible due to both technological and economic issues (Lade, Lin Lawell and Smith, 2016) and many scientists suggest that commercialization of cellulosic is several years down the road (Celebi et al., 2010; Schnepf and Yacobucci, 2012).

The previous literature on ethanol investment includes studies that estimate the viability of ethanol plants. Schmit, Luo and Tauer (2009) point out that previous studies of firm investment and operation of ethanol plants have focused largely on break-even or net present value analysis, return on investment, or similar assessments in a deterministic framework, with sensitivity analyses conducted on important costs, technologies, or prices (Whims, 2002, Gallagher et al., 2006; Eidman, 2007; Ellinger, 2007; Dal-Mas et al., 2011). To evaluate the viability of ethanol plants under stochastic conditions, price risk and cost risk have been incorporated by some studies to evaluate the profitability of a representative ethanol plant (Richardson et al., 2007; Richardson, Lemmer and Outlaw, 2007; Gallagher, Shapouri and Brubaker, 2007; Dal-Mas et al., 2011); in addition, demand uncertainty and competitive effect uncertainty are also assessed by Jouvet, Le Cadre and Orset (2012). Other studies have estimated the most profitable plant size under different market conditions (Gallagher, Brubaker and Shapouri, 2005; Gallagher, Shapouri and Brubaker, 2007; Khoshnoud, 2012). Several recent studies analyze ethanol plant investment option values (Schmit, Luo and Tauer, 2009; Gonzalez, Karali and Wetzstein, 2012) based on engineering cost information and various simulations, but these studies do not empirically estimate costs.

There are somewhat fewer studies focusing on how government policies impact investment in ethanol plants. In their survey, Cotti and Skidmore (2010) find that subsidies can have a significant effect on a state's production capacity. Schmit, Luo and Tauer (2009) and Schmit, Luo and Conrad (2011) use dynamic programming methods to show that without government policies, the recent expansionary periods would have not existed and market conditions in the late 1990s would have led to some plant closure. Bielen, Newell and Pizer (2016) estimate the incidence of the ethanol subsidy and find compelling evidence that ethanol producers captured two-thirds of the subsidy, and suggestive evidence that a small portion of this benefit accrued to corn farmers. Thome and Lin Lawell (2016) show empirically that the Renewable Fuel Standard has contributed to ethanol plant investment. Babcock (2013) uses simulations to evaluate the viability of the ethanol industry in the absence of a mandate under different gasoline prices and ethanol demand elasticities, and concludes that without subsidies, low gasoline prices imply low viability for ethanol. These findings emphasize the importance of government support in the development of ethanol industry. On the other hand, Babcock (2011) argues that the recent high gasoline prices and phase-out of MTBE increased ethanol prices far above levels needed to justify investment in a corn ethanol plant, which means that a subsidy might not be necessary.

In this paper, we first develop a stylized theory model of subsidies in which we examine which types of subsidies are more cost-effective for inducing investment in firm capacity. Our theory model shows that whether it costs more to the government to induce investment via a production subsidy or an investment subsidy depends on the parameters, and is therefore an empirical question.[3]

We then empirically analyze how government subsidies and the Renewable Fuel Standard affect ethanol production, investment, entry, and exit by estimating a structural econometric model of a dynamic game. We estimate the structural econometric model in two steps. In the first step, we characterize the policy functions for the plants' decisions regarding entry, capacity investment, and exit, which are functions of state variables. In the second step, we use a simulation-based minimum distance estimator proposed by Bajari, Benkard and Levin (2007) to recover the entire cost structure of the industry including the distributions of investment costs, entry costs, and exit scrap values.

We build upon the previous literature in several ways. First, we develop a theory of subsidies in which we examine which types of subsidies are more cost-effective to the government for inducing firm investment. Second, we empirically examine whether it costs more to the government to induce investment via a production subsidy or an investment subsidy in the context of the ethanol industry in the United States by estimating a structural model and by using the estimated parameters to simulate alternative forms of subsidies. Third, we

[3] For a theory model of the Renewable Fuel Standard, Lade and Lin Lawell (2016) develop a theory model of renewable fuel mandates and apply it to the RFS; and Lade, Lin Lawell and Smith (2016) develop a dynamic model of RFS compliance.

empirically estimate the various investment and production costs in the ethanol industry. Fourth, we allow for two different types of entry: entry via constructing a new plant and entry via buying a shut-down plant. Fifth, we allow our estimated cost parameters to depend on production subsidy levels and on the implementation of the Renewable Fuel Standard. In contrast to our paper, which empirically estimates costs, the cost information used in previous studies of the ethanol industry are mainly from the literature or from engineering experiments (Eidman, 2007; Ellinger, 2007; Schmit, Luo and Tauer, 2009; Schmit, Luo and Conrad, 2011; Gonzalez, Karali and Wetzstein, 2012).

As we find in the theory model, whether it costs more to the government to induce investment via a production subsidy or an investment subsidy depends on the parameters, and is therefore an empirical question. Our empirical results show that the RFS decreased investment costs, increased entry costs, and increased both the mean and standard deviation of exit scrap values.

We then use our estimated structural model of the ethanol industry to run counterfactual simulations to analyze the effects of three different types of subsidy: a volumetric production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. We find that investment subsidies and entry subsidies are more cost-effective than production subsidies. Our results have important implications for the design of government policies for ethanol.

The rest of paper is organized as follows. We develop a theory of subsidies in Section 2. In Section 3, we describe our structural econometric model. Section 4 describes our data. In Section 5, we present our empirical results. We use counterfactual simulations to analyze the effects of three different types of subsidy in Section 6. Section 7 concludes.

2 A Theory of Subsidies

We first develop a stylized theory model to provide intuition on which types of subsidies are more cost-effective for inducing investment in firm capacity. In this simple model, there are two time periods. The discount factor is β.

Per-period production profits are a function of capacity s and the production subsidy ϕ_p, and are given by $\pi(s, \phi_p)$. We assume the per-period production profits $\pi(s, \phi_p)$ take the following functional form:

$$\pi(s, \phi_p) = (p + \phi_p)\kappa s - c_p(s), \tag{1}$$

where p is output price, where $\kappa \in [0, 1]$ is a fixed capacity utilization rate so that output is given by κs, and where $c_p(s)$ is the production cost as a function of capacity s.

In the first period, a firm can choose to invest in adding x units of capacity at cost c_x net of any investment subsidy ϕ_c. A firm can also choose to exit after producing in the first period, and earn a scrap value d. The firm's value function in the first period is therefore given by:

$$v_1(s; \phi_p, \phi_c) = \pi(s, \phi_p) + \max \{-(c_x - \phi_c) + \beta E[v_2(s + x; \phi_p, \phi_c)], \beta E[v_2(s; \phi_p, \phi_c)], d\}. \tag{2}$$

If the firm chooses to invest, the firm earns the production profits $\pi(s, \phi_p)$ for that period, minus the investment cost c_x net of any investment subsidy ϕ_c, plus the discount factor β times the continuation value $E[v_2(s + x; \phi_p, \phi_c)]$, which is the expected value of the value function next period conditional on the state and action this period. When the firm chooses to invest, the continuation value $E[v_2(s+x; \phi_p, \phi_c)]$ is the expected value of the second period value function $v_2(\cdot)$ evaluated at next period's state, which is this period's capacity s plus the investment x.

If the firm does not invest, the firm earns the production profits $\pi(s, \phi_p)$ for that period plus the discount factor β times the continuation value $E[v_2(s, \phi_p)]$, where in this case next period's capacity is the same as this period's capacity s since no investment was made.

If the firm chooses to exit, the firm earns the production profits $\pi(s, \phi_p)$ for that period plus the scrap value scrap value d.

The firm's value function for the second period is simply that period's production profits as a function of that period's capacity, and is given by:

$$v_2(s; \phi_p, \phi_c) = \pi(s, \phi_p). \tag{3}$$

Substituting equation (3) for the second period value function $v_2(\cdot)$ into equation (2) for the first period value function $v_1(\cdot)$, the first period value function becomes:

$$v_1(s; \phi_p, \phi_c) = \pi(s, \phi_p) + \max\left\{-(c_x - \phi_c) + \beta E[\pi(s + x, \phi_p)], \beta E[\pi(s, \phi_p)], d\right\}. \tag{4}$$

2.1 Production subsidy

Suppose there is an production subsidy ($\phi_p > 0$) but no investment subsidy ($\phi_c = 0$). Then, the production subsidy ϕ_p induces investment if both of the following two conditions hold:

$$\beta E[\pi(s + x, \phi_p)] - \beta E[\pi(s, \phi_p)] \quad > \quad c_x \tag{5}$$

$$\beta E[\pi(s + x, \phi_p)] \quad > \quad c_x + d. \tag{6}$$

Using our functional form assumption (1) on per-period production profits $\pi(s, \phi_p)$, the conditions for the production subsidy to induce investment reduce to the following two lower bounds for the production subsidy ϕ_p:

$$
\begin{aligned}
\phi_p &> -E[p] + \frac{1}{\kappa x}\left(E[c_p(s+x) - c_p(s)] + \frac{c_x}{\beta}\right) && (7) \\
\phi_p &> -E[p] + \frac{1}{\kappa(s+x)}\left(E[c_p(s+x)] + \frac{c_x + d}{\beta}\right). && (8)
\end{aligned}
$$

Combining (7) and (8) yields the following lower bound $\underline{\phi_p}$ for the production subsidy ϕ_p to induce investment:

$$
\phi_p > \underline{\phi_p}, \tag{9}
$$

where:

$$
\underline{\phi_p} = -E[p] + \max\left\{\frac{1}{\kappa x}\left(E[c_p(s+x) - c_p(s)] + \frac{c_x}{\beta}\right), \frac{1}{\kappa(s+x)}\left(E[c_p(s+x)] + \frac{c_x + d}{\beta}\right)\right\}. \tag{10}
$$

The production subsidy induces investment that otherwise would not occur if in addition to (7) and (8), either of the following two conditions holds as well:

$$
\begin{aligned}
-c_x + \beta E[\pi(s+x, \phi_p = 0)] &< \beta E[\pi(s, \phi_p = 0)] && (11) \\
-c_x + \beta E[\pi(s+x, \phi_p = 0)] &< d. && (12)
\end{aligned}
$$

Under the functional form assumption (1) for production profits, the condition that either (11) or (12) holds reduces to:

$$
-E[p] > -\max\left\{\frac{1}{\kappa x}\left(E[c_p(s+x)] - E[c_p(s)] + \frac{c_x}{\beta}\right), \frac{1}{\kappa(s+x)}\left(E[c_p(s+x)] + \frac{c_x + d}{\beta}\right)\right\}. \tag{13}
$$

Combining conditions (7), (8), and either (11) or (12) yields the following lower bound $\underline{\underline{\phi_p}}$ for the production subsidy ϕ_p to induce investment that otherwise would not occur:

$$\phi_p > \underline{\underline{\phi_p}}, \tag{14}$$

where:

$$\begin{aligned}
\underline{\underline{\phi_p}} \quad &= \quad -\max\left\{ \tfrac{1}{\kappa x}\left(E[c_p(s+x)] - E[c_p(s)] + \tfrac{c_x}{\beta} \right), \tfrac{1}{\kappa(s+x)}\left(E[c_p(s+x)] + \tfrac{c_x+d}{\beta} \right) \right\} \\
&\qquad +\max\left\{ \tfrac{1}{\kappa x}\left(E[c_p(s+x) - c_p(s)] + \tfrac{c_x}{\beta} \right), \tfrac{1}{\kappa(s+x)}\left(E[c_p(s+x)] + \tfrac{c_x+d}{\beta} \right) \right\} \\
&= \quad 0.
\end{aligned} \tag{15}$$

Thus, the production subsidy would induce investment that otherwise would not occur as long as it is positive.

Since the production subsidy ϕ_p must be paid for each unit of production in both periods, the total cost $C(\phi_p)$ to the government of a production subsidy ϕ_p that induces investment is given by:

$$C(\phi_p) = \phi_p((1+\beta)\kappa s + \beta\kappa x). \tag{16}$$

The minimum cost $C(\underline{\phi_p})$ to the government of inducing investment via a production subsidy is given by:

$$\begin{aligned}
C(\underline{\phi_p}) = \quad & -((1+\beta)\kappa s + \beta\kappa x)E[p] + \beta E[c_p(s+x)] + c_x \\
& +\max\Bigg\{ \tfrac{(1+\beta)s}{x}\left(E[c_p(s+x)] + \tfrac{c_x}{\beta} \right) - \left(\tfrac{(1+\beta)s}{x} + \beta \right) E[c_p(s)], \\
& \tfrac{s}{s+x}\left(E[c_p(s+x)] + \tfrac{c_x+d}{\beta} \right) + d \Bigg\}.
\end{aligned} \tag{17}$$

2.2 Investment subsidy

Suppose there is an investment subsidy ($\phi_c > 0$) but no production subsidy ($\phi_p = 0$). Then, the investment subsidy ϕ_c induces investment if both of the following two conditions hold:

$$\phi_c > -\beta E[\pi(s+x, \phi_p = 0)] + \beta E[\pi(s, \phi_p = 0)] + c_x \tag{18}$$

$$\phi_c > -\beta E[\pi(s+x, \phi_p = 0)] + c_x + d. \tag{19}$$

Under the functional form assumption (1) for production profits, the conditions for the investment subsidy to induce investment reduce to the following lower bounds for the investment subsidy ϕ_c:

$$\phi_c > -\beta\kappa x E[p] + \beta E[c_p(s+x)] - \beta E[c_p(s)] + c_x \tag{20}$$

$$\phi_c > -\beta\kappa(s+x)E[p] + \beta E[c_p(s+x)] + c_x + d. \tag{21}$$

Combining (20) and (21) yields the following lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment:

$$\phi_c > \underline{\phi_c}, \tag{22}$$

where, assuming non-negative expected production profits $E[\pi(s, \phi_p)] \geq 0$, which implies that $\kappa s E[p] \geq E[c_p(s)]$:

$$\underline{\phi_c} = \beta E[c_p(s+x)] + c_x - \beta\kappa x E[p] - \min\left\{\beta E[c_p(s)], \beta\kappa s E[p] - d\right\}. \tag{23}$$

The investment subsidy induces investment that otherwise would not occur if, in addition to (20) and (21), either of the following conditions holds as well:

$$-c_x + \beta E[\pi(s+x, \phi_p = 0)] \;<\; \beta E[\pi(s, \phi_p = 0)] \tag{24}$$

$$-c_x + \beta E[\pi(s+x, \phi_p = 0)] \;<\; d. \tag{25}$$

Under the functional form assumption (1) for production profits, the condition that either (24) or (25) holds reduces to:

$$\beta E[c_p(s+x)] + c_x - \beta\kappa x E[p] < \max\left\{E[c_p(s)], \beta\kappa x E[p] - d\right\}. \tag{26}$$

Combining conditions (20), (21), and either (24) or (25) yields the following upper bound for the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur:

$$\underline{\phi_c} < \max\left\{E[c_p(s)], \beta\kappa x E[p] - d\right\} - \min\left\{\beta E[c_p(s)], \beta\kappa s E[p] - d\right\}. \tag{27}$$

The total cost $C(\phi_c)$ to the government of an investment subsidy ϕ_c is given by:

$$C(\phi_c) = \phi_c. \tag{28}$$

2.3 Comparing production and investment subsidies

Calculating the difference between the cost to the government of the lower bound $\underline{\phi_p}$ for the production subsidy ϕ_p to induce investment, and the cost to the government of the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment, we obtain:

$$C(\underline{\phi_p}) - C(\underline{\phi_c}) = -(1+\beta)\kappa s E[p] + \max\left\{A1, A2\right\} + \min\left\{B1, B2\right\}, \tag{29}$$

where:

$$A1 = \frac{(1+\beta)s}{x}\left(E[c_p(s+x)] + \frac{c_x}{\beta}\right) - \left(\frac{(1+\beta)s}{x} + \beta\right) E[c_p(s)] \quad (30)$$

$$A2 = \frac{s}{s+x}\left(E[c_p(s+x)] + \frac{c_x + d}{\beta}\right) + d \quad (31)$$

$$B1 = \beta E[c_p(s)] \quad (32)$$

$$B2 = \beta \kappa s E[p] - d. \quad (33)$$

Thus, the difference $C(\underline{\phi_p}) - C(\underline{\phi_c})$ between the minimum cost to the government of inducing investment via a production subsidy and the minimum cost to the government of inducing investment via an investment subsidy is greater the lower the expected output price $E[p]$, the greater the production cost after investment $E[c_p(s+x)]$, the greater the investment cost c_x, and the greater the exit scrap value d.

However, the sign of the diffference $C(\underline{\phi_p}) - C(\underline{\phi_c})$ in costs depends on the parameters. Thus, whether it costs more to the government to induce investment via a production subsidy or an investment subsidy is an empirical question. In this paper, we empirically examine whether it costs more to the government to induce investment via a production subsidy or an investment subsidy in the context of the ethanol industry in the United States.

3 Econometric Model

The structural econometric model of a dynamic game we use builds on the framework of industry dynamics developed by Maskin and Tirole (1988) and Ericson and Pakes (1995); on a model developed by Pakes, Ostrovsky and Berry (2007), which has been applied to the multi-stage investment timing game in offshore petroleum production (Lin, 2013) and to the decision to wear and use glasses (Ma, Lin Lawell and Rozelle, 2016); on a model developed by Bajari et al. (2015), which has been applied to ethanol investment in Canada (Yi and Lin Lawell 2016a) and Europe (Yi and Lin Lawell, 2016b); and on models developed by

Aguirregabiria and Mira (2007), Pesendorfer and Schmidt-Dengler (2008), Bajari and Hong (2006), and Srisuma and Linton (2012). Aguirregabiria and Suzuki (forthcoming) survey the recent empirical literature on structural models of market entry and spatial competition in retail industries.

In particular, we use the structural econometric model of a dynamic game developed by Bajari, Benkard and Levin (2007), which has been applied to the cement industry (Ryan, 2012; Fowlie, Reguant and Ryan, 2016), to fisheries (Huang and Smith, 2015), and to dynamic natural monopoly regulation (Lim and Yurukoglu, forthcoming).

We model the decisions of two types of agents: incumbents and potential entrants in the ethanol market. Incumbents choose how much to produce, whether to invest in capacity and if so by how much, and whether to exit. Potential entrants choose whether to construct a new plant, buy a shut-down plant, or not to enter. The actions a_i of each agent i are assumed to be functions of a set of state variables and private information:

$$a_i = \sigma_i(s, \varepsilon_i), \tag{34}$$

where s is a vector of publicly observable state variables and ε_i is a vector of private information shocks to agent i which are not observed by either other agents or the econometrician. State variables include own capacity, competitors' capacity, number of shut-down plants, ethanol price, and ethanol policies. The private information shocks include the individual-specific fixed costs to investment, entry, and exit, and idiosyncratic preference shocks to potential entrants for building a new plant, buying a shut-down plant, or not entering.

We assume that ethanol plants compete in quantities in a homogeneous goods market. Ethanol demand is given by:

$$\ln Q = \alpha_0 + \alpha_1 \ln P, \tag{35}$$

where Q is the aggregate demand for ethanol, P is the market price, and α_1 is the price elasticity of demand.

For each ethanol plant i, the cost of output is assumed to be the following quadratic function of output:

$$c_i(q_i; \theta) = \delta_1 q_i + \delta_2 q_i^2, \tag{36}$$

where δ_1 and δ_2 are variable cost coefficients, q_i is the output of plant i, and θ is a vector of all the parameters in the model, including δ_1 and δ_2 as well as the parameters described below.

Since the U.S. government subsidizes ethanol plants based on the volume of their production, the production subsidy a ethanol plant receives is:

$$r_i(q_i) = \varphi q_i, \tag{37}$$

where φ is the subsidy level per unit of ethanol.

At each period of time, an incumbent firm chooses its output q_i to maximize its profits from production, subject to the capacity constraint that q_i cannot exceed the firm's capacity level y_i. The maximized static production profit function for an incumbent is thus given by:

$$\bar{\pi}_i(s; \theta) = \max_{q_i \leq y_i} \left(P q_i - \delta_1 q_i - \delta_2 q_i^2 + \varphi q_i \right). \tag{38}$$

Firms can change their capacities by x_i, and we assume the cost associated with capacity change is given by:

$$\Gamma(a_i, \varepsilon_i; \theta) = 1(x_i > 0)(\gamma_{1i} + \gamma_2 x_i + \gamma_3 x_i^2), \tag{39}$$

where the vector of actions a_i includes the capacity investment decision x_i, the vector of shocks ε_i includes the individual-specific fixed cost γ_{1i}; and where the vector of parameters θ includes γ_2 and γ_3 (in addition to the parameters above). Our capacity adjustment cost function is different from the power function used in Gallagher, Brubaker and Shapouri (2005) and in Gallagher, Shapouri and Brubaker (2007), but the implicit assumption is the same: the construction cost of an ethanol plant is U-shaped. Since we do not observe disinvestment in our data set, the capacity change is only for capacity expansion. The capacity adjustment cost function shows that investment in capacity will have fixed cost γ_{1i} and quadratic variable cost with parameters γ_2 and γ_3. The individual-specific fixed cost γ_{1i}, which is private information and drawn from the distribution F_{γ_1} with mean μ_{γ_1} and standard deviation σ_{γ_1}, captures the necessary setup costs such as the costs of obtaining permits and constructing support facilities, which accrue regardless of the size of the capacity.

An ethanol plant i also faces a fixed cost $\Phi_i(a)$ unrelated to production given by:

$$\Phi_i(a_i;\varepsilon_i) = \begin{cases} k_{1i} & \text{if the new entrant constructs a plant} \\ k_{2i} & \text{if the new entrant bought a plant from a previous owner} \\ d_i & \text{if the firm exit the market} \end{cases}, \tag{40}$$

where the vector of actions a_i includes the entry and exit decisions, k_{1i} and k_{2i} are the sunk costs of entry, d_i is the scrap value. k_{1i} is the sunk cost of constructing a new ethanol plant. Instead of constructing a new plant, another way to enter the market is to buy an existing ethanol plant that has shut down; the purchasing of existing plants was more common after 2008. Therefore, k_{2i} is the sunk cost of buying a shut-down plant. These sunk costs are private information and drawn from the distributions F_{k_1} and F_{k_2}, with means μ_{k_1} and μ_{k_2} and standard deviations σ_{k_1} and σ_{k_2}, respectively. If a plant exits the market, it can receive a scrap value d_i, for example from selling off the land or facility, which is private information and drawn from the distribution F_d with mean μ_d and standard deviation σ_d. The individual-level sunk costs of entry k_{1i} and k_{2i} and the individual-level scrap value d_i are all components of the vector of shocks ε_i (in addition to the shocks above).

The per-period payoff function is therefore as follows:

$$\pi_i(s, a_i, \varepsilon_i; \theta) = \bar{\pi}_i(s;\theta) - \Gamma(a_i, \varepsilon_i; \theta) - \Phi_i(a_i, \varepsilon_i; \theta). \tag{41}$$

Hence, the value function for an incumbent, who chooses how much to produce, whether to invest in capacity and if so by how much, and whether to exit, is given by:

$$
\begin{aligned}
V_i(s;\sigma(s),\theta,\varepsilon_i) \quad = & \\
& \bar{\pi}_i(s;\theta)+ \\
& \max\Big\{\max_{x_i>0}\big[-\gamma_{1i}-\gamma_2 x_i-\gamma_3 x_i^2+\beta\int E_{\varepsilon_i'}V_i(s';\sigma(s'),\theta,\varepsilon_i')dp(s';s,a_i,\sigma_{-i}(s))\big] \\
& \beta\int E_{\varepsilon_i'}V_i(s';\sigma(s'),\theta,\varepsilon_i')dp(s';s,a_i,\sigma_{-i}(s)),\ d_i\Big\},
\end{aligned}
\tag{42}
$$

where the continuation value $\int E_{\varepsilon_i'}V_i(s';\sigma(s'),\theta,\varepsilon_i')dp(s';s,\sigma(s))$ is the expected value of the value function next period conditional on the state variables and strategies in the current period, s' is the vector of next period's state variables, $p(s';s,a_i,\sigma_{-i}(s))$ is the conditional probability of state variable s' given the current state s, player i's action a_i (including any capacity changes x_i), and the strategies $\sigma_{-i}(s)$ of all other players. Incumbents receive the profits $\bar{\pi}_i(s;\theta)$ from production this period and then, depending on their action, additionally incur the costs of capacity investment if they invest, additionally receive the continuation value if they stay in the market (regardless of whether they invest), and additionally receive the scrap value from exiting if they exit.

Similarly, the value function for a potential entrant, who can either stay out of the ethanol market, build a new plant, or buy a shut-down plant from a previous owner, is given by:

$$
\begin{aligned}
V_i(s;\sigma(s),\theta,\varepsilon_i) \quad = & \\
& \max\Big\{\varepsilon_{0i}, \\
& \max_{y_i>0}\left[-k_{1i}-\gamma_{1i}-\gamma_2 y_i-\gamma_3 y_i^2+\varepsilon_{1i}+\beta\int E_{\varepsilon_i}V_i(s';\sigma(s',\theta,\varepsilon_i))dp(s';s,a_i,\sigma_{-i}(s))\right], \\
& \max_{\substack{y_i>0,\\ y_i\in\boldsymbol{Y}}}\left[-k_{2i}-\gamma_4 y_i-\gamma_5 y_i^2+\varepsilon_{2i}+\beta\int E_{\varepsilon_i}V_i(s';\sigma(s',\theta,\varepsilon_i))dp(s';s,a_i,\sigma_{-i}(s))\right]\Big\},
\end{aligned}
\tag{43}
$$

where y_i is the capacity for plant i; γ_4 and γ_5 are transaction cost parameters for an entrant buying an shut-down plant; $\boldsymbol{Y}$ is the set of shut-down plants' sizes in the market; and $\varepsilon_{0i}, \varepsilon_{1i}$, and ε_{2i} are idiosyncratic preference shocks that we assume are independently distributed with an extreme value distribution. The value function for a potential entrant is therefore the maximum of: (1) the payoff from staying out of the market, which is the idiosyncratic preference shock ε_{0i}; (2) the payoff from building a new plant of capacity y_i, which includes the fixed cost of entry k_{1i}, the costs of capacity investment y_i, the idiosyncratic preference shock ε_{1i}, and the continuation value; and (3) the payoff from buying a shut-down plant of capacity y_i, which includes the fixed cost of entry k_{2i}, the variable transactions costs, the idiosyncratic preference shock ε_{2i}, and the continuation value. If an entrant decides to buy an existing shut-down plant, its plant size choice is limited to set $\boldsymbol{Y}$.

We assume, as does Ryan (2012), that potential entrants are short-lived and that if they do not enter this period they disappear and their payoff is zero forever so that they never enter in future. This assumption is for computational convenience; otherwise, we would have to solve an optimal waiting problem for the potential entrants. In addition, once an ethanol plant is constructed, we assume the capacity is used at a fixed rate, and therefore that plants do not suspend operations. Option value issues are carefully discussed by Schmit, Luo and Tauer (2009) and Gonzalez, Karali and Wetzstein (2012).

We assume that each plant optimizes its behavior conditional on the current state variables, other agents' strategies, and its own private shocks, which results in a Markov perfect equilibrium (MPE). The optimal strategy $\sigma_i^*(s)$ for each player i should therefore satisfy the following condition that, for all state variables s and alternative strategies $\tilde{\sigma}_i(s)$, the present discounted value of the entire stream of expected per-period payoffs should be weakly higher under the optimal strategy $\sigma_i^*(s)$ than under any alternative strategy $\tilde{\sigma}_i(s)$:

$$V_i(s; \sigma_i^*(s), \sigma_{-i}, \theta, \varepsilon_i) \geq V_i(s; \tilde{\sigma}_i(s), \sigma_{-i}, \theta, \varepsilon_i).$$

We estimate the structural econometric model in two steps. In the first step, we characterize the equilibrium policy functions for the plants' decisions regarding entry, capacity expansion, and exit as functions of state variables by using reduced-form regressions correlating actions to states. We also estimate parameters in the per-period production profit function and the transition density for the state variables.

In the second step, we use a simulation-based minimum distance estimator proposed by Bajari, Benkard and Levin (2007) to estimate the distribution of fixed costs and the variable costs for investment in plant capacity; the distribution of scrap values a plant would receive if it exited the market; and the distribution of entry costs and the variable costs for either constructing a new plant or buying a shut-down plant.

3.1 Production profits, policy functions, and transition densities

3.1.1 Ethanol demand

We estimate ethanol demand at time t as follows:

$$\ln Q_t = \alpha_0 + \alpha_1 \ln P_t + \alpha_2' X_t + \varepsilon_t, \tag{44}$$

where α_1 is the elasticity of demand and X is a vector of covariates that influence demand, including dummy variables for RFS1 and RFS2. We assume that the production subsidy does not affect the parameters in the demand function. To address the endogeneity of price in the demand function, we use supply shifters to instrument for price.

3.1.2 Cost function

All the ethanol plants are assumed to be competing in a homogeneous goods Cournot game. Let $P(Q)$ be the inverse of the demand function estimated above. The first-order condition from each plant's profit-maximization problem for an interior solution ($q_i < y_i$) is given by:

$$\frac{\partial P(Q)}{\partial Q}q_{it} + P(Q) - \delta_1\left[1 + \alpha_{11}RFS1_t + \alpha_{12}RFS2_t\right]$$
$$-2\delta_2\left[1 + \alpha_{21}RFS1_t + \alpha_{22}RFS2_t\right]q_{it} + \varphi_t \qquad = 0, \tag{45}$$

where $\alpha = [\alpha_{11}\ \alpha_{12}; \alpha_{21}\ \alpha_{22}]$ are the parameters for interactions between the policy variables and the cost parameters and φ_t is the level of the production subsidy at time t. $RFS1_t$ is a dummy for the years 2005 and 2006. $RFS2_t$ is a dummy for the years 2007, 2008, and 2009.

Since the level of the federal ethanol production subsidy has been modified a couple of times since it was first initiated in 1978 at \$0.40 per gallon (Tyner, 2007), it is reasonable to assume that both the timing and level of the subsidy changes were unanticipated by firms in years prior to each change. Similarly, since details about RFS1 were still being issued by the EPA in 2007, the year when RFS2 was implemented (EPA, 2013b), it is reasonable to assume that the timing of RFS2 were unanticipated by firms in years prior to RFS2. Moreover, since the Energy Policy Act of 2005 which created RFS1 was both introduced in Congress and passed in 2005, it is reasonable to assume that the timing of RFS1 were unanticipated by firms in years prior to RFS1.[4]

We derive the predicted quantity of output $\hat{q}_i$ from rearranging the above first-order condition to get:

$$\hat{q}_{it}(\theta) = \frac{P(Q) - \delta_1[1+\alpha_{11}RFS1_t + \alpha_{12}RFS2_t] + \varphi_t}{2\delta_2[1+\alpha_{21}RFS1_t + \alpha_{22}RFS2_t] - \frac{\partial P(Q)}{\partial Q}}. \tag{46}$$

We estimate the parameters $\theta = (\delta_1, \delta_2, \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22})$ in the production profit function by finding the values of the parameters that minimize the sum of squared difference between observed quantity and predicted output:

$$\min_{\theta} \sum_{i,t} (q_{it} - \hat{q}_{it}(\theta))^2. \tag{47}$$

[4] Lade, Lin Lawell and Smith (2016) discuss uncertainty regarding the Renewable Fuel Standard.

3.1.3 Investment policy function

We use a Tobit model to estimate an ethanol plant's capacity investment policy function $p_i(s)$. We assume that a latent capacity investment variable s^*_{it} exists for every ethanol plant at specific state variables that determines if a plant will invest; investment x_i will only occur if the latent variable x^*_{it} is positive. The latent investment variable is assumed to be a linear function of regressors X_{it} with additive error u_{it} that is normally distributed and homoskedastic. Thus,

$$x^*_{it} = X'_{it}\xi + u_{it}, \tag{48}$$

where ξ are the parameters to be estimated and X_{it} is a vector of state variables including own capacity, rivals' capacity, dummies for RFS1 and RFS2, and a time trend. The Tobit model is shown as follows:

$$x_{it} = \begin{cases} 0 & \text{if } x^*_{it} \leq 0 \\ x^*_{it} & \text{if } 0 < x^*_{it} \leq \overline{x} \\ \overline{x} & \text{if } x^*_{it} > \overline{x} \end{cases}, \tag{49}$$

where $\overline{x}$ is a maximum investment level in capacity. Consistent with the data, investment in capacity is censored both from left and from right. Also consistent with the data, we observe no disinvestment. The Tobit model enables us to estimate the probability $p_i(s)$ of investment as well as the amount x_{it} of investment.

3.1.4 Entry and exit policy functions

The equilibrium strategy for each potential entrant is to choose from its three possible actions — construct a new plant, buy a shut-down plant, or not to enter — with probabilities $p_c(s)$, $p_b(s)$, and $p_o(s)$, respectively. We estimate these choice probabilities as functions of state variables using a multinomial logit. For an incumbent, the exit policy probability $p_e(s)$ is estimated as a function of state variables using a logit model.

3.1.5 State transitions

In addition to estimating the optimal policy functions, we also estimate the state transition probabilities as a function of the current state variables and of the firms' strategies in investment, entry, and exit. We assume the changes of state variables through entry, investment, and exit take one period to occur, which is a standard assumption in discrete time models.

3.2 Recovering the structural parameters

In a Markov perfect equilibrium, each incumbent plant follows optimal strategies for output, investment, and exit; and each potential entrant follows optimal strategies for constructing a new plant, buying a shut-down plant, or doing nothing, all as functions of state variables. After estimating the policy functions in the first step, we then estimate the structural parameters in the second step by imposing optimality on the recovered policy functions. In particular, from the definition of a Markov perfect equilibrium, we impose that the optimal strategy $\sigma_i^*(s)$ for each player i should satisfy the following condition for all state variables s and alternative strategies $\tilde{\sigma}_i(s)$:

$$V_i(s; \sigma_i^*(s), \sigma_{-i}, \theta, \varepsilon_i) \geq V_i(s; \tilde{\sigma}_i(s), \sigma_{-i}, \theta, \varepsilon_i), \tag{50}$$

where θ are the structural parameters to be estimated. The structural parameters we estimate include the distribution of fixed costs and the variable costs for capacity investment; the distribution of scrap values a plant would receive if it exited the market; and the distribution of entry costs and the variable costs for either constructing a new plant or buying a shut-down plant.

Following Bajari, Benkard and Levin (2007), we assume the per-period payoff function is linear in the unknown parameters θ so that:

$$\pi_i(a, s, \varepsilon_i; \theta) = \Psi_i(a, s, \varepsilon_i) \cdot \theta, \tag{51}$$

where $\Psi_i(a, s, \varepsilon_i)$ is an M-dimensional vector of "basis functions" $\psi_i^1(a, s, \varepsilon_i), \psi_i^2(a, s, \varepsilon_i), \ldots,$ $\psi_i^M(a, s, \varepsilon_i)$. The value function can then be written as:

$$V_i(s; \sigma, \theta) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \Psi_i(\sigma(s_t, \varepsilon_t), s_t, \varepsilon_{it})\right] \cdot \theta = W_i(s; \sigma) \cdot \theta. \tag{52}$$

With a linear per-period payoff function, $W_i = [W_i^1 \ \cdots \ W_i^M]$ does not depend on the unknown parameters θ.

3.2.1 Parameters for incumbents

Given the strategy profile $\boldsymbol{\sigma}$, we can define an incumbent's value function as:

$$\begin{aligned} V_i(s; \sigma(s), \theta) &= W_i^1(s; \sigma) - W_i^2(s; \sigma) \cdot \gamma_{1i} - W_i^3(s; \sigma) \cdot \gamma_2 - W_i^4(s; \sigma) \cdot \gamma_3 + W_i^5(s; \sigma) \cdot d_i \\ &= \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \bar{\pi}_i(s_t)\right] - \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t p_i(s_t)\right] \cdot \gamma_{1i} - \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t p_i(s_t) x_{it}\right] \cdot \gamma_2 \\ &\quad - \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t p_i(s_t) x_{it}^2\right] \cdot \gamma_3 + \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t p_e(s_t)\right] \cdot d_i, \end{aligned} \tag{53}$$

where the expected values are taken over the various strategy choices $\sigma(s)$ of the other firms.

We cannot directly estimate the parameters in the unconditional distributions for the individual-specific fixed cost of investment γ_{1i} and the individual-specific scrap value d_i in the above equation. The reason is that firms only undertake actions when the associated shock is sufficiently favorable. To account for the conditional distribution of the two parameters, Ryan (2012) suggests using flexible linear b-spline functions of the strategy probabilities to estimate conditional expectations of the random draws. The main argument is that because all the strategy probabilities capture the relevant information faced by a plant at a specific state, the conditional mean of fixed cost or scrap value is also a function of those probabilities. The intuition behind this method is straightforward: if other alternatives become more attractive, which would be reflected in a higher choice probability for those alternatives, the draw of the investment or scrap value should represent such preference.

To estimate the conditional distributions for γ_{1i} and d_i, we first construct linear b-spline functions to estimate the conditional means of γ_{1i} and d_i:

$$E[\gamma_{1i}|V_i^+(s) - \gamma_{1i} > V_i^0(s),\ V_i^+(s) - \gamma_{1i} > d_i] = \theta_{\gamma_1} \cdot bs(p_i(s)) \tag{54}$$

$$E[d_i|d_i > V_i^0(s),\ d_i > V_i^+(s) - \gamma_{1i}] = \theta_d \cdot bs(p_e(s)). \tag{55}$$

$V_i^+(s)$ is the value after optimal investing capacity, and $V_i^0(s)$ is the value using current capacity.

Assuming that there exits a set of state variables s such that $p_i(s) \approx 0$ for all $p_e(s) \in (0, 1)$, and vice versa, where $p_i(s)$ and $p_e(s)$ are the probabilities of investment in capacity and exit, respectively, we can invert the probability of investment (exit) onto the distribution of fixed investment costs (scrap value), without having to worry about the exit (investment) cost. By incorporating equations (54) and (55) into equation (53), we can simultaneously estimate the unknown parameters θ_{γ_1} and θ_d and thereafter compute the conditional mean and variance for γ_{1i} and d_i.

Following Bajari, Benkard and Levin (2007), we calculate $W_i(s; \sigma)$ via forward simulation. Based on the definition of a Markov perfect equilibrium, the optimal strategy $\sigma_i^*(s)$ for each incumbent i should satisfy the following condition for all state variables s and alternative strategies $\tilde{\sigma}_i(s)$:

$$W_i(s; \sigma_i^*, \sigma_{-i}) \cdot [1 \quad \theta]' \geq W_i(s; \tilde{\sigma}_i, \sigma_{-i}) \cdot [1 \quad \theta]'. \tag{56}$$

To estimate the unknown parameters above, we can construct a criterion condition:

$$g(\tilde{\sigma}; \theta) = [W_i(s; \sigma_i^*, \sigma_{-i}) - W_i(s; \tilde{\sigma}_i, \sigma_{-i})] \cdot [1 \quad \theta]'. \tag{57}$$

Then we search for incumbent parameters $\theta = (\theta_{\gamma 1}, \theta_d, \gamma_2, \gamma_3)$ such that profitable deviations from the optimal actions are minimized:

$$\min_{\theta_I} Q_n(\theta) = \frac{1}{n_c} \sum_{j=1}^{n_c} (\min\{g(\tilde{\sigma}_{i,j}; \theta), 0\})^2, \tag{58}$$

where n_c is the number of random draws. In practice, to construct alternative strategies $\tilde{\sigma}_i(s)$, we add a noise term to the optimal policy function $\sigma_i^*(s)$. For example, to perturb the exit policy function for an incumbent, we draw errors to the exit policy function from the standard normal distribution n_c times. Then, the random action drawn from the above procedure is used in both per-period profit function and the state transition probabilities, and the corresponding state variables are estimated. These steps are repeated until each firm reaches a terminal state with known payoff such as the scrap value from exiting the market, or repeated $T = 70$ periods such that β^T becomes insignificantly small relative to the simulation error generated by averaging over only a finite number of paths (Bajari, Benkard and Levin, 2007).

The objective function (58) is a non-smooth function with numerous local optima, which makes it difficult to use an extremum estimator. To handle this, we use the Laplace Type Estimator (LTE) proposed by Chernozhukov and Hong (2003) to search for the parameters θ in equation (58). The LTE is defined similarly as a Bayesian estimator, but it uses a general statistical criterion function instead of the parametric likelihood function. We use a Markov chain Monte Carlo (MCMC) approach for the LTE, and the estimates are the mean values of a Markov chain sequence of draws from the quasi-posterior distribution of θ, generated by the tailored Metropolis Hastings Algorithm (Zubairy, 2011). The first advantage of the LTE is that it is a global optimization method. When the number of the Monte Carlo draws approaches to infinity, the mean and standard deviation of the posterior distribution of θ corresponds to its asymptotic distribution counterpart (Houde, 2012). Then the estimation results are the mean values and standard deviation of the 5000 Markov chain draws and the first 1000 draws in the burn-in stage are discarded.

To empirically compute the posterior distribution of θ, we use Metropolis Hastings algorithm as follows:

1. Start with $j = 0$. Choose θ^0 and compute $Q_n(\theta^0)$.

2. For each j from $j = 0$ to $j = 5000$:

   (a) Draw θ^+ from the distribution $q(\theta^+|\theta^j)$ and compute $Q_n(\theta^+)$.

   (b) Update θ^{j+1} using:

$$\theta^{j+1} = \begin{cases} \theta^+ \text{ with probability } \rho(\theta^j, \theta^+) \\ \theta^j \text{ with probability } 1 - \rho(\theta^j, \theta^+) \end{cases}, \tag{59}$$

   where

$$\rho(x, y) = \min \left\{ \frac{e^{Q_n(y)} h(y) q(x|y)}{e^{Q_n(x)} h(x) q(y|x)}, 1 \right\}. \tag{60}$$

Following Chernozhukov and Hong (2003), we let the distribution $q(x|y)$ be a symmetric mean-0 Gaussian distribution $f(x - y)$, which we choose to be $N(0, \sigma^2)$, where the variance σ^2 is updated with the variance of $(x - y)$ every 100 draws. We also assume uninformative priors: $h(x) = 1$.

3.2.2 Parameters for potential entrants

A potential entrant chooses an action $a_i \in \{0,\ 1,\ 2\}$, where $a = 0$ represents not entering the market, $a = 1$ represents entering the biofuel market by constructing a new plant, and $a = 2$ represents buying an existing shut-down plant.

We define the choice specific value function $V_i(a_i, s; \theta)$ as:

$$\begin{aligned}
V_i(a_i = 0, s; \theta) &= 0 \\
V_i(a_i = 1, s; \theta) &= -k_{1i} - \gamma_{1i} - \gamma_2 y_{it} - \gamma_3 y_{it}^2 + \beta E \left[V^c(s'; a_i = 1, s) \right] \\
V_i(a_i = 2, s; \theta) &= -k_{2i} - \gamma_4 y_{it} - \gamma_5 y_{it}^2 + \beta E \left[V^b(s'; a_i = 2, s) \right].
\end{aligned} \tag{61}$$

The conditional distribution of γ_{1i} and the parameters γ_2 and γ_3 were estimated from the incumbent's problem. The continuation values $E\left[V^c(s'; a_i = 2, s)\right]$ and $E\left[V^b(s'; a_i = 3, s)\right]$ can be computed through forward simulation. The individual sunk costs $k_{1i},\ k_{2i}$ are drawn from private information. Using an argument similar to the one regarding the fixed cost of investing capacity and scrap values for incumbents, we can use a linear b-spline function of the entry probabilities to estimate the conditional means of k_{1i} and k_{2i}:

$$\begin{aligned}
&E[k_{1i} | V_i(a_i = 1, s; \theta) > V_i(a_i = 0, s; \theta),\ V_i(a_i = 1, s; \theta) > V_i(a_i = 2, s; \theta)] \\
&\quad = \theta_{k_1} \cdot bs(p_c(s), p_b(s))
\end{aligned} \tag{62}$$

$$\begin{aligned}
&E[k_{2i} | V_i(a_i = 2, s; \theta)) > V_i(a_i = 0, s; \theta),\ V_i(a_i = 2, s; \theta) > V_i(a_i = 1, s; \theta)] \\
&\quad = \theta_{k2} \cdot bs(p_c(s), p_b(s)),
\end{aligned} \tag{63}$$

where $V^c(s)$ and $V^b(s)$ are the values from constructing a new plant and buying a shut-down plant, which also include the optimal plant size decision, respectively, and where $p_c(s)$ and $p_b(s)$ are the probabilities of constructing a new plant and buying an existing plant, respectively.

If we assume the preference shocks ε_{0i}, ε_{1i}, and ε_{2i} in the value function are distributed extreme value, the equilibrium probabilities and choice specific value functions are related through the following equation for the probability of each choice:

$$Pr(a_i = k | s) = \frac{\exp(V_i(a_i = k, s))}{\sum_{l=0}^{2} \exp(V_i(a_i = l, s))}. \tag{64}$$

The choice probabilities on the left-hand side of equation (64) are given by the entry policy function. To estimate the potential entrant parameters $\theta = (\theta_{k_1}, \theta_{k_2}, \gamma_4, \gamma_5)$, we draw n_s random states of the ethanol industry and search for the parameters θ which best match the choice probabilities from the entry policy function on the left-hand side of equation (64) to the logit share equation on the right-hand side of equation (64) by minimizing the sum of the squared differences:

$$\min_{\theta} \frac{1}{n_s} \sum_{j=1}^{n_s} \sum_{a_i=0}^{2} \left\{ Pr(a_i|s_j) - \frac{\exp(V_i(a_i, s_j; \theta))}{\sum_{l=0}^{2} \exp(V_i(a_i = l, s_j; \theta))} \right\}^2 . \tag{65}$$

4 Data

According to the Energy Information Administration, over 90% of the ethanol produced in the U.S. over the years 1995 to 2009 was produced in following 10 Midwestern states: Iowa, Illinois, Indiana, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin. According to the Renewable Fuels Association (RFA), there were 164 ethanol plants located in these 10 Midwestern states in 2010, making up roughly 80% of the total number of ethanol plants in the U.S. Because the majority of ethanol is produced in these 10 Midwestern states, we focus our analysis of ethanol entry, exit, production, and investment decisions on these states.

We create an unique panel dataset of information on ethanol plants in the 10 Midwestern states from 1995 to 2009, which includes plant start-up date, nameplate capacity, and the size of any capacity expansions. The original list of ethanol plants are from the Renewable Fuels Association (RFA) and Ethanol Producer magazine; these lists do not match perfectly. We rectify inconsistencies between the two lists as well as collect additional information on plant owners by searching through plant websites and newspaper articles.

Because these 10 Midwestern states only constitute around 35% of U.S. ethanol consumption, we estimate a national demand function for ethanol. For our demand estimation, we

Table 1: Summary statistics

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
National data				
Consumption (billion gallon)	2.2602	2.7335	0.0831	11.0366
Ethanol price ($/gallon)	1.1160	0.2859	0.7782	1.7774
Population (million)	265.5156	24.4643	229.4657	307.0066
Gasoline price ($/gallon)	1.4868	0.3830	1.0189	2.3641
Number of ethanol plants	32.3103	43.1112	0	141
State-level data				
Natural gas price ($/million Btu)	5.5494	1.5960	2.5120	9.9024
Corn price ($/bushel)	2.9560	0.9442	1.5783	5.8783
Plant-level data				
Capacity (million gallons)	58.3555	51.7771	5	290
Capacity investment (million gallons)	0.95	5.9724	0	60

Notes: Prices are in constant 2000 US dollars. The data span the years 1981 to 2009.

use national consumption quantity and consumption expenditure data from the U.S. Energy Information Administration (EIA). As most of ethanol is produced in the 10 Midwestern states, we use the following supply shifters as instruments for price in the demand estimation: average natural gas price over the 10 states, total number of plants in the 10 states, and lagged average corn price over the 10 states. The natural gas price data are from EIA. Corn prices are available annually from the National Agricultural Statistics Service of the USDA (NASS) at the state level. For covariates in the estimation of the demand curve, we use gasoline prices from the EIA and population from the Population Division of U.S. Census Bureau. All prices and income are adjusted to 2000 constant dollars.

Summary statistics are presented in Table 1.

The Renewable Fuels Association reports plant-level production from 2007 onwards. Our data set for the years 1995 to 2009 therefore includes plant-level production data for the years 2007 to 2009. As seen in Table 2, the industrial rate of operation over the years 1998 to 2010 is around 88.8%.

Table 2: Ethanol plant capacity, production, and operation rate

Year	**Capacity (10^6 gallon)**	**Production (10^6 gallon)**	**Rate of operation (%)**
1998	1701.7	1400	82.27
1999	1748.7	1470	84.06
2000	1921.9	1630	84.81
2001	2347.3	1770	75.41
2002	2706.8	2130	78.69
2003	3100.8	2810	90.62
2004	3643.7	3410	93.59
2005	4336.4	3905	90.05
2006	5493.4	4855	88.38
2007	7888.4	6485	82.21
2008	10569.4	9235	87.37
2009	11877.4	10600	89.25
2010	13507.9	13230	97.94
Average	5449.5	4841	88.83

Source: Renewable Fuels Association.

5 Empirical Results

5.1 Ethanol demand

We use national data on prices and quantities over the period 1995 to 2009 to estimate the U.S. ethanol demand function in equation (44). In addition to ethanol price, we include gasoline prices and a time trend in the demand function as demand shifters. To address the endogeneity of ethanol price, we use the following supply shifters as instruments for price: average natural gas price over the 10 Midwestern states, total number of plants in the 10 Midwestern states, and lagged average corn price over the 10 Midwestern states. We use supply shifters from the 10 Midwestern states since most of the ethanol produced in the U.S. is produced in these states.

The results of the demand estimation are shown in Table 3. The first specification includes a time trend and log gasoline price as covariates. Specifications II, III, and IV control for the effects of the RFS and log population.

We test whether the instruments used in the demand estimation are both correlated with endogenous ethanol price and uncorrelated with the error term. The first-stage F-statistics are greater than 10. The p-values from the Sargan-Hansen overidentification test are greater than 10%, which means that we cannot reject the joint null hypothesis that our instruments are uncorrelated with the error term and that the instrument variables are correctly excluded from the estimated equation.

The demand elasticities estimated across the 4 specifications are higher than previous estimates by Rask (1998) and Luchansky and Monks (2009), which are in the range -2.915 to -0.37. In his analysis using Minnesota data only, Anderson (2011) estimates that the elasticity of demand for flexible fuel vehicle (FFV) ethanol consumption is in the range -3.2 to -3.8. However, Anderson (2011) treats E85 as pure ethanol and E10 as pure gasoline, even though both have ethanol as well as gasoline. Since the total consumption of E85 for FFV until 2011 is less than 0.02% of the E10 used by conventional gasoline vehicles (EIA, 2011), our estimation covers the entire demand for ethanol rather than just FFV fuel demand.

Babcock (2013) suggests two situations under which the ethanol demand elasticities could be high: (1) consumers do not discern the lower efficiency of ethanol compared with gasoline if the volume of ethanol blended into gasoline is low; and (2) the ratio of ethanol to gasoline price is consistent with the ratio of the energy content between the two fuels when the ethanol blending ratio is high enough for consumers to perceive the difference between the two fuels. These two situations are often assumed in theoretical analyses, including those by de Gorter and Just (2009) and Cui et al. (2011). In reality, it is likely that we are in the first situation, where the volume of ethanol blended into gasoline is low, due to the so-called E10 blend wall.

We believe that our high long-run demand elasticity is reasonable because of two characteristics of the ethanol market. First, ethanol is almost a perfect substitute for gasoline and MTBE, making ethanol demand very sensitive to ethanol price. Most current U.S. engines can run on at most 10% ethanol, which means that the fuel efficiency reduction is less than one mile per gallon in a 25-mile-per-gallon vehicle (Babcock, 2013). Therefore, we believe that it is really hard for consumers to recognize that ethanol generates lower miles per gallon than gasoline. Before 1992, ethanol was used as a gasoline substitute (Rask, 1998), which can explain the high elasticity of demand for ethanol with respect to gasoline price. Then, the Clean Air Act Amendments of 1990 mandated the use of oxygenates in gasoline, of which ethanol is one and MTBE is another. Ethanol was treated as a substitute to MTBE for more than a decade until MTBE was found to contaminate groundwater and was completely phased out in 2006, making ethanol the primary oxygenate that can be blended into gasoline to satisfy the oxygenate requirement, which means that it may be necessary to add a small quantity of ethanol into gasoline. Therefore, beyond the minimum amount of ethanol needed to satisfy the oxygenate requirement, the demand for ethanol can be easily satisfied by consuming gasoline instead, which yields a high elasticity of demand for ethanol.

A second reason for the high demand elasticity is that even after the implementation of the RFS in 2005, the federal government did not require fixed proportions of ethanol to be blended in gasoline, as it only mandated that a specific amount ethanol be sold in each state.[5] Therefore, the actual blending rates differ among states. The idea that the percentage of ethanol blended into gasoline needs to be treated as an endogenous variable for blenders is often ignored by theoretical studies, including those by de Gorter and Just (2009) and Cui et al. (2011). Typically, for those states who have E85 gas pumps, the blending rate of ethanol in regular gasoline is flexible, which enables ethanol to still be a substitute to gasoline and therefore makes it sensitive to its own price. Once the actual blending rate is higher than the government's requirements, ethanol demand should be sensitive to the price because gasoline can perfectly substitute for it. Thus, over the period 1995 to 2009, ethanol was a substitute for gasoline and for MTBE and therefore had a high own-price elasticity of demand.

We use the results from specification III for our structural model. This specification

[5] Over 90% of all gasoline sold at public gas stations now contains ethanol. However, labeling when ethanol is added in many states is not required in such states as California, Indiana, and Kentucky. For the states who require a label on pump for ethanol presence, 1% is the minimum threshold rate. More information is available at `http://www.fuel-testers.com/state_guide_ethanol_laws.html`.

Table 3: Ethanol demand

	I	II	III	IV
	Dependent variable is log ethanol quantity			
Log ethanol price	-17.8458***	-14.8192**	-15.5770*	-16.6773**
	(4.3265)	(5.2876)	(6.1693)	(6.2796)
Log population		-4.2720	-5.1722	
		(5.5648)	(5.8822)	
RFS1			-0.1917	-0.1274
			(0.1981)	(0.1894)
RFS2			-0.0892	0.0085
			(0.2723)	(0.2555)
Log gasoline price	18.0676***	15.1125**	16.0371**	17.0296**
	(4.193857)	(5.1469)	(6.1660)	(6.2987)
Time trend	0.1375***	0.1868**	0.1989**	0.1353***
	(0.0132)	(0.0660)	(0.0740)	(0.0153)
Constant	-258.6429***	-273.2905***	-280.2716***	-253.8891***
	(26.5992)	(32.8619)	(42.9981)	(31.4838)

Notes: Standard errors are in parentheses. Ethanol price is instrumented with average natural gas price over the 10 Midwestern states, total number of plants in the 10 Midwestern states, and lagged average corn price over the 10 Midwestern states. Significance codes: * 5% level, ** 1% level, *** 0.1% level.

controls more factors that can affect ethanol demand and the estimated elasticity is neither the highest nor the lowest estimated elasticity among our 4 specifications. Ryan (2012) argues that, in this stage of estimation, a lower demand elasticity results in firms facing unreasonably large investment costs in order to rationalize their behavior. In other words, firms would be leaving very large amounts of money on the table. Fortunately, our estimates of demand elasticities are high even for the relatively conservative one we choose to use.

5.2 Production costs

After estimating the demand curve for ethanol, we estimate the cost parameters $\theta = (\delta_1, \delta_2, \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22})$ in the production profit function by finding the values of the parameters that minimize the sum of squared difference between observed quantity and predicted output in equation (47). The results are shown in Table 4.

As we only have plant-level data on ethanol production from 2007 to 2009, the first specification uses data from 2007 to 2009 only. The second specification uses the data from all the years 1995 to 2009, and assumes that all the plants produce at a rate of 88.8% of their capacity, which is the approximate industrial rate of operation over the years 1998-2010 as seen in Table 2. The results for both specifications show that the coefficient δ_1 in the linear term in the cost function is not significant at a 5% level and that the only significant parameter is the coefficient δ_2 in the quadratic term. The results suggest that the marginal cost of producing ethanol follows a curve through the origin. Our results also suggest that the RFS does not have significant effects on the production cost function, since none of the parameters α are statistically significant.

The two different output assumptions show similar estimates. We use the results from specification II for the structural model. Given that (1) the estimation using the available production data over the last 3 years shows similar results, and (2) the U.S. demand for ethanol is always greater than production which should drive plants to utilize their capacity efficiently, we believe that the results from specification II are plausible. Apply our parameter estimates to the summary statistics in Table 1, our back-of-the-envelope estimate of the yearly gross revenue of a firm with average capacity is around 91 million dollars with the production subsidy, and 65 million dollars without the production subsidy. Accordingly, the profit margins are around 51% and 32%, respectively. In comparison, the production cost from Gonzalez, Karali and Wetzstein (2013) for a typical 50-million-gallon plant in Georgia is 0.77 dollars per gallon, which is a little higher than our result of 0.65 dollars per gallon.[6]

5.3 Investment policy function

Table 5 reports the results from the Tobit model we use to estimate the investment policy function. The dependent variable of capacity change is censored at two points. On the left-hand side, we do no observe decreases in capacity, likely due to the relatively high fixed

[6] The operating cost in Schmit, Luo and Tauer (2009), which does not include feedstock expenditure, is around 0.05 dollars per gallon.

Table 4: Production cost

Coefficient in production cost on:		I	II
quantity	$\hat{\delta}_1$	0.7155	0.3343
		(0.3680)	(0.2107)
quantity^2	$\hat{\delta}_2$	0.0101*	0.0129***
		(0.0046)	(0.0026)
quantity * RFS1	$\hat{\alpha}_{11}$	0.4297	-5.6273
		(3.7418)	(51.6538)
quantity * RFS2	$\hat{\alpha}_{12}$	2.7174	-28.6464
		(8.6458)	(138.2005)
quantity^2 * RFS1	$\hat{\alpha}_{21}$	-0.2645	1.7522
		(0.5771)	(32.5416)
quantity^2 * RFS2	$\hat{\alpha}_{22}$	1.9967	6.5274
		(1.9525)	(98.6967)

Notes: Standard errors are in parentheses. Significance codes:
* 5% level, ** 1% level, *** 0.1% level.

cost of completely shutting down part of a plant. On the right-hand side, we do not observe capacity changes over 60 million gallons. The reason for the right-hand side truncation might be that for a manager, expanding a plant's capacity to more than 60 million gallons may be prohibitively expensive over the time period of our data set. Therefore, we set two censoring limits, 0 and 60 million gallons.

In all of the specifications of Table 5, the coefficients on own capacity and on the sum of competitors' capacity are quite robust when other regressors are added, including lag ethanol price, a time trend, and the RFS dummies. Both own capacity and the sum of competitors' capacity have negative effects on the probability of expanding plant size. It makes sense that large competitors' capacities will dampen a manager's production goal and also that a large plant has less incentive to expand capacity because of increasing marginal costs. Our estimates are also consistent with the results from Ryan (2012). The main policies we focus on, the RFS1 and RFS2, do not have any significant impacts on the investment decisions although the relevant parameters have the expected signs. We use the results from specification IV for the structural model.

Table 5: Investment policy function

Dependent variable is change in capacity				
	I	II	III	IV
Capacity	-0.8486**	-0.8935**	-0.8776**	-0.8918**
	(0.3219)	(0.3361)	(0.3303)	(0.3351)
National sum of rivals' capacity	-0.0244**	-0.0295**	-0.0246*	-0.0321**
	(0.0090)	(0.0108)	(0.0096)	(0.0121)
Lag ethanol price	173.9980**	119.7424	106.4171	79.0058
	(66.3847)	(70.3478)	(88.7526)	(89.7191)
Year		8.1522		9.0305
		(4.6079)		(5.1419)
RFS 1			25.6302	5.5133
			(26.4087)	(27.7078)
RFS 2			45.5659	31.8906
			(44.1365)	(44.6544)
Constant	-202.8695***	-16455.6400	-141.4422	-18168.53
	(56.43481)	(9201.0100)	(76.0280)	(10273.9700)
Prob > χ^2	0.0000	0.0000	0.0000	0.0000

Notes: Standard errors are in parentheses. Significance codes: * 5% level, ** 1% level, *** 0.1% level.

5.4 Entry and exit policies

Table 6 presents the results of the exit policy function estimation. A plant owner who exits receives a scrap value, which represents the payoff the plant owner receives from either selling or scapping his plant. The total number of plants that have exited the market in a particular period then becomes the set of possible plants a potential entrant can buy that period. We abstract away from any further detailed modeling of the secondary market for ethanol plants because we believe that the scrap value appropriately accounts for the payoff an exiting plant owner can receive from either selling or scrapping his plant, and because detailed modeling of the secondary market for ethanol plants is in of itself a complicated problem, and out of the scope of this paper.

In estimating the exit policy function, specifications I and II in Table 6 consider the effects from own capacity and nation-wide competitors' capacity, without and with regional fixed effects, respectively. Own capacity has a negative effect on the exit probability, which means that the larger size of a plant, the more costly it is to shut it down, perhaps because of the higher opportunity costs of leaving the industry. We also notice that competitors' capacity increases the probability of exit. In these two specifications, we also include an RFS dummies for different periods, which have negative effects on the exit probability. Compared with specification I, adding regional fixed effects in specification II makes the coefficient of RFS2 significant at a 10% level. One might also expect that the competition from plants in the same state may be more important than competition from plants in other states, but specifications III and IV do not find evidence to support this conjecture. Since the log likelihood is the highest in specification II, we use specification II for the structural model.

The results of the entry policy function estimation are in Table 7. We evaluate the effects of the number of ethanol plants that shut down and of the RFS policies on entry. Each column in the table lists the all the coefficients estimated for a particular specification of the multinomial logit. Results from specification I and II show that the RFS policies only have significantly positive effects on entry through constructing a new plant, most likely because

Table 6: Exit policy function

Dependent variable is probability of exit				
	I	II	III	IV
Capacity	-0.0089	-0.0140*	-0.0090	-0.0146*
	(0.0054)	(0.0062)	(0.0054)	(0.0064)
National sum of rivals' capacity	0.0006*	0.0006**		
	(0.0002)	(0.0003)		
State-wide sum of rivals' capacity			0.0001	0.0009
			(0.0002)	(0.0006)
RFS 1	-2.0925*	-1.9992*	-0.8549	-0.9326
	(0.9231)	(0.9505)	(0.7866)	(0.7955)
RFS 2	-3.3693	-3.3409	0.8299*	-0.0318
	(1.7794)	(1.8922)	(0.4445)	(0.7008)
Constant	-4.4668***	-4.5514***	-3.0443***	-3.2131***
	(0.7146)	(0.9264)	(0.3778)	(0.6736)
Regional fixed effects	No	Yes	No	Yes
Log likelihood	-139.4789	-127.4499	-144.0805	-130.0029
Prob > χ^2	0.0001	0.0000	0.0083	0.0002

Notes: Standard errors are in parentheses. Significance codes: * 5% level, ** 1% level, *** 0.1% level.

they provide an expectation that both demand and production will increase. The number of shut-down plants increases the possibility of entering the ethanol industry through buying a plant because the potential entrant has more options from which to buy an appropriate plant. Another benefit from more exiting plants is less competition in the feedstock input market and in the ethanol output market. We use specification IV for the structural model due to its relatively high likelihood value.

5.5 Structural parameters

In the structural estimation, we set the discount factor β to 0.9. The estimation results are shown in Table 8. We report results for 3 policy regimes. In the period before 2005, there is no RFS. In the period between 2005 and 2006, the RFS1 was in place. The RFS2 was in place after 2007. All parameters are significant at a 5% level.

In terms of investment costs, we find that both the mean μ_{γ_1} of the fixed costs to investment and the variable costs of investment are lower under RFS1 or RFS1 than they are in the absence of the RFS, potentially because having a policy that reduces uncertainty in ethanol demand also decreases the costs of capacity investment. Our estimate of the mean investment fixed cost in the absence of the RFS of 0.1127 dollars per gallon is in the range estimated by Schmit, Luo and Tauer (2009) of 0.08 to 0.13 dollars per gallon.

In terms of entry costs, we find that the mean μ_{k_1} of the fixed cost k_1 of constructing a new plant is higher under both RFS1 and RFS2. Similarly, the mean μ_{k_2} of the fixed cost k_2 of buying a shut-down plant is higher under both RFS1 and RFS2, perhaps because ethanol plants became more valuable under the RFS. Even though the RFS1 and RFS2 increase both types of entry fixed costs, the fixed costs of constructing a plant is lower than that of buying a plant under all policy scenarios.

In terms of exit scrap values, we find that the mean μ_d of the scrap values under the policy regime with RFS1 or RFS2 is higher than it is under the case without RFS. However, the standard deviation σ_d of the scrap values for the policy regime with the RFS1 or RFS2

Table 7: Entry policy function

	Dependent variable is probability of:			
	I	II	III	IV
Constructing a new plant				
Number of incumbent plants			-0.0077	-0.0052
			(0.0114)	(0.0116)
RFS 1	0.8580**	0.9454**	1.1387*	1.1322*
	(0.2875)	(0.2911)	(0.5080)	(0.5135)
RFS 2	2.2460***	2.4451***	2.7957**	2.8142**
	(0.2854)	(0.2971)	(0.8620)	(0.8735)
Number of shut-down plants	0.1279***	0.1462***	0.1446***	0.1567***
	(0.0314)	(0.0338)	(0.0411)	(0.0435)
Dummy for whether a plant has shut down	0.1439	0.1440	0.2299	0.2030
	(0.2602)	(0.2625)	(0.2857)	(0.2885)
Constant	-3.0961***	-3.6115***	-2.8585***	-3.4494***
	(0.1704)	(0.3839)	(0.3880)	(0.5259)
Buying a shut-down plant				
Number of incumbent plants			0.0050	0.0115
			(0.0258)	(0.0272)
RFS 1	-0.9208	-0.8250	-1.0624	-1.1780
	(1.0602)	(1.0657)	(1.3255)	(1.3608)
RFS 2	-0.8567	-0.1667	-1.3060	-1.0326
	(1.0586)	(1.0393)	(2.1924)	(2.2119)
Number of shut-down plants	0.3646***	0.3624***	0.3699***	0.3550***
	(0.0714)	(0.0708)	(0.0795)	(0.0810)
Dummy for whether a plant has shut down	14.6600	15.1037	14.9660	14.4837
	(574.5750)	(699.5930)	(709.0272)	(569.4793)
Constant	-19.3869	-21.4847	-19.9613	-21.4371
	(574.5748)	(699.5983)	(709.0274)	(569.4808)
Regional fixed effects	No	Yes	No	Yes
Log likelihood	-493.4371	-472.6782	-493.1743	-472.4609
Prob > χ^2	0.0000	0.0000	0.0000	0.0000

Notes: Standard errors are in parentheses. Significance codes: * 5% level, ** 1% level, *** 0.1% level.

is much higher than it is for the policy regime without the RFS. These results suggest that a plant owner is likely to get a better scrap value under the RFS but may need to bear more uncertainty.

Table 8: Structural parameters

	I No RFS		II RFS1		III RFS 2	
			Investment Costs			
Fixed cost of capacity investment						
Mean (μ_{γ_1})	0.1127	(0.0063)	0.0322	(0.0058)	0.0239	(0.0060)
Standard deviation (σ_{γ_1})	0.0100	(0.0058)	0.0072	(0.0028)	0.0779	(0.0026)
Variable cost of capacity investment						
Coefficient on capacity (γ_2)	0.5902	(0.0045)	0.5215	(0.0146)	0.4467	(0.0031)
Coefficient on capacity^2 (γ_3)	0.0072	(0.0001)	0.0072	(0.0003)	0.0074	(0.0000)
			Entry costs			
Fixed cost of constructing a new plant						
Mean (μ_{k_1})	0.2911	(0.0909)	1.7563	(0.5091)	7.0468	(2.1239)
Standard deviation (σ_{k_1})	0.2445	(0.0779)	1.5041	(0.3904)	6.5494	(1.7700)
Fixed cost of buying a shut-down plant						
Mean (μ_{k_2})	0.6757	(0.0909)	6.6449	(0.5091)	7.0967	(2.0726)
Standard deviation (σ_{k_2})	0.5674	(0.0779)	4.7227	(0.3969)	7.0479	(1.7311)
Variable cost of buying a shut-down plant						
Coefficient on capacity (γ_4)	0.4557	(0.0302)	0.5491	(0.0047)	0.5202	(0.0088)
Coefficient on capacity^2 (γ_5)	0.0083	(0.0004)	0.0076	(0.0000)	0.0078	(0.0003)
			Exit scrap values			
Scrap value from exit						
Mean (μ_d)	18.2667	(4.3104)	54.9415	(23.3630)	42.4350	(0.3849)
Standard deviation (σ_d)	4.3684	(1.0981)	23.6666	(2.5794)	40.5914	(2.7128)

Notes: Costs and values are in millions of dollars. Standard errors are in parentheses. All parameters are significant at a 5% level.

6 Policy simulations

We use our estimated structural econometric model to run counterfactual policy simulations to analyze three different types of subsidy: a volumetric production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. To do this, we compute the Markov perfect equilibrium using the estimated structural parameters and then use the model to simulate the ethanol industry over the years 2012 to 2022.

The initial conditions for our simulations, which begin in the year 2012, are based on the most recent observations of state variables in 2012, including total market capacity, ethanol price, average number of plants over all the states that have ethanol plants, and average plant size. We would ideally wish to simulate all the scenarios for all the main ethanol producing states in the U.S. However, due to computational constraints, we simulate the ethanol market in a representative state in which there are 15 incumbent plants in the year 2012, which is close to the number of incumbent plants in a typical state in the Midwest in 2012; and in which the average plant capacity is 73 million gallon per year, which is consistent with the mean capacity in 2012 over all the states that have ethanol plants. We set the number of potential entrants to be 15, which is large enough to allow for the possibility that the number of ethanol plants may approach the maximum it has reached in any state in any year during the 1995-2009 time period of our data set, which is 37 plants.

For each policy scenario, we report the change in total market capacity from 2012 to 2022, the present discounted value of the entire stream of producer profit over the years 2012 to 2022, the present discounted value of the entire stream of consumer surplus over the years 2012 to 2022, the present discounted value of the entire stream of government subsidy payments over the years 2012 to 2022, and the present discounted value of the entire stream of net social welfare (producer profits plus consumer surplus minus government subsidy payments) over the years 2012 to 2022. For the predicted price of ethanol, we use our estimates of the transition density for ethanol price that conditions on the RFS and the production subsidy, which shows that the RFS significantly increases the ethanol price.

Table 9 reports the results of counterfactual simulations of different alternative production subsidies. Scenarios I and II vary the production subsidy in the absence of the RFS; scenarios III, IV, and V vary the production subsidy in the presence of the RFS.

Our results yield several important findings. First, the implementation of the RFS increases producer profits and consumer surplus. When the production subsidy is 51 cents per gallon, scenario III with the RFS has around twice the producer profit and twice the consumer surplus of scenario I without the RFS.

Second, consumer surplus is low compared to producer surplus across all specifications because our estimation of the demand elasticity is high.

Third, net social welfare taking into account the government subsidy is positive for all production subsidy scenarios.

Fourth, we find that the RFS increases the total market capacity between 2012 and 2022, a result which is consistent with that of Cui et al. (2011). For the scenarios in which the production subsidy level is 51 cents per gallon, total market capacity will increase over the years 2012 to 2022 by 16.62% if the RFS is in place, but will decrease by 5.52% if there is no RFS. When there is no production subsidy, RFS still can stimulate total market capacity to expand by 4.19%; however, total market capacity will dramatically decrease by 16.62% if the RFS is not implemented.

Fifth, we find that lower levels of the production subsidy lead to lower total capacity of ethanol supply, although having the RFS in place mitigates this change. In scenarios III and V, which represent high production subsidy and no production subsidy, respectively, both with the RFS in place, our simulation results are consistent with the most recent ethanol capacity change: market capacity increases quickly when subsidy level is high and the market capacity increases slowly when subsidy level is low. This finding is also consistent with the results of Schmit, Luo and Conrad (2011) and Thome and Lin Lawell (2016).

Since the variable cost of ethanol production increases rapidly if the capacity size becomes large, a volumetric subsidy is critically important for those large plants. Therefore, the elimination of the production subsidy drives some plants to exit if the ethanol price does not increase much. However, when the RFS is in place, the ethanol price has an increasing trend due to the RFS and the expansion of fuel demand from flex-fuel vehicles. An increase in ethanol price makes the entry of small-size plants possible, which is consistent with the result of Dal-Mas et al. (2011). Therefore, the entry of smaller size plants causes the average plant size to decrease over the years 2012 to 2022 when there is an RFS in place but no production subsidy. Without considering the above policy and market conditions, Gallagher, Shapouri and Brubaker (2007) predict a larger future plant scale.

In addition to the volumetric production subsidy, we also simulate the effects of an investment subsidy and an entry subsidy on the ethanol market in a representative state. We define an investment subsidy to be a subsidy based on capacity that is only paid to a newly constructed plant. We define an entry subsidy to be a flat-rate subsidy that does not vary by capacity and that is only paid to a newly constructed plant above a threshold size. We set the threshold size to be 5 million gallon per year, the minimim capacity of any plant in any state during the 1995-2009 time period of our data set. In order to make the investment subsidy and entry subsidy comparable with the production subsidy, we adjust the investment and entry subsidy levels so that the total subsidy payments from the government for each subsidy over the years 2012 to 2022 is approximately 4 billion dollars, which is the approximately the level of the government subsidy payment in Scenario I of Table 9 of a 51 cents per gallon production subsidy without the RFS.

Table 10 reports the results of simulations under different alternative investment and entry subsidies. From scenarios I-IV, we can see that with either an investment subsidy or an entry subsidy, the total capacity in the representative state will increase by 24% if there is no RFS and by 36% if there is an RFS. The changes in total capacity under an investment subsidy are close to those under an entry subsidy because in both cases the subsidy can cover the entry cost easily and leads to a high entry probability; therefore, all 15 potential entrants choose to enter through constructing plants. In other words, with either an investment subsidy or an entry subsidy that is set at a level that yields the same total subsidy payment as the government would pay with a 51 cents per gallon production subsidy, all the potential entrants enter. It is therefore possible for the government to reduce the subsidy level and still sustain the total capacity at 2012 levels. Therefore, scenarios V-VIII simulate subsidy levels that have been dramatically reduced. Even when the investment subsidy is only 10 cents per gallon or the entry subsidy is only 1 million dollars for every new entrant, total capacity will increase more than 14% and 24% without and with the RFS, respectively. Hence, using an investment subsidy or an entry subsidy is more cost-effective than using a volumetric production subsidy. Our result that even a minor investment subsidy or entry subsidy can lead to capacity expansion is evidence that potential entrants might face liquidity constraints.

Table 9: Production subsidy simulations

	I		II		III		IV		V	
	No RFS		No RFS		RFS		RFS		RFS	
	\$0.51/gal subsidy		\$0/gal subsidy		\$0.51/gal subsidy		\$0.45/gal subsidy		\$0/gal subsidy	
Total Producer Profits (million \$ in NPV)	4733.11	(438.01)	734.68	(452.74)	8446.69	(963.86)	7671.38	(521.63)	3771.33	(426.51)
Total Consumer Surplus (million \$ in NPV)	270.77	(18.51)	215.59	(20.08)	406.62	(30.90)	392.52	(21.00)	381.23	(21.96)
Total Subsidy Payment (million \$ in NPV)	3981.03	(256.51)	0	-	4485.46	(319.86)	2822.63	(182.68)	0	-
Total Net Social Welfare (million \$ in NPV)	1022.88	(469.67)	950.28	(445.21)	4367.85	(739.17)	4241.27	(439.25)	4152.56	(439.23)
Average Plant Capacity (million gallons)	42.36	(3.11)	32.75	(3.32)	48.48	(3.89)	46.58	(2.56)	45.04	(2.67)
Change in Market Capacity (from 2012 to 2022)	-5.52%	(0.14)	-26.62%	(0.14)	16.62%	(0.14)	9.54%	(0.11)	4.19%	(0.11)
Average Market Price (\$/gallon)	1.15	(0.04)	1.15	(0.04)	1.64	(0.04)	1.64	(0.04)	1.65	(0.04)

Note: Standard deviations are in parentheses.

Table 10: Investment subsidy and entry subsidy simulations

	Investment subsidy				**Entry subsidy**			
	No RFS		RFS		No RFS		RFS	
	$14 million/million gallons				$260 million/plant			
	I		II		III		IV	
Total Producer Profits (million $ in NPV)	839.79	(362.90)	4762.77	(397.57)	839.79	(362.90)	4762.77	(397.56)
Total Consumer Surplus (million $ in NPV)	323.54	(11.06)	452.29	(24.27)	323.54	(11.06)	452.29	(24.27)
Total Subsidy Payment (million $ in NPV)	4043.71	(112.80)	4198.02	(182.62)	4003.75	(132.29)	4165.71	(201.32)
Total Net Social Welfare (million $ in NPV)	-2880.38	(376.88)	1017.03	(449.16)	-2840.42	(383.84)	1049.34	(464.35)
Average Plant Capacity (million gallons)	52.01	(1.05)	54.46	(3.16)	52.01	(1.05)	54.46	(3.16)
Change in Market Capacity (from 2012 to 2022)	23.55%	(0.04)	36.13%	(0.15)	23.55%	(0.04)	36.13%	(0.15)
Average Market Price ($/gallon)	1.15	(0.04)	1.15	(0.04)	1.64	(0.04)	1.64	(0.04)
	$0.1 million/million gallons				$1 million/plant			
	V		VI		VII		VIII	
Total Producer Profits (million $ in NPV)	831.43	(375.17)	4605.26	(414.70)	778.82	(496.55)	4512.46	(396.60)
Total Consumer Surplus (million $ in NPV)	315.57	(12.53)	445.54	(24.36)	309.71	(14.18)	427.76	(23.76)
Total Subsidy Payment (million $ in NPV)	28.96	(1.42)	27.91	(1.36)	16.08	(1.03)	15.39	(0.78)
Total Net Social Welfare (million $ in NPV)	1118.04	(381.27)	5022.89	(424.31)	1072.44	(410.44)	4924.83	(410.01)
Average Plant Capacity (million gallons)	50.47	(1.65)	53.68	(3.13)	49.47	(2.16)	51.23	(3.02)
Change in Market Capacity (from 2012 to 2022)	17.80%	(0.07)	34.86%	(0.15)	14.78%	(0.09)	24.20%	(0.14)
Average Market Price ($/gallon)	1.15	(0.04)	1.15	(0.04)	1.64	(0.04)	1.64	(0.04)

Note: Standard deviations are in parentheses.

7 Conclusion

This paper analyses the effects of government subsidies and the Renewable Fuel Standard (RFS) on the U.S. ethanol industry. Analyses that ignore the dynamic implications of these policies, including their effects on incumbent ethanol firms' investment, production, and exit decisions and on potential entrants' entry behavior, may generate incomplete estimates of the impact of the policies and misleading predictions of the future evolution of the ethanol industry.

We first develop a stylized theory model of subsidies in which we examine which types of subsidies are more cost-effective for inducing investment in firm capacity. We then empirically analyze how government subsidies and the Renewable Fuel Standard affect ethanol production, investment, entry, and exit by estimating a structural econometric model of a dynamic game that enables us to recover the entire cost structure of the industry, including the distributions of investment costs, entry costs, and exit scrap values. We use the estimated parameters to evaluate three different types of subsidy: a volumetric production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS.

According to our results, even though we have already attained an ethanol production capacity in 2012 of 15 million gallons, which was the target capacity that the RFS had set for corn ethanol for 2022, this market capacity will not be sustained over the years 2012 to 2022 in the absence of an RFS. On the other hand, if the RFS is in place, total market capacity will still increase even if there are no subsidies. We therefore find that the RFS is a critically important policy for supporting the sustainability of corn ethanol production. We also find that investment subsidies and entry subsidies are more cost-effective than production subsidies. With an investment subsidy or an entry subsidy the government can pay much less than it would under a production subsidy but still reach the goal set by the RFS.

This study is the first to implement a structural econometric model of a dynamic game to empirically estimate various ethanol production and investment costs. Our approach differs from the existing literature, which uses a financial framework and cost information from engineering experiments, because the production and investment costs we estimate are estimated econometrically and are allowed to vary smoothly with plant capacity, which is more realistic. In addition, we allow investment and entry fixed costs to vary for each plant and potential entrant, and we estimate the distributions of these fixed costs. Econometric estimates based on real observations are more accurate than engineering predictions. We use our model to estimate the costs under various policy scenarios, providing important insights into how various forms of subsides and the RFS affect costs and the ethanol market. Our results have important implications for the design of government policies for ethanol.

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