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The Effects of Subsidies and Mandates: A Dynamic Model of the Ethanol Industry

Authors
Lawell, Cynthia Lin
Yi, Fujin
Thome, Karen E

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A Research Report from the National Center for Sustainable Transportation

C. -Y. Cynthia Lin Lawell, University of California, Davis, and Cornell University

Fujin Yi, Nanjing Agricultural University

Karen E. Thome , USDA Economic Research Service

National Center for Sustainable Transportation

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C. –Y. Cynthia Lin Lawell, Department of Agricultural and Resource Economics, University of California, Davis, and Environmental, Energy and Resource Economics, Cornell University

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The Effects of Subsidies and Mandates: A Dynamic Model of the Ethanol Industry

Fujin Yi, C.-Y. Cynthia Lin Lawell, and Karen E. Thome*

November 28, 2017

Abstract

This paper analyzes the effects of government subsidies and the Renewable Fuel Standard (RFS) on the U.S. 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, and how the presence of a mandate affects the relative cost-effectiveness of different types of subsidies. 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 production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. While conventional wisdom and some of the previous literature favor production subsidies over investment subsidies, and while historically the federal government has used production subsidies to support ethanol, our results show that, for the ethanol industry, investment subsidies and entry subsidies are more cost-effective than production subsidies for inducing investment that otherwise would not have occurred.

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

***JEL* codes:** Q16, Q42, Q48, L21

*Yi: Nanjing Agricultural University; fujinyi@njau.edu.cn. Lin Lawell: Cornell University; clinlawell@cornell.edu. Thome: USDA Economic Research Service; karen.thome@ers.usda.gov. We thank Trevor Bakker, Natalie Bau, Aureo de Paula, Liran Einav, Ian Fillmore, Todd Gerarden, Michael Kremer, Ashley Langer, Erin Mansur, Mar Reguant, Aaron Smith, Rich Sweeney, Frank Wolak, and Ali Yurukoglu for helpful discussions. We received helpful comments from conference participants at the Stanford Institute for Theoretical Economics (SITE), the Northeast Workshop on Energy Policy and Environmental Economics, the Berkeley Bioeconomy Conference, the U.S. Association for Energy Economics (USAEE) conference, and the University of California at Davis Agricultural and Resource Economics Ph.D. Program 50th Anniversary; and from seminar participants at the Research Institute of Economics and Management in Chengdu, China. We received funding from the University of California at Davis Sustainable Transportation Energy Pathways program; from a University of California at Davis Hellman Fellowship; and from the National Center for Sustainable Transportation, which is supported by the U.S. Department of Transportation through the University Transportation Centers program. All errors are our own.

1 Introduction

Renewable fuels such as ethanol have received international attention and support. The motivating factors for this attention and support include 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., 2017).

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, 2017).

The development of the ethanol industry in the U.S. has historically been accompanied by government subsidies. 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 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 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. For example, 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 (O'Brien and Woolverton, 2010).

In addition to production subsidies, the ethanol industry has more recently been supported by the federal Renewable Fuel Standard (RFS). The Renewable Fuel Standard is a form of a fuel mandate. Whenever unpriced emissions are the sole market failure, fuel mandates are unable to replicate the first-best solution (Lade and Lin Lawell, 2017).

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 of biofuels 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]

This paper analyzes the effects of government subsidies and the Renewable Fuel Standard on the U.S. 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, and how the presence of a mandate affects the relative cost-effectiveness of different types of subsidies.

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 production subsidy, an investment subsidy, and an entry subsidy – each with and without the RFS. We evaluate the effects of government subsidies and the Renewable Fuel Standard on production, investment, entry, exit, producer profits, consumer surplus, net social welfare, average plant capacity, and market capacity.

We use a dynamic model because decisions of investment, entry, and exit are forms of decisions of investment under uncertainty: these decisions are at least partially irreversible, there is uncertainty over the payoffs to these decisions, and ethanol producers have leeway over the timing of these decisions. As a consequence, there is an option value to waiting that is best modeled with a dynamic model (Dixit and Pindyck, 1994). Moreover, government policies may have important effects on entry, production, investment, and exit costs and decisions that a static analysis would overlook. 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 use a model of a dynamic game because an ethanol producers payoffs are affected by

[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, 2017b). The industry production capacity for corn ethanol reached its targeted volume of 15 billion gallons at the end of 2012. Cellulosic ethanol production is still negligible due to both technological and economic issues (Lade, Lin Lawell and Smith, 2017b) and many scientists suggest that commercialization of cellulosic is several years down the road (Celebi et al., 2010; Schnepf and Yacobucci, 2012).

the decisions of other producers in the market. As a consequence, firms behave strategically and base their production, investment, entry, and exit decisions on those of other firms in the market.

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. While conventional wisdom and some of the previous literature favor production subsidies over investment subsidies, and while historically the federal government has used production subsidies to support ethanol, our theory shows that, owing in part to dynamic considerations, whether production subsidies are more cost-effective than investment subsidies depends on the parameters, and is therefore an empirical question.

A second way in which we build upon the previous literature is that we empirically examine whether it costs more to the government to induce investment via a production subsidy, an investment subsidy, or an entry 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.

A third way in which we build upon the previous literature is that we empirically estimate the various investment and production costs in the ethanol industry. In contrast, 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). We allow our estimated cost parameters to depend on the presence of the Renewable Fuel Standard.

Our theory model reveals the following tradeoff between production and investment subsidies. Although any investment induced by a positive production subsidy is investment that would not have occurred otherwise, the government must pay the production subsidy for each unit of production in both periods, including inframarginal units of production. In contrast, an investment subsidy must be high enough to induce investment that otherwise would not occur, but there is a cap to how high that minimum investment subsidy needs to be. Our theory model also reveals a similar tradeoff between production and entry subsidies.

Our theory results show that whether it costs more to the government to induce investment via a production subsidy or an investment subsidy depends on the parameters, even if there is also a mandate, and is therefore an empirical question. Our theory results also show that, whether or not a mandate is present, it costs more to the government to induce investment via a production subsidy than via an entry subsidy. 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.

Conventional wisdom and some of the previous literature favor production subsidies over investment subsidies, and historically the federal government has used production subsidies to support ethanol. However, the results of our counterfactual simulations show that, for the ethanol industry, investment subsidies and entry subsidies are more cost-effective than production subsidies for inducing investment that otherwise would not have occurred. Our results have important implications for the design of government policies for ethanol in particular, and more generally for renewable energy and socially desirable commodities as well.

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 Previous Literature

2.1 Ethanol investment and the effects of government policy

The first strand of literature upon which we build is that on ethanol investment and the effects of government policy. The previous literature on ethanol investment includes studies that estimate the viability of ethanol plants. Many of these studies 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, Jouvet, Le Cadre and Orset (2012) also incorporate uncertainty in demand and competition.

Other studies of ethanol investment 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. We build on these studies by estimating costs empirically.

The previous literature also studies of how government policies impact investment in ethanol plants. 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.

In their survey of the effects of ethanol subsidies, Cotti and Skidmore (2010) find that subsidies can have a significant effect on a state's production capacity. Babcock (2013) similarly finds that without subsidies, low gasoline prices imply low viability for ethanol, and thus that government support is important for 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. 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.

As for studies of the Renewable Fuel Standard, Skolrud et al. (2016) examine the role of the Renewable Fuel Standard and market structure on the growth of the cellulosic biofuel sector. Skolrud and Galinato (2017) examine the welfare implications of the Renewable Fuel Standard with an integrated tax-subsidy policy. Thome and Lin Lawell (2017) show empirically that the Renewable Fuel Standard has contributed to ethanol plant investment.

2.2 Subsidies

While sparse, the previous literature comparing different types of subsidies suggests that production subsidies are preferred over investment subsidies. According to conventional wisdom, an output subsidy is more efficient than an input subsidy as a means of encouraging output of a good, because an input subsidy distorts the choice of inputs away from the least-cost combination, while an output subsidy does not (Parish and McLaren, 1982).

Similarly, Schmalensee (1980) argues that if some commodity is more valuable to society than its market price indicates, then the best remedy is to use an output subsidy to increase its market value. Because other types of subsidies are less direct and build in extraneous incentives, they are strictly inferior in cost and efficiency terms (Schmalensee, 1980).

In their analysis of the choice between using capital and output subsidies to promote socially desirable production, Aldy, Gerarden and Sweeney (2017) find from their theory model that output will be greater under the output subsidy, though the extent of the difference in output depends on the convexity of the production costs. They find empirically that, owing to subsidy incentives, wind farms choosing the capital subsidy produce 11 to 12 percent less electricity per unit capacity than wind farms selecting the output subsidy, and that capital subsidies cost more to the Federal government per unit of output from wind farms than an output subsidy (Aldy, Gerarden and Sweeney, 2017).

Parish and McLaren (1982) analyze the relative cost-effectiveness of input and output subsidies using a static model. They observe that subsidy payments to inframarginal units of input or output are wasted from the point of view of encouraging expanded production. Subsidies may differ in their cost-effectiveness if they differ in the amounts absorbed by inframarginal units of the item subsidized, and these differences arise in the presence of increasing of decreasing returns to scale, and because of changes in input intensities as production expands. In particular, Parish and McLaren (1982) find that with decreasing returns, inputs are more productive on the average than at the margin, and thus total payments made under an input subsidy, if spread over the total output, would represent a lower rate of subsidy per unit output (and a lower total payment) than under the output subsidy.

We build on the insight of Parish and McLaren (1982) that subsidy payments to inframarginal units of input or output are wasted from the point of view of encouraging expanded production, and analyze the relative cost-effectiveness of production subsidies and investment subsidies using a dynamic model rather than a static model. We find that, owing in part to dynamic considerations, whether production subsidies are more cost-effective than investment subsidies depends on the parameters, and is therefore an empirical question.

2.3 Structural econometric models of dynamic games

Structural econometric models of dynamic behavior have been applied to model bus engine replacement (Rust, 1987), nuclear power plant shutdown decisions (Rothwell and Rust, 1997), water management (Timmins, 2002), air conditioner purchase behavior (Rapson, 2014), wind turbine shutdowns and upgrades (Cook and Lin Lawell, 2017), agricultural disease management (Carroll et al., 2017b), supply chain externalities (Carroll et al., 2017a), agricultural productivity (Carroll et al., forthcoming), pesticide spraying decisions (Sambucci, Lin Lawell and Lybbert, 2017), and decisions regarding labor supply, job search, and occupational choices (see Keane, Todd and Wolpin, 2011). Aguirregabiria and Slade (forthcoming) review the literature on dynamic structural econometric models.

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), to ethanol investment decisions (Thome and Lin Lawell, 2017), and to the decision to wear and use glasses (Ma, Lin Lawell and Rozelle, 2017); on a model developed by Bajari et al.

(2015), which has been applied to ethanol investment in Canada (Yi and Lin Lawell 2017a) and Europe (Yi and Lin Lawell, 2017b); 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 (2016) survey the recent empirical literature on structural models of market entry and spatial competition in retail industries. These models have also been applied to fisheries (Huang and Smith, 2015), to dynamic natural monopoly regulation (Lim and Yurukoglu, forthcoming), and to Chinese shipbuilding (Kalouptsidi, forthcoming).

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), migration decisions (Rojas Valdes, Lin Lawell and Taylor, 2017) and to the world petroleum industry (Kheiravar et al., 2017).

3 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, and how the presence of a mandate affects the relative cost-effectiveness of different types of subsidies.

We build on the insight of Parish and McLaren (1982) that subsidy payments to infra-marginal units of input or output are wasted from the point of view of encouraging expanded production, and analyze the relative cost-effectiveness of different types of subsidies for inducing investment in firm capacity using a dynamic model rather than a static model.

While Parish and McLaren (1982) find in their static analysis that input subsidies are more cost-effective than output subsidies when there are decreasing returns to scale, our dynamic model shows that, owing in part to dynamic considerations, whether production subsidies are more cost-effective than investment subsidies depends on the parameters, even under decreasing returns to scale, and is therefore an empirical question.

In our simple dynamic model, there are two time periods. The discount factor is β. In our two-period model, a firm produces output in both periods. Output is a function of the firm's capacity s.

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.[2] The output price p and production cost $c_p(s)$ evolve stochastically; there is therefore uncertainty about what their values in the second period will be.

In the first period, in addition to producing output κs, a firm with capacity s 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:

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

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.

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

$$v_2(s; \phi_p, \phi_c) = \pi(s, \phi_p). \quad (3)$$

Substituting equation (3) for the second period value function $v_2(\cdot)$ into equation (2) for

[2]We model production as being determined by capacity for analytical simplicity, and also because such a model is well-suited for describing industries such as ethanol and oil where there is little or no idle capacity and output is highly correlated with capacity. In the oil industry, for example, production is essentially determined by the number of wells drilled, as once a well is drilled, there is a high opportunity cost of shutting in a well (Anderson, Kellogg and Salant, forthcoming; Boomhower, 2016). As we show and explain in our empirical analysis, although we relax this assumption in our empirical model, our empirical estimates are robust to whether we use plant-level data on ethanol production or if we instead assume that all the plants produce at a fixed rate of capacity.

the first period value function $v_1(\cdot)$, the first period value function becomes:

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

3.1 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 under the production subsidy ϕ_p investment is preferred over no investment, which implies:

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

and investment is preferred over exit, which implies:

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

Using our functional form assumption (1) on per-period production profits $\pi(s,\phi_p)$, the conditions (5) and (6) for the production subsidy to induce investment respectively reduce to the following two lower bounds for the production subsidy ϕ_p:

$$\phi_p > -E[p] + \frac{1}{\kappa x}\left(E[c_p(s+x) - c_p(s)] + \frac{c_x}{\beta}\right) \quad (7)$$

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

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

$$\phi_p > \max\left\{\underline{\phi_p}, 0\right\}, \quad (9)$$

where:

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

However, it is possible that some of the investment that occurs under the production subsidy ϕ_p may still have occurred in the absence of the production subsidy. The production subsidy induces investment that otherwise would not occur if, in addition to investment being preferred over both no investment and exit under the production subsidy, it must also be the case that either no investment or exit is preferred over investment in the absence of the production subsidy. That is, the production subsidy induces investment that otherwise would not occur if, in addition to (7) and (8), either investment would not have been preferred to no investment in the absence of the production subsidy, which implies:

$$-c_x + \beta E[\pi(s+x, \phi_p = 0)] < \beta E[\pi(s, \phi_p = 0)], \tag{11}$$

or investment would not have been preferred to exit in the absence of the production subsidy, which implies:

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

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:

$$\phi_p > \max\left\{\underline{\underline{\phi_p}}, 0\right\}, \tag{14}$$

where:

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

Thus, as long as the production subsidy is positive, any investment induced by the production subsidy is investment that would not have occurred otherwise. This means that the lower bound for the production subsidy ϕ_p to induce investment that otherwise would not occur is the same lower bound $\underline{\phi_p}$ for the investment subsidy ϕ_p to induce investment.

Although any investment induced by a positive production subsidy is investment that would not have occurred otherwise, the government must pay the production subsidy for each unit of production in both periods, which includes each unit of production in the first period even before investment has taken place, and each unit of inframarginal production in the second period even though this inframarginal production would have taken place even if there were no investment.

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:

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

3.2 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 under the investment subsidy ϕ_c investment is preferred over no investment, which implies:

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

and investment is preferred over exit, which implies:

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

Under the functional form assumption (1) for production profits, the conditions (18) and (19) for the investment subsidy to induce investment respectively reduce to the following two 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:

$$\phi_c > \max\left\{\underline{\phi_c}, 0\right\}, \tag{22}$$

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

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

However, it is possible that some of the investment that occurs under the investment subsidy ϕ_c may still have occurred in the absence of the investment subsidy. The investment subsidy induces investment that otherwise would not occur if, in addition to investment being preferred over both no investment and exit under the investment subsidy, it must also be the case that either no investment or exit is preferred over investment in the absence of the investment subsidy. That is, the investment subsidy induces investment that otherwise would not occur if, in addition to (20) and (21), either investment would not have been preferred to no investment in the absence of the investment subsidy, which implies:

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

or investment would not have been preferred to exit in the absence of the investment subsidy, which implies:

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

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

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

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:

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

Since the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur is the same lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment, this means that if the investment subsidy is too low to induce investment that otherwise would not occur, then the investment subsidy is also too low to induce any investment.

However, because there is an upper bound for the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur, this means that there is a cap to how high the minimum investment subsidy needs to be in order to induce investment that otherwise would not occur.

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

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

3.3 Entry subsidy

We model an entry subsidy ϕ_e as an investment subsidy in the case in which the first-period capacity s of the firm is equal to 0. The entry decision is therefore equivalent to the decision of a firm with initial capacity $s = 0$ in period 1 of whether to invest in capacity x so that it can begin producing in period 2.

Suppose there is an entry subsidy ($\phi_e > 0$) but no production subsidy ($\phi_p = 0$). The entry subsidy ϕ_e induces investment if under the entry subsidy ϕ_e investment is preferred over no investment. Evaluating the expression for the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment at $s = 0$, we obtain the following lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_e to induce investment:

$$\phi_e > \max\left\{\underline{\phi_e}, 0\right\}, \tag{29}$$

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

$$\underline{\phi_e} = \beta E[c_p(x)] + c_x - \beta\kappa x E[p] + d. \tag{30}$$

However, it is possible that some of the investment that occurs under the entry subsidy ϕ_e may still have occurred in the absence of the entry subsidy. The entry subsidy induces investment that otherwise would not occur if, in addition to investment being preferred over no investment under the entry subsidy, it must also be the case that either no investment is preferred over investment in the absence of the entry subsidy. Evaluating the expression for the upper bound for the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur at $s = 0$, we obtain the following upper bound for the lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_e to induce investment that otherwise would not occur:

$$\underline{\phi_e} < \max\left\{d, \beta\kappa x E[p]\right\}. \tag{31}$$

Since the lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_e to induce investment that otherwise would not occur is the same lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_c to induce investment, this means that if the entry subsidy is too low to induce investment that otherwise would not occur, then the entry subsidy is also too low to induce any investment.

However, because there is an upper bound for the lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_e to induce investment that otherwise would not occur, this means that there is a cap to how high the minimum entry subsidy needs to be in order to induce investment that otherwise would not occur.

The total cost $C(\phi_e)$ to the government of an entry subsidy ϕ_e is given by:

$$C(\phi_e) = \phi_e. \tag{32}$$

3.4 Comparing production and investment subsidies

For production subsidies, as long as the production subsidy is positive, any investment induced by the production subsidy is investment that would not have occurred otherwise. However, the government must pay the production subsidy for each unit of production in both periods, which includes each unit of production in the first period even before investment has taken place, and each unit of inframarginal production in the second period even though this inframarginal production would have taken place even if there were no investment.

For investment subsidies, if the investment subsidy is too low to induce investment that otherwise would not occur, then the investment subsidy is also too low to induce any investment. However, because there is an upper bound for the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur, this means that there is a cap to how high the minimum investment subsidy needs to be in order to induce investment that otherwise would not occur. There is therefore a cap to the minimum cost to the government of inducing investment via an investment subsidy.

The tradeoff between production and investment subsidies is therefore as follows. Although any investment induced by a positive production subsidy is investment that would not have occurred otherwise, the government must pay the production subsidy for each unit of production in both periods, including inframarginal units of production. In contrast, an investment subsidy must be high enough to induce investment that otherwise would not occur, but there is a cap to how high that minimum investment subsidy needs to be.

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 that otherwise would not occur, and the cost to the government of the lower bound $\underline{\phi_c}$ for the investment subsidy ϕ_c to induce investment that otherwise would not occur, we obtain:

$$C(\underline{\phi_p}) - C(\underline{\phi_c}) = -(1+\beta)\left(E[p]\kappa s - E[c_p(s+x)]\right) + \max\{A1, A2\} + \min\{B1, B2\}, \quad (33)$$

where:

$$\begin{aligned} A1 &= \tfrac{(1+\beta)s}{x}\left(E[c_p(s+x)] - E[c_p(s)]\right) - E[c_p(s+x)] - \beta E[c_p(s)] + \tfrac{(1+\beta)s}{\beta x} c_x \quad &(34)\\ A2 &= \left(\tfrac{x}{s+x} + \beta\right) E[c_p(s+x)] + \tfrac{s}{s+x}\tfrac{c_x+d}{\beta} + d \quad &(35)\\ B1 &= \beta E[c_p(s)] \quad &(36)\\ B2 &= \beta\kappa s E[p] - d. \quad &(37) \end{aligned}$$

Thus, the difference $C(\underline{\phi_p}) - C(\underline{\phi_c})$ between the minimum cost to the government of inducing investment that otherwise would not occur via a production subsidy and the minimum cost to the government of inducing investment that otherwise would not occur 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 difference $C(\underline{\phi_p}) - C(\underline{\phi_c})$ in costs depends on the parameters.

Parish and McLaren (1982) find in their static analysis that input subsidies are more cost-effective than output subsidies when there are decreasing returns to scale. In our model, decreasing returns to scale similarly makes an investment subsidy relatively more cost-effective than production subsidies in inducing investment that otherwise would not occur: decreasing returns to scale leads to a higher $(E[c_p(s+x)] - E[c_p(s)])$ and therefore a higher $A1$, and thus a higher relative cost of a production subsidy relative to an investment subsidy in inducing investment that otherwise would not occur. However, in our dynamic model, even with decreasing returns to scale, whether production subsidies are more cost-effective than investment subsidies depends on the parameters, and is therefore an empirical question.

Thus, owing in part to dynamic considerations, whether it costs more to the government to induce investment via a production subsidy or an investment subsidy is an empirical question.

3.5 Comparing production and entry subsidies

The tradeoff between production and entries subsidies is similar to the tradeoff between production and investment subsidies. Although any investment induced by a positive production subsidy is investment that would not have occurred otherwise, the government must pay the production subsidy for each unit of production in both periods, including infra-marginal units of production. In contrast, an entry subsidy must be high enough to induce investment that otherwise would not occur, but there is a cap to how high that minimum entry subsidy needs to be.

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 that otherwise would not occur, and the cost to the government of the lower bound $\underline{\phi_e}$ for the entry subsidy ϕ_e to induce investment that otherwise would not occur, we obtain:

$$C(\underline{\phi_p}) - C(\underline{\phi_e}) = 2(1+\beta)E[c_p(x)] > 0. \tag{38}$$

The difference $C(\underline{\phi_p}) - C(\underline{\phi_e})$ between the minimum cost to the government of inducing investment that otherwise would not occur via a production subsidy and the minimum cost to the government of inducing investment that otherwise would not occur via an entry subsidy is positive, and increases with the discount factor β and the production cost $E[c_p(x)]$.

Thus, it costs more to the government to induce investment via a production subsidy than via an entry subsidy.

3.6 Comparing subsidies in the presence of a mandate

How do production subsidies and investment subsidies compare in the presence of a renewable fuel mandate?[3]

Because the Renewable Fuel Standard mandates a minimum volume of ethanol consumption, and since the obligated parties under the RFS are primarily refiners (Lade and Lin Lawell, 2017), it is likely to increase the demand for ethanol by refiners, and therefore the expected output price $E[p]$ of ethanol that ethanol producers would receive. Baumeister, Ellwanger and Kilian (2017) show that the Renewable Fuel Standard (RFS) is likely to have increased ethanol price expectations by as much \$1.45 per gallon in the year before and in the year after the implementation of the RFS had started. Their analysis of the term structure of expectations provides support for the view that a shift in ethanol storage demand starting in 2005 caused an increase in the price of ethanol.

According to our model, an increase in the expected output price $E[p]$ would decrease the

[3]For a theory model of the Renewable Fuel Standard, Lade and Lin Lawell (2017) develop a theory model of renewable fuel mandates and apply it to the RFS; and Lade, Lin Lawell and Smith (2017b) develop a dynamic model of RFS compliance. Lade, Lin Lawell and Smith (2017a) draw lessons from the Renewable Fuel Standard for the design of climate policy. Anderson, Fischer and Egorenkov (2016) analyze the effects of overlapping energy policies in the personal transportation sector.

relative cost of inducing investment that otherwise would not occur via a production subsidy instead of via an investment subsidy. Thus, if the Renewable Fuel Standard increases the expected output price $E[p]$, then it would decrease the relative cost of inducing investment that otherwise would not occur via a production subsidy instead of via an investment subsidy.

However, the Renewable Fuel Standard may also increase input costs as well. Carter, Rausser and Smith (forthcoming) find that because the Renewable Fuel Standard increased the net amount of corn required to be processed annually into ethanol for motor-fuel use, corn prices were about 30 percent higher from 2006 to 2014 than they would have been without this demand increase.

If the Renewable Fuel Standard also increases input costs as well, then it may also increase the production cost after investment $E[c_p(s+x)]$. All else equal an increase in the production cost after investment $E[c_p(s+x)]$ would increase the relative cost of inducing investment that otherwise would not occur via a production subsidy instead of via an investment subsidy.

Thus, once again the sign of the net difference $C(\underline{\phi_p}) - C(\underline{\phi_c})$ depends on the parameters, even if there is also a fuel mandate. As a consequence, whether or not there is also a fuel mandate, the relative cost-effectiveness of inducing investment via a production subsidy or an investment subsidy is an empirical question.

In comparing production subsidies and entry subsidies in the presence of a mandate, if the Renewable Fuel Standard increases input costs and therefore the production cost $E[c_p(x)]$, it would increase the relative cost of inducing investment that otherwise would not occur via a production subsidy instead of via an entry subsidy.

In this paper, we empirically examine whether it costs more to the government to induce investment via a production subsidy, an investment subsidy, or an entry in the context of the ethanol industry in the United States.

4 Econometric Model

4.1 Dynamic game

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, how much to invest; and whether to exit.

Potential entrants can enter by either constructing a new plant, or by buying an existing ethanol plant that has shut down; the purchasing of existing plants was more common after 2008. Potential entrants therefore 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:

$$a_i = \sigma_i(s, \varepsilon_i), \tag{39}$$

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 s include own capacity, competitors' capacity, number of shut-down plants, ethanol price, and ethanol policies. The private information shocks ε_i 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. The market price for ethanol is given by the inverse demand function $P(Q)$, where Q is the aggregate demand for ethanol.

For each ethanol plant i, the cost of output is given by $c_i(q_i;\theta)$, where θ is a vector of parameters to be estimated.

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

$$r_i(q_i) = \phi_p q_i, \tag{40}$$

where ϕ_p 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, in a homogeneous goods Cournot game. The maximized static production profit function for an incumbent is thus given by:

$$\bar{\pi}_i(s;\theta) = \max_{q_i \le y_i} (P(Q) + \phi_p)q_i - c_i(q_i;\theta). \tag{41}$$

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

$$\Gamma(a_i, \varepsilon_i; \theta) = 1(x_i > 0)(\gamma_{1i} + \gamma_2 x_i + \gamma_3 x_i^2), \tag{42}$$

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. 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 fixed investment costs such as the fixed costs of obtaining permits and constructing support facilities, which accrue regardless of the size of the capacity change.

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

$$\Phi_i(a_i;\varepsilon_i) = \begin{cases} k_{1i} & \text{if the new entrant constructs a plant} \\ k_{2i} & \text{if the new entrant bought a plant from a previous owner} \\ d_i & \text{if the firm exit the market} \end{cases}, \tag{43}$$

where the vector of actions a_i includes the entry and exit decisions; k_{1i} and k_{2i} are the sunk costs of entry via constructing a new ethanol plant and via buying a shut-down plant from a previous owner, respectively; and d_i is the scrap value. The sunk costs k_{1i} and k_{2i} of entry 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:

$$\pi_i(s, a_i, \varepsilon_i; \theta) = \bar{\pi}_i(s;\theta) - \Gamma(a_i, \varepsilon_i; \theta) - \Phi_i(a_i, \varepsilon_i; \theta). \tag{44}$$

The value function $V_i(s; \sigma(s), \theta, \varepsilon_i)$ for an incumbent, who chooses how much to produce; whether to invest in capacity and, if so, how much to invest; and whether to exit, is given by:

$$\begin{aligned} V_i(s;\sigma(s),\theta,\varepsilon_i) &= \\ &\bar{\pi}_i(s;\theta) + \\ &\quad \max\Big\{ \max_{x_i>0}\big[-\gamma_{1i} - \gamma_2 x_i - \gamma_3 x_i^2 + \beta V_i^c(s, a_i; \sigma(s), \theta)\big], \\ &\quad \beta V_i^c(s, a_i; \sigma(s), \theta), \\ &\quad d_i\Big\}, \end{aligned} \tag{45}$$

where the continuation value $V_i^c(s, a_i; \sigma(s), \theta)$ is the expected value of the value function next period conditional on the state variables, actions, and strategies in the current period:

$$V_i^c(s, a_i; \sigma(s), \theta) = \int E_{\varepsilon_i'}\left[V_i(s'; \sigma(s'), \theta, \varepsilon_i')\right] dp(s'; s, a_i, \sigma_{-i}(s), \theta), \tag{46}$$

where s' is the vector of next period's state variables, $p(s'; s, a_i, \sigma_{-i}(s), \theta)$ 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 $V_i^e(s; \sigma(s), \theta, \varepsilon_i)$ 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:

$$\begin{aligned} V_i^e(s; \sigma(s), \theta, \varepsilon_i) &= \\ \max\Big\{ & \varepsilon_{0i}, \\ & \max_{y_{ci}>0}\left[-k_{1i} - \gamma_{1i} - \gamma_2 y_{ci} - \gamma_3 y_{ci}^2 + \varepsilon_{1i} + \beta V_i^c(s, a_i; \sigma(s), \theta)\right], \\ & -k_{2i} - \gamma_4 y_{bi} - \gamma_5 y_{bi}^2 + \varepsilon_{2i} + \beta V_i^c(s, a_i; \sigma(s), \theta)\Big\}, \end{aligned} \tag{47}$$

where y_{ci} is the capacity of any new plant i that is constructed; y_{bi} is the expected capacity of any existing shut-down plant i that is bought; γ_4 and γ_5 are parameters in the variable cost to an entrant of buying a shut-down plant of capacity y_{bi}; and ε_{0i}, ε_{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_{ci}, which includes the fixed cost of entry k_{1i}, the costs of capacity investment y_i^c, the idiosyncratic preference shock ε_{1i}, and the continuation value; and (3) the payoff from buying a shut-down plant of expected capacity y_{bi}, which includes the fixed cost of entry k_{2i}, the variable costs, the idiosyncratic preference shock ε_{2i}, and the continuation value.

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.

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.

4.2 Production profits, policy functions, and transition densities

4.2.1 Production profits

We estimate ethanol demand at time t as follows:

$$\ln Q_t = \alpha_0 + \alpha_1 \ln P_t + \alpha_2' X_t + \varepsilon_t, \tag{48}$$

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. However, we allow for the possibility that the Renewable Fuel Standard may affect ethanol demand. To address the endogeneity of price in the demand function, we use supply shifters to instrument for price.

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

$$c_i(q_i;\theta) = \delta_1\left[1 + \alpha_{11}RFS1_t + \alpha_{12}RFS2_t\right]q_i + \delta_2\left[1 + \alpha_{21}RFS1_t + \alpha_{22}RFS2_t\right]q_i^2, \tag{49}$$

where $RFS1_t$ is a dummy for the years 2005 and 2006; $RFS2_t$ is a dummy for the years 2007, 2008, and 2009; q_i is the output of plant i; and $\theta = (\delta_1, \delta_2, \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22})$ are the parameters to be estimated.

We assume that the production subsidy does not affect the parameters in the production cost function. However, we allow for the possibility that the Renewable Fuel Standard may affect the costs of ethanol production.

All the ethanol plants are assumed to be competing in a capacity-constrained homogeneous goods Cournot game. Let $P(Q)$ be the inverse of the demand function estimated above. Let ϕ_{pt} be the level of the production subsidy at time t.

The first-order condition from each plant's profit-maximization problem for an interior solution $(q_i < y_i)$ is given by:

$$\begin{aligned} \frac{\partial P(Q)}{\partial Q} q_{it} + P(Q) - \delta_1 \left[1 + \alpha_{11} RFS1_t + \alpha_{12} RFS2_t\right] & \\ -2\delta_2 \left[1 + \alpha_{21} RFS1_t + \alpha_{22} RFS2_t\right] q_{it} + \phi_{pt} & = 0. \end{aligned} \tag{50}$$

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:

$$\hat{q}_{it}(\theta) = \frac{P(Q) - \delta_1[1 + \alpha_{11} RFS1_t + \alpha_{12} RFS2_t] + \phi_{pt}}{2\delta_2[1 + \alpha_{21} RFS1_t + \alpha_{22} RFS2_t] - \frac{\partial P(Q)}{\partial Q}}. \tag{51}$$

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:

$$\min_{\theta} \sum_{i,t} (q_{it} - \hat{q}_{it}(\theta))^2. \tag{52}$$

[4]Lade, Lin Lawell and Smith (2017) discuss uncertainty regarding the Renewable Fuel Standard.

4.2.2 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 x^*_{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,

$$x^*_{it} = X'_{it}\xi + u_{it}, \tag{53}$$

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. We allow for the possibility that the Renewable Fuel Standard may affect the investment policy function.

Our Tobit model for the investment policy function is given by:

$$x_{it} = \begin{cases} 0 & \text{if } x^*_{it} \leq 0 \\ x^*_{it} & \text{if } 0 < x^*_{it} \leq \overline{x} \\ \overline{x} & \text{if } x^*_{it} > \overline{x} \end{cases}, \tag{54}$$

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.

4.2.3 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. We allow for the possibility that the Renewable Fuel Standard may affect the entry and exit policy functions.

4.2.4 State transitions

In addition to estimating the optimal policy functions, we also estimate transition densities which give the distribution of state variables next period as a function of the current state variables and of the firms' strategies in investment, entry, and exit. To estimate the transition densities, we regress each state variable on lagged state variables and lagged action variables. 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.

4.3 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 $\tilde{\sigma}_i(s)$:

$$V_i(s;\sigma_i^*(s),\sigma_{-i},\theta,\varepsilon_i) \geq V_i(s;\tilde{\sigma}_i(s),\sigma_{-i},\theta,\varepsilon_i), \tag{55}$$

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:

$$\pi_i(a,s,\varepsilon_i;\theta) = \Psi_i(a,s,\varepsilon_i)\cdot\theta, \tag{56}$$

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:

$$V_i(s;\sigma,\theta) = \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\Psi_i(\sigma(s_t,\varepsilon_t),s_t,\varepsilon_{it})\right]\cdot\theta = W_i(s;\sigma)\cdot\theta. \tag{57}$$

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

4.3.1 Parameters for incumbents

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

$$\begin{aligned} V_i(s;\sigma(s),\theta) &= W_i^1(s;\sigma) - W_i^2(s;\sigma)\cdot\gamma_{1i} - W_i^3(s;\sigma)\cdot\gamma_2 - W_i^4(s;\sigma)\cdot\gamma_3 + W_i^5(s;\sigma)\cdot d_i \\ &= \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\bar{\pi}_i(s_t)\right] - \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t p_i(s_t)\right]\cdot\gamma_{1i} - \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t p_i(s_t)x_{it}\right]\cdot\gamma_2 \\ &\quad -\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t p_i(s_t)x_{it}^2\right]\cdot\gamma_3 + \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t p_e(s_t)\right]\cdot d_i, \end{aligned} \tag{58}$$

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:

$$E[\gamma_{1i}|V_i^+(s) - \gamma_{1i} > V_i^0(s),\ V_i^+(s) - \gamma_{1i} > d_i] = \theta_{\gamma_1}\cdot bs(p_i(s)) \tag{59}$$

$$E[d_i|d_i > V_i^0(s),\ d_i > V_i^+(s) - \gamma_{1i}] = \theta_d \cdot bs(p_e(s)). \tag{60}$$

$V_i^+(s)$ 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 (59) and (60) into equation (58), 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 $\tilde{\sigma}_i(s)$:

$$W_i(s;\sigma_i^*,\sigma_{-i})\cdot[1\quad\theta]'\geq W_i(s;\tilde{\sigma}_i,\sigma_{-i})\cdot[1\quad\theta]'. \tag{61}$$

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

$$g(\tilde{\sigma};\theta)=[W_i(s;\sigma_i^*,\sigma_{-i})-W_i(s;\tilde{\sigma}_i,\sigma_{-i})]\cdot[1\quad\theta]'. \tag{62}$$

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:

$$\min_{\theta_I} Q_n(\theta)=\frac{1}{n_c}\sum_{j=1}^{n_c}(\min\{g(\tilde{\sigma}_{i,j};\theta),0\})^2, \tag{63}$$

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 (63) 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 (63). 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). One 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:

$$\theta^{j+1} = \begin{cases} \theta^+ \text{ with probability } \rho(\theta^j, \theta^+) \\ \theta^j \text{ with probability } 1 - \rho(\theta^j, \theta^+) \end{cases}, \tag{64}$$

   where

$$\rho(x, y) = \min \left\{ \frac{e^{Q_n(y)} h(y) q(x|y)}{e^{Q_n(x)} h(x) q(y|x)}, 1 \right\}. \tag{65}$$

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: $h(x) = 1$.[5]

4.3.2 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 $V_i^e(a_i, s; \theta)$ as:

$$\begin{aligned} V_i^e(a_i = 0, s; \theta) &= 0 \\ V_i^e(a_i = 1, s; \theta) &= -k_{1i} - \gamma_{1i} - \gamma_2 y_{it} - \gamma_3 y_{it}^2 + \beta V_i^c(s, a_i; \sigma(s), \theta) \\ V_i^e(a_i = 2, s; \theta) &= -k_{2i} - \gamma_4 y_{it} - \gamma_5 y_{it}^2 + \beta V_i^c(s, a_i; \sigma(s), \theta). \end{aligned} \tag{66}$$

[5] Jacobi, Joshi and Zhu (2017) assess the robustness of results from Markov chain Monte Carlo (MCMC) methods in terms of the first-order derivatives with respect to the prior parameters, as well as the convergence of the chain based on the derivatives with respect to the starting values of the chain, and find that an alternative approach based on the likelihood ratio-based technique leads to less stable and slower to converge estimates.

The conditional distribution of γ_{1i}; the parameters γ_2 and γ_3; and the continuation value $V_i^c(s, a_i; \sigma(s), \theta)$ are estimated from the incumbent's problem. The individual sunk costs k_{1i} and k_{2i} to entry 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}:

$$\begin{aligned} &E[k_{1i}|V_i^e(a_i = 1, s; \theta) > V_i^e(a_i = 0, s; \theta),\ V_i^e(a_i = 1, s; \theta) > V_i^e(a_i = 2, s; \theta)] \\ &\quad = \theta_{k_1} \cdot bs(p_c(s), p_b(s)) \qquad (67) \\ &E[k_{2i}|V_i^e(a_i = 2, s; \theta)) > V_i^e(a_i = 0, s; \theta),\ V_i^e(a_i = 2, s; \theta) > V_i^e(a_i = 1, s; \theta)] \\ &\quad = \theta_{k2} \cdot bs(p_c(s), p_b(s)), \qquad (68) \end{aligned}$$

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:

$$Pr(a_i = k|s) = \frac{\exp(V_i^e(a_i = k, s))}{\sum_{l=0}^{2} \exp(V_i^e(a_i = l, s))}. \qquad (69)$$

The choice probabilities on the left-hand side of equation (69) 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 (69) to the logit share equation on the right-hand side of equation (69) by minimizing the sum of the squared differences:

$$\min_{\theta} \frac{1}{n_s} \sum_{j=1}^{n_s} \sum_{a_i=0}^{2} \left\{ Pr(a_i|s_j) - \frac{\exp(V_i^e(a_i, s_j; \theta))}{\sum_{l=0}^{2} \exp(V_i^e(a_i = l, s_j; \theta))} \right\}^2. \qquad (70)$$

5 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.

Although these 10 Midwestern states constitute over 90% of the ethanol produced in the U.S. over the years 1995 to 2009, ethanol consumption in these 10 states only constitute around 35% of U.S. ethanol consumption. We therefore estimate a national demand function for ethanol. For our demand estimation, we 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 of the variables in our data set 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%. As we show and explain in our results below, our estimates are robust to whether we use plant-level data on ethanol production or if we instead assume 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. Thus, similar to the oil industry, where production is essentially determined by the number of wells drilled, as once a well is drilled, there is a high opportunity cost of shutting in a well (Anderson, Kellogg and Salant, forthcoming; Boomhower, 2016), in the ethanol industry over the time period of our data set, there is little or no idle capacity, and output is highly correlated with capacity.

6 Empirical Results

6.1 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 (48). 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. The RFS is not significant in any of the specifications for ethanol demand.

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.

Across all of our specifications, our results show that the demand for ethanol is highly elastic in the long run.[6] 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.

[6] In his analysis using Minnesota data only, Anderson (2012) estimates that the demand for flexible fuel vehicle (FFV) ethanol consumption is highly elastic, with a demand elasticity in the range -3.2 to -3.8. However, as Anderson (2012) treats E85 as pure ethanol and E10 as pure gasoline, even though both have ethanol as well as gasoline, and 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), the demand for ethanol is likely to be even more elastic than his estimates for FFV fuel demand.

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.[7] 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 controls for more factors that can affect ethanol demand, and the estimated elasticity is neither the highest nor the lowest estimated elasticity among all our 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

[7] 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.

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.

6.2 Production costs

After estimating the demand curve for ethanol, we estimate the parameters in the production cost function by finding the values of the parameters that minimize the sum of squared difference between observed quantity and predicted output in equation (52). 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 two different output assumptions yield similar estimates. Our estimates are therefore robust to whether we use plant-level data on ethanol production or if we instead assume 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. Thus, similar to the oil industry, where production is essentially determined by the number of wells drilled, as once a well is drilled, there is a high opportunity cost of shutting in a well (Anderson, Kellogg and Salant, forthcoming; Boomhower, 2016), in the ethanol industry over the time period of our data set, there is little or no idle capacity, and output is highly correlated with capacity.

The results for both specifications show that the only significant parameter is the positive coefficient on quantity squared, which suggests that there are decreasing returns to scale in ethanol production. Our results also suggest that the RFS does not have significant effects on ethanol production costs, since none of the coefficients on the terms with RFS interactions are statistically significant.

Parish and McLaren (1982) find in their static analysis that input subsidies are more cost-effective than output subsidies when there are decreasing returns to scale. However, in our dynamic theory model, even with decreasing returns to scale, whether production subsidies are more cost-effective than investment subsidies depends on the parameters, and is therefore an empirical question. Thus, even though our empirical results show decreasing returns to scale in ethanol production, it is still an empirical question whether production subsidies are more cost-effective than investment subsidies.

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 during the time period of our data set, which should lead to little or no idle capacity and cause output to be highly correlated with capacity, we believe that the results from specification II are plausible.

Applying 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. Our estimate of 0.65 dollars per gallon for production costs is comparable to that of 0.77 dollars per gallon from Gonzalez, Karali and Wetzstein (2013) for a typical 50-million-gallon plant in Georgia.[8]

6.3 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 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 in the investment policy function, providing evidence for diminishing returns to investment and for competition effects, respectively. The RFS does not have any significant effects in the investment policy function. We use the results from specification IV for the structural model.

6.4 Exit policy function

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 scrapping 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

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

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 in the exit policy function, 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.

As expected, the capacity of competitors increases the probability of exit, since increased market power from competitors may decrease one's profitability of staying in the ethanol industry. 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.

We find that the RFS has negative effects on the exit probability when regional fixed effects are included, probably because the RFS increases the demand for ethanol and therefore increases the payoff to producing rather than exiting.

Since the log likelihood is the highest in specification II, we use specification II for the structural model.

6.5 Entry policy function

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 has significant positive effects on entry through constructing a new plant, but no significant effects on entry through buying a shut-down plant, most likely because it provides 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.

6.6 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 the mean μ_{γ_1} of the fixed costs to investment is lower and the variable costs of investment are slightly lower under both RFS1 and RFS2 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 RFS1 and RFS2 is higher than it is under the case without RFS. However, the standard deviation σ_d of the scrap values under RFS1 and RFS2 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.

7 Policy simulations

We use our estimated structural econometric model to run counterfactual policy simulations to analyze three different types of subsidy – a 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 target date specified in the RFS.

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 gallons 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.[9]

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 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.

[9] For the predicted price of ethanol, we use our estimates of the transition density for ethanol price that controls for the RFS and the production subsidy, which shows that the RFS significantly increases the ethanol price.

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 (2017).

Since the variable cost of ethanol production increases rapidly if the capacity size becomes large, a production 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 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 for each unit increase in capacity. 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 the threshold size of 5 million gallon per year, the minimum 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, for each subsidy, the total subsidy payment from the government over the years 2012 to 2022 is approximately 4 billion dollars, which is the approximately the level of the total 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.

We use the results of our counterfactual simulations to evaluate the cost-effectiveness of three different types of subsidy: a production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. We evaluate cost-effectiveness along three different criteria: the cost to the government per change in market capacity, the cost to the government per change in consumer surplus, and the cost to the government per change in producer profits.

Table 11 compares the cost-effectiveness of the three types of subsidy with and without the RFS in terms of cost to the government per change in market capacity compared to no subsidy. Results show that cost to the government per change in market capacity is much lower under an investment subsidy or an entry subsidy than it is under a production subsidy. In the absence of the RFS, the cost to the government of increasing market capacity is $17.23 million per million gallon under a production subsidy, but can be as low as only $0.06 million per million gallon under an investment subsidy and $0.04 million per million gallon under an entry subsidy. In the presence of the RFS, the cost to the government of increasing market capacity can be as high as $48.18 million per million gallon under a production subsidy, but can be as low as only $0.08 million per million gallon under an investment subsidy and $0.07 million per million gallon under an entry subsidy. Thus, investment subsidies and entry subsidies are more cost-effective for increasing market capacity than production subsidies are.

Table 12 compares the cost-effectiveness of the three types of subsidy with and without the RFS in terms of cost to the government per change in consumer surplus compared to no subsidy. Results show that cost to the government per change in consumer surplus is lower under an investment subsidy or an entry subsidy than it is under a production subsidy. Results also show that in the presence of an RFS, production subsidies do not lead to a significant increase in consumer surplus. Thus, investment subsidies and entry subsidies are more cost-effective for increasing consumer surplus than production subsidies are.

Table 13 compares the cost-effectiveness of the three types of subsidy with and without the RFS in terms of cost to the government per change in producer profit compared to no subsidy. Results show that in the absence of an RFS, each dollar spent by the government on the production subsidy increases producer profit by one dollar. In the presence of an RFS, each dollar spent by the government on the production subsidy increases producer profit by less than one dollar. Neither investment subsidies nor entry subsidies lead to a significant change in producer profit.

8 Conclusion

This paper analyzes the effects of government subsidies and the Renewable Fuel Standard on the U.S. 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, and how the presence of a mandate affects the relative cost-effectiveness of different types of subsidies.

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 production subsidy, an investment subsidy, and an entry subsidy – each with and without the RFS. We evaluate the effects of government subsidies and the Renewable Fuel Standard on production, investment, entry, exit, producer profits, consumer surplus, net social welfare, average plant capacity, and market capacity.

Our theory model reveals the following tradeoff between production and investment subsidies. Although any investment induced by a positive production subsidy is investment that would not have occurred otherwise, the government must pay the production subsidy for each unit of production in both periods, including inframarginal units of production. In contrast, an investment subsidy must be high enough to induce investment that otherwise would not occur, but there is a cap to how high that minimum investment subsidy needs to be. Our theory model also reveals a similar tradeoff between production and entry subsidies.

Our theory results show that whether it costs more to the government to induce investment via a production subsidy or an investment subsidy depends on the parameters, even if there is also a mandate, and is therefore an empirical question. Our theory results also show that, whether or not a mandate is present, it costs more to the government to induce investment via a production subsidy than via an entry subsidy. 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.

Conventional wisdom and some of the previous literature favor production subsidies over investment subsidies, and historically the federal government has used production subsidies to support ethanol. However, the results of our counterfactual simulations show that, for the ethanol industry, investment subsidies and entry subsidies are more cost-effective than production subsidies for inducing investment that otherwise would not have occurred.

In this paper, we have taken the objective of the government of inducing investment in ethanol as given, and have explored cost-effective means of achieving this objective. One motivation for inducing investment in ethanol may be owing to possible environmental benefits of blending ethanol with gasoline as a source transportation fuel in place of fueling cars with exclusively gasoline. As the environmental costs and benefits of ethanol has been a subject of much debate in the literature (Searchinger et al., 2008; Witcover, Yeh and Sperling, 2013; Lade and Lin Lawell, 2015), and therefore require a full and thorough treatment to address well, we do not include environmental costs and benefits in this paper, but instead take the objective of the government of inducing investment in ethanol as given. We hope to incorporate environmental costs and benefits in future work.

Another set of factors that may affect the costs and benefits of ethanol, and that would also require a full and thorough treatment to address well, regards the food versus fuel debate. Because the feedstocks used for the production of ethanol can also be used for food, there is a concern that ethanol policies might affect the relationship between food and fuel markets (Chen and Khanna, 2012), and, in particular, have potential adverse effects on the price of basic food prices for the world's poor (Rajagopal et al., 2007; Wright, 2014; Poudel et al., 2012; Abbott, Hurt and Tyner, 2011; de Gorter, Drabik and Just, 2013; de Gorter et al., 2013; Si et al., 2017). We do not include costs and benefits regarding food versus fuel in this paper, but instead take the objective of the government of inducing investment in ethanol as given. We hope to incorporate the food versus fuel issue in future work.

Our results have important implications for the design of government policies for ethanol in particular, and more generally for renewable energy and socially desirable commodities as well.

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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.

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.

Table 3: Ethanol demand

	Dependent variable is log ethanol quantity			
	I	II	III	IV
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.

Table 4: Production cost

Coefficient in production cost on:		I	II
quantity	0.7155	0.3343	
		(0.3680)	(0.2107)
quantity^2	0.0101*	0.0129***	
		(0.0046)	(0.0026)
quantity * RFS1	0.4297	-5.6273	
		(3.7418)	(51.6538)
quantity * RFS2	2.7174	-28.6464	
		(8.6458)	(138.2005)
quantity^2 * RFS1	-0.2645	1.7522	
		(0.5771)	(32.5416)
quantity^2 * RFS2	1.9967	6.5274	
		(1.9525)	(98.6967)

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

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.

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.

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.

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. Significance code: * 5% level.

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)

Notes: Standard errors are in parentheses. Significance code: * 5% level.

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)

Notes: Standard errors are in parentheses. Significance code: * 5% level.

Table 11: Cost-effectiveness of different types of subsidies: Cost per change in market capacity

		Change in Market Capacity (million gallons) compared to no subsidy		Cost to Government (million $ in NPV) per Change in Market Capacity (million gallons) compared to no subsidy	
No RFS					
Production subsidy	$0.51 per gallon	231.05*	(2.17)	17.23*	(1.12)
Investment subsidy	$14 million per million gallons	549.36*	(1.59)	7.36*	(0.21)
Investment subsidy	$0.1 million per million gallons	486.40*	(1.71)	0.06*	(0.003)
Entry subsidy	$260 million per plant	549.36*	(1.59)	7.29*	(0.24)
Entry subsidy	$1 million per plant	453.33*	(1.82)	0.04*	(0.002)
With RFS					
Production subsidy	$0.51 per gallon	136.11*	(1.95)	32.96*	(2.40)
Production subsidy	$0.45 per gallon	58.58*	(1.70)	48.18*	(3.42)
Investment subsidy	$14 million per million gallons	349.74*	(2.04)	12.00*	(0.53)
Investment subsidy	$0.1 million per million gallons	335.84*	(2.04)	0.08*	(0.004)
Entry subsidy	$260 million per plant	349.74*	(2.04)	11.91*	(0.58)
Entry subsidy	$1 million per plant	219.11*	(1.95)	0.07*	(0.004)

Notes: Standard errors are in parentheses. Significance code: * 5% level.

Table 12: Cost-effectiveness of different types of subsidies: Cost per change in consumer surplus

		Change in Consumer Surplus (million $ in NPV) compared to no subsidy		Cost to Government (million $ in NPV) per Change in Consumer Surplus (million $ in NPV) compared to no subsidy	
No RFS					
Production subsidy	$0.51 per gallon	55.18*	(27.31)	72.15*	(36.01)
Investment subsidy	$14 million per million gallons	107.95*	(22.92)	37.46*	(8.02)
Investment subsidy	$0.1 million per million gallons	99.98*	(23.67)	0.29*	(0.07)
Entry subsidy	$260 million per plant	107.95*	(22.92)	37.09*	(7.97)
Entry subsidy	$1 million per plant	94.12*	(24.58)	0.17*	(0.05)
With RFS					
Production subsidy	$0.51 per gallon	25.39	(45.54)	176.66	(317.14)
Production subsidy	$0.45 per gallon	11.29	(30.38)	250.01	(673.05)
Investment subsidy	$14 million per million gallons	71.06*	(32.73)	59.08*	(27.33)
Investment subsidy	$0.1 million per million gallons	64.31*	(32.80)	0.43	(0.22)
Entry subsidy	$260 million per plant	71.06*	(32.73)	58.62*	(27.15)
Entry subsidy	$1 million per plant	46.53	(32.35)	0.33	(0.23)

Notes: Standard errors are in parentheses. Significance code: * 5% level.

Table 13: Cost-effectiveness of different types of subsidies: Cost per change in producer profits

		Change in Producer Profits (million $ in NPV) compared to no subsidy		Cost to Government (million $ in NPV) per Change in Producer Profits (million $ in NPV) compared to no subsidy	
No RFS					
Production subsidy	$0.51 per gallon	3998.43*	(629.94)	1.00*	(0.17)
Investment subsidy	$14 million per million gallons	105.11	(580.23)	38.47	(212.37)
Investment subsidy	$0.1 million per million gallons	96.75	(587.98)	0.30	(1.82)
Entry subsidy	$260 million per plant	105.11	(580.23)	38.09	(210.28)
Entry subsidy	$1 million per plant	44.14	(671.96)	0.36	(5.55)
With RFS					
Production subsidy	$0.51 per gallon	4675.36*	(1054.01)	0.96*	(0.23)
Production subsidy	$0.45 per gallon	3900.05*	(673.80)	0.72*	(0.13)
Investment subsidy	$14 million per million gallons	991.44	(583.07)	4.23	(2.50)
Investment subsidy	$0.1 million per million gallons	833.93	(594.88)	0.03	(0.02)
Entry subsidy	$260 million per plant	991.44	(583.06)	4.20	(2.48)
Entry subsidy	$1 million per plant	741.13	(582.41)	0.02	(0.02)

Notes: Standard errors are in parentheses. Significance code: * 5% level.