Ethanol production in the United States: The roles of policy, price, and demand

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ABSTRACT

Assessments of the impact of the U.S. renewable fuel standard (RFS) should inform consideration of future biofuels policy. Conventional wisdom suggests the RFS played a major role in stimulating the ten-fold expansion in ethanol production and consumption in the United States from 2002 to 2019, but evidence increasingly suggests the RFS may have had a smaller effect than previously assumed. Price competitiveness, federal and state policies such as reformulated gasoline requirements, and octane content in ethanol also affect ethanol market attractiveness. This study explores the roles of policy and economic factors by comparing historical data with results from scenarios simulated in a system dynamics model. Results suggest price competitiveness may explain much of the growth in the ethanol industry from 2002 to 2019. The Volumetric Ethanol Excise Tax Credit and phaseout of the oxygenate methyl tert-butyl ether contributed to earlier growth relative to expected timing of growth based on fuel price alone. The RFS (modeled through observed Renewable Identification Numbers) contributed to increased ethanol production in later years and may have increased production in the earlier years if risk of investment was decreased by the RFS Program.

1. Introduction

1.1. Objective

The rate of ethanol production and consumption in the United States grew rapidly in the 2000s, coinciding with the promulgation of numerous ethanol policies (both state and federal). Some peer reviewed studies suggest the renewable fuel standard (RFS) program was the major driver of the growth in the ethanol market in the United States (e.g., Carter et al., 2017; Wallander et al., 2011; Wright et al., 2017). This proposition is certainly logical, as the RFS program was specifically designed to increase ethanol production and consumption, and it coincided with the major period of growth. Nevertheless, a number of recent studies (Babcock, 2013; Taher-ipour et al., 2020) suggest that after accounting for many additional factors that also affect ethanol markets, the incremental effect of the RFS Program[1]

(esp. The RFS2) may be smaller than originally thought. Basic economic principles underpinning relatively arcane variables also support this notion (i.e., D6 RIN prices, discussed below). This study provides a detailed assessment of the various factors that affected the corn starch ethanol industry (hereafter "ethanol industry") build-out to help shed light on the role of the RFS program in the context of many other coincident factors. The objective of this analysis is to provide insight into the contributions to ethanol market growth of economic and policy factors—federal and state policies, relative prices, and octane demand—by comparing historical data with results from test case scenarios, using a system dynamics model built for this purpose. Insights gained are useful not only in understanding the past but also to inform future consideration of whether and how to use federal policies to stimulate growth in the use of biofuels, and which types of fuels might be more appropriate to incentivize under various conditions.

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[1] Administered by the U.S. Environmental Protection Agency, the RFS states that fuel sold in the United states must have at least a certain amount of renewable fuels in order to decrease emissions and increase U.S. energy independence. The policy began with the Energy Policy Act of 2005 (RFS1) and later supplemented by the Energy Independence and Security Act of 2007 (RFS2) (U.S. Environmental Protection Agency, 2015).

1.2. Background

Annual ethanol production historically featured rapid growth followed by a plateau, as depicted in Fig. 1. The figure identifies the timing of major policies (bottom) and quantifies annual ethanol production and consumption (orange and blue bars, respectively, left axis) and the annual change in production ("+", right axis). This paper explores potential explanatory factors for the historical growth pattern, using retrospective time series data and a modeling analysis of policy measures, gasoline and ethanol prices, and demand for octane in a unique system dynamics simulation model.

1.3. Significance/contribution to the literature

A substantial body of literature considers the role of policy and economic factors in the expansion of the ethanol market in the United States over the past 20 years. In contrast to the prospective nature of much of this literature, the present study is retrospective, considers policy and fuel market data through 2019, and uses a system-dynamics modeling framework. Most existing studies looking at the RFS assume that the set volumes will be met. To our knowledge, three published retrospective studies look at the RFS allow for it to be nonbinding (Babcock, 2012; Bento and Klotz, 2014; Taheripour et al., 2020, 2021). Only one (Taheripour et al., 2021) considered several factors simultaneously that are known to be important for ethanol industry expansion (i.e., MTBE, octane, and oil price), and it covered the entire period of the RFS (2006–current). Taheripour et al. (2021, 2020), used partial equilibrium and computable general equilibrium economic models to explore the role of the RFS. The analysis found that energy and agricultural markets and federal and state incentives drove much of the increases in ethanol production before 2011, and that the RFS played a more dominant role in supporting production from 2011 to 2016. Taheripour et al. (2021, 2020) reported from their partial equilibrium modeling that the RFS had a binding effect on increasing ethanol consumption in only one year between 2005 and 2010 (2008, the year oil prices crashed at the start of the Great Recession), increasing ethanol consumption by roughly 0.3 billion gallons. From 2011 to 2016, Taheripour et al. (2020) estimate the RFS had a binding effect every year, increasing ethanol consumption by roughly 1–2 billion gallons per year over what otherwise would have been produced without the RFS program.

In this study, we present a novel contribution to the literature by assessing for the first time the incremental and combined effects of various critical factors on ethanol production in the United States from 2002 to 2019 through a series of test cases. Most of the increase in ethanol production in the United States was from 2002 to 2012 (Fig. 1), with increases after that mostly of exports and not of domestic consumption. Most existing studies do not include sufficient detail of the fuel markets to be able to tease out the effects of individual drivers (e.g., MTBE phase out, price competitiveness between gasoline and ethanol, octane value, etc.) (Bento et al., 2015; Carter et al., 2017; Tyner et al., 2010). This has the effect of conflating the RFS Program with other factors, obscuring the true effect of the Program. The few that do include good market detail (e.g., Taheripour et al., 2020) often combine all non-RFS factors into the baseline such that their individual contribution cannot be estimated or compared to that of the RFS. This study advances our understanding of these complex energy-agricultural markets by exploring five major drivers for ethanol production in the U.S.: (1) price competitiveness with oil, (2) the MTBE phaseout, (3) the octane value of ethanol, (4) VEETC, and (5) the RFS program, highlighting the expected incremental effects of these overlapping factors. The system dynamics methodology employed here accounts for bottlenecks, lags, and feedbacks in the complex biomass-to-biofuels supply chain, representing these considerations more explicitly than the economic modeling frameworks used by others (Peterson et al., 2019). This feature of system dynamics methodology may better represent transition states with nonequilibrium, suboptimal characteristics.

2. Methodology

We modified the Biomass Scenario Model (BSM) to simulate the development of the domestic ethanol industry in a set of test cases designed to explore the roles of various policies and economic factors. Scenarios estimated quantitative effects of each factor alone and in combination, attempting to attribute effects to specific factors. The system dynamics methodology is adept at examining the feedbacks within the ethanol supply chain for robust hindcasting policy analysis. The BSM is not a partial equilibrium (PE; e.g., Taheripour et al., 2020) or general computable equilibrium (GCE; e.g., Cai et al., 2013; Hertel et al., 2010) model. It is a nonlinear model that explicitly links individual steps in the supply chain and factors in the market to examine nonlinear complex dynamics in the system. Mass-balance is required (like market-clearing in the PE and CGE models), though optimization of the overall market is not. The overall approach of the BSM is discussed in more detail in Peterson et al. (2019) and associated publications. This section describes the scenarios, data sources, and system dynamics model simulation environment.

2.1. Scenarios

We designed scenarios to explore the effects of policy and economic factors on the ten-fold ethanol production increase in the 2002–2019 timeframe. Table 1 shows the five factors considered in the scenario design.

2.2. Model

This analysis used a system dynamics model as a simulation environment in which to explore test cases to estimate the effects of policy and economic factors on ethanol production growth. This simulation environment was created using a modified version of the BSM that we call BSM-EtOH. The BSM was developed by NREL for the U.S. Department of Energy (DOE) Bioenergy Technologies Office.[2] The BSM was designed to explore the impacts of various policy and economic drivers on the evolution of a bio-economy within the United States (Newes et al., 2011, 2015; Peterson et al., 2019; Vimmerstedt et al., 2012, 2015). A primary focus of the BSM is the supply chain for bioenergy products, including ethanol and drop-in fuels; accordingly, the model addresses dynamics associated with the U.S. agricultural system, investment and operation of conversion facilities, and "downstream" use of fuels.

The BSM is composed of a set of interconnected modules (Fig. 2) that represent essential aspects of the supply chain for bioenergy. These include feedstock production, logistics, and markets; development and operation of conversion facilities; downstream inventory, pricing, distribution, exports, and domestic use of fuel ethanol; vehicles; and the oil industry. Details of the model are available in previous publications (Newes et al., 2011, 2015; Peterson et al., 2019; Vimmerstedt et al., 2012, 2015). Feedback processes within and across modules capture dynamics related to land use; inventory and pricing of agricultural products; industrial learning, investment, and utilization of conversion facilities; and fuel use. Table 2 displays major data sources used to parameterize the model. Agricultural modules are calibrated to historical crop data, and oil price inputs align with values from the U.S. Energy Information Administration (EIA). Techno-economic inputs such as facility scale, capital cost, and process yields are aligned with published literature (Biddy et al., 2019; McAloon et al., 2000).

In general, the model views actors as economic decision makers who respond to available information regarding costs and revenues of choices available to them. For example, farmers allocate crop land in response to expected per-acre net grower payment associated with different commodity crops. Grower payment is based on per-acre

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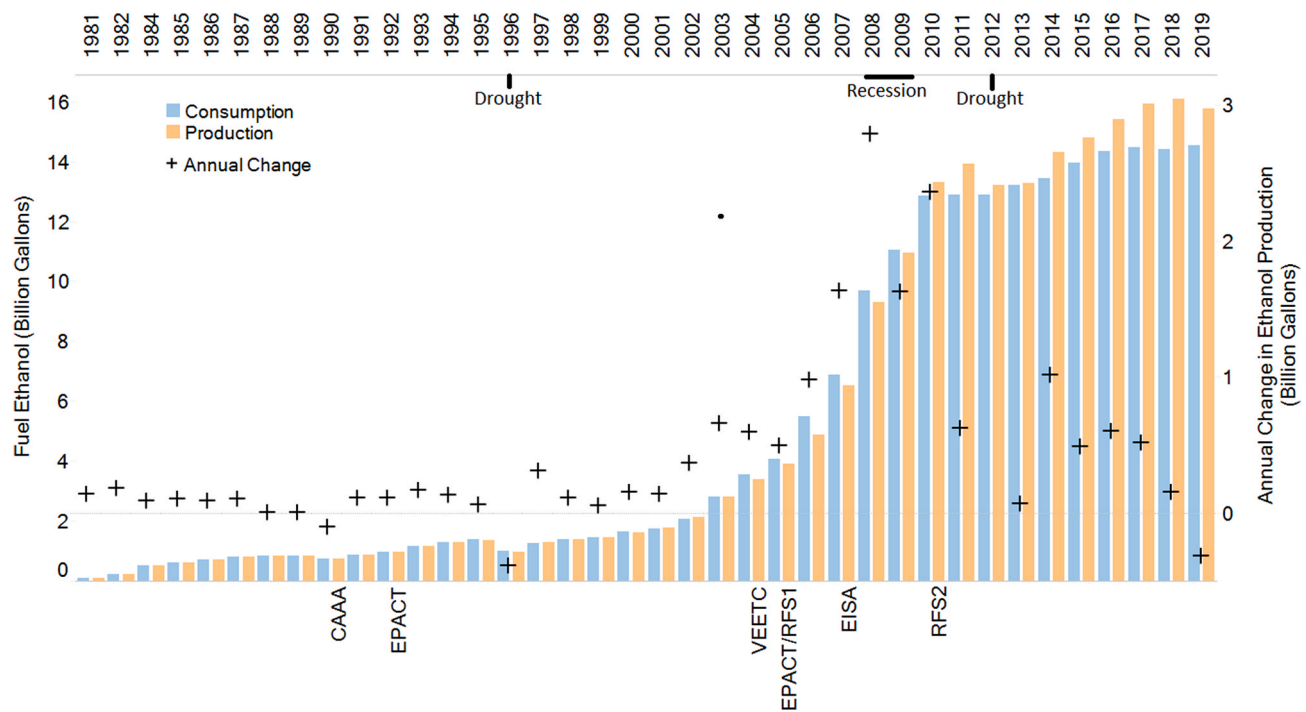
Fig. 1. Annual production and consumption of ethanol in the United States (left axis and bars) and the change from one year to the next (right axis and plus signs) from 1981 to 2019 (note different y-axis zero levels). Units are in billions of gallons per year. Production was greater than 56% of capacity in all years, with an average of 88% and median of 91% (Alternative Fuels Data Center, 2020). Data are from the U.S. Department of Agriculture (USDA Economic Research Service, 2019). Timing of key federal policy events is shown below the figure (CAAA=Clean Air Act Amendments of 1990; EPACT = Energy Policy Act; VEETC = Volumetric Ethanol Excise Tax Credit; RFS = renewable fuels standard; EISA = Energy Independence and Security Act of 2007). Timing of droughts and recession is shown at the top of the figure.

production costs, expected yields, and expected prices. Allocation is made using a nested logit function, which has been calibrated to historical data taken from USDA baseline forecasts.

Investment in conversion facilities is based on the net present value of the marginal conversion facility, where net present value is based on technoeconomic considerations such as capital cost, plant scale, process yield, operating costs (including feedstock) and expected revenues. Net present value is compared to an assumed net present value of an alternative investment, with the overall rate of industry investment increasing in response to greater relative NPV. This continuous approach contrasts optimizations approaches in which very small changes in inputs can lead to a "penny switching" effect that causes all investment to switch from one technology to another. Utilization of existing industry conversion facilities is based on per-unit production costs relative to per-unit revenue. Investment and utilization responsiveness have been calibrated to historical values.

The BSM is typically used to conduct prospective scenario analyses. To support this retrospective analysis, we modified the underlying logic of the BSM to construct the BSM-EtOH version of the model. A causal loop diagram depicting how historical policies and financial data influence ethanol production in the model is shown in Fig. 2.

To implement this revised logic, we made several modifications (See supplemental information [S.I.]). The BSM was designed in a modular fashion to facilitate development and analysis. For this analysis, non-ethanol-related modules were deactivated. The change in default timeframe from prospective to retrospective necessitated new initialization and calibration of the model. In the publicly available version of BSM (Bush et al., 2020 - https://github.com/NREL/bsm-public), the starch ethanol industry (but not lignocellulosic ethanol production) is fully mature and meets demand for blending with U.S. motor gasoline demand and for exports. To explore historical and alternative scenarios relating to the ethanol industry development from 2002 to 2019, we incorporated model changes that estimated domestic fuel ethanol

demand based on historical motor gasoline sales, modified the domestic demand for ethanol, set D6 RINs to historical values, showed the build-out that is due to MTBE phaseout, and showed price competition between ethanol and gasoline. D6 RINs are the type of RINs used for conventional biofuels under the RFS Program, which historically have been almost entirely corn ethanol. We added a mechanism to account for the use of ethanol as an octane enhancer. Finally, we modified the model's ethanol import-export structure such that net exports act to regulate inventory levels around target levels, which in turn reflect domestic demand for ethanol. More details are available in the S.I.

These modifications enable us to use the model to simulate historical conditions. Validation of this simulation environment is critical to the value of comparisons of historical to various test case simulations. For the study period (2002–2019), the model can simulate historical conditions and generates results that are consistent with empirically observed data for a broad set of metrics (see S.I.). These metrics include commodity crop production, commodity prices, land use, ethanol production, ethanol consumption, and ethanol net imports. The simulated historical conditions are generated from the combined effects of individually modeled processes that mirror actual markets, incentives, and industry practices during the study period. One or more of these processes can be disabled in the model to generate counterfactual simulations for comparison to historical and simulated historical conditions, potentially providing insight into the role each driver played in the evolution of the system.

2.3. Data sources

Major sources of data are listed in Table 2. (Additional details of data sources are documented in the S.I.) The analysis used historical time series data on oil prices, gasoline prices by octane level, ethanol prices, ethanol production, ethanol consumption, ethanol trade, and agricultural commodities. Initial values for land allocation and number of

Table 1

Potential drivers of changes in ethanol production, 2002–2020. MTBE = methyl tertiary butyl ether; VEETC = volumetric ethanol excise tax credit; RFS = renewable fuel standard.

Driver	Inclusion in BSM-EtOH	Years of Effect[a]
Oil prices	If ethanol prices are less than oil prices, it is financially advantageous to blend ethanol into gasoline if it is available, up to applicable constraints.	All years (baseline assumption)
Phasing out of MTBE	As part of the Clean Air Act requirements for reformulated gasoline (RFG), MTBE was replaced by ethanol as an oxygenate.	2002–2006
Blenders credit/ VEETC	Incorporate $X/gal[b] volumetric ethanol excise tax credit.	2002–2011
RFS program[c]	Use historical values for D6 RINs, the accounting metric for RFS implementation. for conventional biofuels (i.e., corn in the U.S.).	2006[d]–2019
Match blending[e]	As ethanol blending became more widespread, the market transitioned from splash to match blending.	2005–2019

[a] The Years of Effect denote years that a factor was explicitly coded in the model. A factor could have effects in later years because of path-dependencies and other non-linearities from such a systems dynamic model.

[b] The blenders credit changed in value and form through the years as it was updated, from $0.45/gal to $0.54/gal (Duffield et al., 2015).

[c] In using historical RIN values, we modeled the RFS program as implemented by EPA. Decisions made by EPA, such as decisions related to small refinery exemptions, may have impacted RIN prices and ethanol production. We have not attempted to quantify the impact of these decision in this paper.

[d] Though passed legislatively in 2005 with the Energy Policy Act, RFS1 did not begin as an EPA Program until 2006. Furthermore, although the use of RINs started in 2007, public data for RINs did not begin until 2010 with the RFS2, and private companies began collecting data (used for this study) in mid-2008.

[e] Match blending combines an octane enhancer with a lower-cost, unfinished gasoline blendstock to reach a target octane level, but it requires infrastructure investment; splash blending combines ethanol with finished gasoline, without targeting a specific octane level. Match blending began with the use of ethanol in RFG (hence the start date of 2005) and was widespread by 2010.

ethanol facilities are also based on empirical data.

Data lacking for this study included company-proprietary capital and operating costs of ethanol facilities as well as their performance metrics such as conversion and co-product yields,[3] comparable data for octane production from competitor pathways, and comprehensive historical data on state-level ethanol policies. In addition, data on historical ethanol distribution/blending infrastructure build-out were insufficient. Therefore, the BSM-EtOH model does not consider potential infrastructure constraints, such as limited truck, rail, and terminal capacity for ethanol distribution and storage (see Section 3.1 for further discussion).

3. Results and discussion

During the study period, numerous policies and economic conditions created a complex array of interacting incentives that affected various components of the biofuel supply chain and that differed in timing, value, and implementation. The results presented below explain the effects of this complex web of interacting policy and economic factors on increases in ethanol production, using evidence from historical time series and simulated test case scenario analysis results from the BSM-EtOH model.

3.1. Potential effects of different factors on ethanol production

Fig. 3 presents two different baselines that are based on the economic considerations of blending ethanol. Fig. 3a includes only price competition in the baseline, as it can be argued that the gasoline market may have used ethanol on an economic basis, even if ethanol had not been incentivized. U.S. Environmental Protection Agency (EPA) and university researchers have estimated that at low blending rates (10%), consumers do not perceive the loss of energy content and thus ethanol prices on a volumetric bases (Babcock, 2013; Burkholder, 2015). For example, at 10% ethanol and with 30% less energy, consumers can drive 3% fewer miles between refueling. This loss appears imperceptible at low blends, and becomes increasingly apparent as blend rates increase.

Our analysis assumes there are no infrastructure or logistical limitations, which was not true in the early years (e.g., 2002–2006 (Denicoff et al., 2007). However, the large increase in rail and storage capacity from 2002 to 2007 (Denicoff et al., 2007) and the large increase in ethanol consumption in California in 2003 and other RFG areas outside the Midwest beginning in 2006 (Anderson and Elzinga, 2014), suggest that infrastructure may not have been limiting after roughly 2006–2007.

The first baseline does not account for the octane value of ethanol. As a second baseline (Fig. 3b), the transition of the gasoline market to match blending is combined with price competition for the entire simulation: ethanol used as an octane enhancer through match blending reduces the cost of the final blend in comparison to splash blending, making it more economical. On top of these different baselines (Fig. 3), we examined three test cases that each isolate the role of a single policy: VEETC (red lines), oxygenation requirements and MTBE restrictions (orange lines), and RFS (constant hypothetical RINs, green lines). These other policy levers are added, with timelines noted in Table 1, to evaluate their individual contributions to ethanol production under these alternate baselines. We acknowledge this may not be realistic in the 2002–2019 timeline studied (e.g., a world with the VEETC but without MTBE phaseout), or mechanistically in some cases as factors might have been codependent (e.g., without the MTBE phaseout, additional ethanol policy might not have been enacted). However, it is instructive to consider the estimated influence of each factor in isolation as well as in combination with other factors in a timeline that represents the sequence of actual events. In addition, the Baseline + RINs scenarios should not be seen as a proxy for the RFS, as the D6 RIN values would have changed under different economic and policy conditions. Rather, the scenarios with D6 RINs should be viewed as what could have happened if the two hypothetical constant D6 RIN values ($0.15/RIN and $1/RIN[4]) had happened in isolation from other policies.

Each figure includes actual historically observed ethanol production as well (black line), as well as a case where none of the modeled drivers are present (grey line).[5] These results illustrate the use of BSM-EtOH simulation to test effects of policy and economic factors on the growth of ethanol production.

Price competitiveness alone accounts for at least 50% of ethanol production in the 2002–2019 simulation (blue versus black line in Fig. 3). Adding oxygenation requirements and MTBE restrictions increases production levels by one to three billion gallons (orange versus blue line in Fig. 3a). The VEETC policy spurs production in the early years (red versus blue line through 2011 in Fig. 3a); however, its

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[3] We proxied ethanol facility data using McAloon et al. (2000) and Biddy et al. (2019).

[4] These two values were chosen based on historical D6 RIN data. $0.15/RIN is close to the median and $1/RIN is rounded down to the nearest dollar from the maximum of the monthly average data (2008–2019).

[5] This represents a world where the price competition had no effect, which could occur from a variety of reasons, including (1) if the transportation logistics of moving ethanol from the Midwest to RFG had not matured, any price advantage could not be capitalized upon, and (2) if refiners had not needed to use any oxygenate, they probably would not have invested in retrofitting refineries to make BOBs in order to make better use of ethanol.
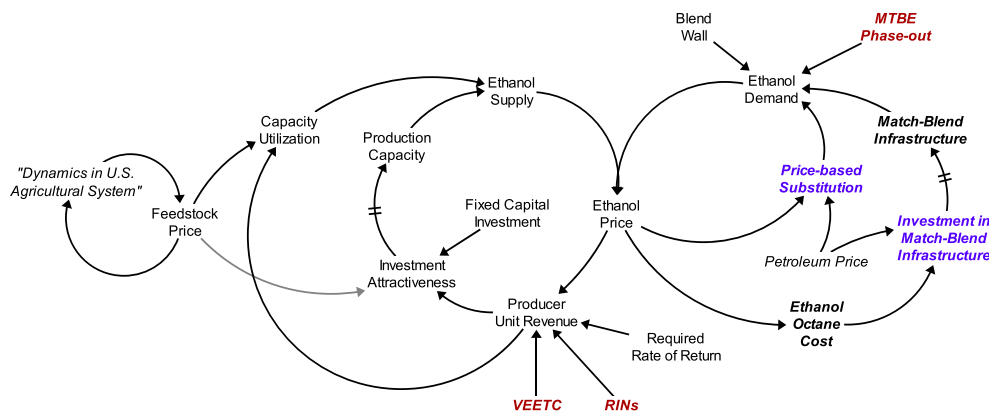
Fig. 2. Causal loop diagram of the BSM-EtOH model. Red text indicates policy factors, and purple text indicates economic drivers; both may have economic effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

expiration in 2011 prompts a production collapse followed by rebound generally back to the price-competitive production levels. (The model does not include foresight, which would likely reduce or eliminate this effect.) Finally, the addition of RFS effects, via the price of D6 RINs, increases production from 2014 to 2019 by up to 1.6 ($0.15/RIN) to 6.2 billion gallons ($1/RIN), depending on the constant D6 RIN assumption (green lines versus blue line in Fig. 3a).

Crude oil prices and their effect on gasoline prices, as well as corn prices and their effect on ethanol prices, in the 2006–2011 timeframe were such that blending ethanol into gasoline lowered fuel production costs, which represents an economic incentive for producers and blenders to do so.[6] This has been reported by others as well (Babcock, 2012; Taheripour et al., 2020).[7] At the same time, the transition from splash blending to match blending increased the profitability of adding ethanol to gasoline, as blenders were able to use lower-cost blendstocks for oxygenate blending (BOBs) instead of finished gasoline to produce E10 between 2005 and 2010. In addition, the transition in effect "locked in" ethanol as the choice for octane enhancement. The BSM-EtOH modeling confirmed these expectations by showing that, with the addition of VEETC, these economic factors (price competition + match blending) are estimated in the model to have been sufficient to increase ethanol production to levels within 4–18% of those observed from 2007 to 2011 (Fig. 3b).

The addition of match blending helps dampen the impact of the VEETC expiration by providing an additional economic incentive (or "lock in") for ethanol production (elimination of dip in production in 2012 in Fig. 3a versus 3b). With the addition of D6 RINs, estimated ethanol production is close to historical levels around 2013 at a higher level ($1/RIN) and around 2020 at a lower level ($0.15/RIN) without the MTBE transition or VEETC. Thus, D6 RINs on the upper end of the historical record are estimated to be sufficient to increase production, while D6 RINs closer to the median are not estimated to be high enough to increase production very much. Fig. 3 shows a larger impact on the timing of rapid growth from VEETC than MTBE, with the red line left of the orange one.

3.2. Estimated effects as the industry actually evolved

In addition to the *potential* for individual policies to drive ethanol industry evolution, there is the estimated *actual* effect as factors entered

(e.g., RFS1 in 2005) and exited (e.g., VEETC at the end of 2011) the system. Thus, the additive effect of each target factor may be contingent on other factors that preceded it (Fig. 4). This type of scenario analysis can show the estimated impact of each policy on actual ethanol production. We use one baseline in these simulations (i.e., price competitiveness between ethanol and gasoline); because match blending was uncommon in non-RFG areas until roughly 2005–2010, we consider it to be an additional factor but not the baseline. Subsequent scenarios added potential drivers chronologically as they emerged, such that effects from potential drivers that predate another are already taken into account. The second scenario added the phaseout of MTBE, which began in 2000–2003 in California and in 2005–2006 in much of the rest of the country (Anderson and Elzinga, 2014). The third scenario incorporated blenders credit (2002–2003) and VEETC (2004–2011).[8] The fourth scenario adds the observed D6 RIN prices of the RFS program (see S.I.). Although D6 RIN prices existed starting in 2007, records only date to mid-2008, which is the beginning of our series.[9] The fifth scenario removed D6 RIN prices as a potential driver of increased ethanol production but added match blending which ramped up from 2005 to 2010. The sixth scenario readded D6 RIN prices and thus included all potential drivers. The sequential approach[10] taken here enables earlier factors to have greater impact, but it may more accurately represent actual historical impacts, as the actual effect of the RFS program, for example, was in addition to whatever effect VEETC already had.

As shown earlier (Fig. 3a) the price competitiveness of ethanol to gasoline is estimated to be a strong driver even in isolation. However, this driver alone suggested decreases in ethanol after oil prices decreased after 2014, a trend not observed (Fig. 4). The Price + MTBE scenario (Fig. 4, orange line) showed that the addition of MTBE replacement to the price competition effect increased ethanol production, especially after 2006, when the swift removal of MTBE from RFG areas occurred once reformulated blendstock production had come online. However, it was still not enough to match observed production. The addition of VEETC (Fig. 4, red line) brought ethanol production close to historical levels from 2002 to 2011, but there was a large drop in ethanol production in 2012 when VEETC expired and coincided with a

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[6] Oil prices were generally high because of various geopolitical factors from 2002 to 2014, except for 2008, due to the Great Recession. After 2014, oil prices began to fall because of increased global production, with unconventional resources being tapped.

[7] See the S.I. for a sensitivity analysis around crude oil prices.

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[8] Tax credits for ethanol preceded the VEETC, but VEETC facilitated incorporation of ethanol into the gasoline pool because it gave blenders more flexibility (Duffield et al., 2015). This analysis references all these credits from 2002 to 2019 under the VEETC label.

[9] D6 RINs were very low in this early period and so the omission of their value in 2007 likely does not affect the outcome. There are no digital records for RIN prices prior to this to our knowledge, thus we are unable to assess the effect or lack of effect from RINs prior to this period.

[10] The fourth and fifth scenarios are not technically sequential since RINs and match blending were phased in around the same time.

Table 2

Major data sources used in BSM-EtOH.

| Item	Description	Reference
Oil prices	Historical refiner cost of crude oil, 2002–2019	U.S. Energy Information Administration (2020)
Initial land allocations (including Conservation Reserve program)	2002 values from regional land allocations based on data from the National Agricultural Statistics Service (NASS)	U.S. Department of Agriculture (2020)
Commodity crops	Yields, production cost per acre for commodity crops (corn, soy, wheat, other grains, and cotton), 2002–2019	National Agricultural Statistics Service (2019)
Ethanol industry	Reference data for production, consumption, and trade for ethanol, 2002–2019; simulated data determined endogenously after 2002	Alternative Fuels Data Center (U.S. Department of Energy, 2020)
Ethanol prices	Reference data for ethanol prices, 2002–2019; simulated data determined endogenously after 2002	Nebraska Department of Environment and Energy (2020)
RIN prices	Daily average RIN prices, 2008–2019	Oil Price Information Service (2020)
Blend wall	The "blend wall" sets a ceiling for domestic fuel ethanol consumption, and represents 10% of domestic motor gasoline demand. We estimated the blend wall for the historical period based on data from Table 3.5 in EIA's monthly energy review	U.S. Energy Information Administration (2019)

significant drought (Rippey, 2015), and production did not increase to observed levels after 2013. The addition of D6 RINs (Fig. 4, green line) did little from 2002 to 2012 because of low or non-existent RINs, but supported increased production from 2013 to 2019 relative to scenarios without the RFS program. Simulated production tapered off again after 2017 because of low D6 RIN values. The addition of match blending and the removal of D6 RIN prices lessened the impact of the two events in 2012 (VEETC expiration and drought), as the transition to match blending (2005–2010) appeared sufficient to sustain production. When all factors were present, the simulation (brown line) matched historical trends during the period of growth (black line) fairly well, though the model underestimated ethanol production in the early years, perhaps partially because of the exclusion of potential effects from RFS1 or state programs (see S.I. for more information on model calibration and validation).

Thus, overall the BSM simulations suggest the price effects, MTBE restrictions, and VEETC were sufficient to drive the system from 2002 to 2010, while the match blending and D6 RINs were needed to sustain production from 2011 to 2019.

Other factors such as the Small Refinery Exemptions (SREs) and Reid Vapor Pressure (RVP) waivers likely did not have a significant effect for the period of major growth in the industry from 2002 to 2012 examined here. Before 2013, the volumes of SREs were re-allocated to obligated parties, and thus the total obligation under the RFS was unchanged by SREs in these years. After 2013, there was little further growth in the industry due to the blend wall. The RVP waiver for E10 went into effect in 1990, and although a critical precursor for growth later, it was not sufficient on its own for growth outside of a few billion gallons in the Midwest. This is already included in the baseline although we did not model it specifically. The RVP waiver for E15 went into effect in 2019, after the major period of growth in the industry. That said, these factors and others (e.g., tariffs, which have had a significant effect after roughly 2018) could have significant effects more recently on ethanol production and consumption. Because of this, our estimates for the more recent effects from the RFS Program may be less certain, and require further investigation.

Finally, it is certainly possible that refineries may have chosen to not use ethanol absent the RFS1 and 2 and replace MTBE with something else. Even as early as 1999, there were large reports by the California Energy Commission (California Energy Commission, 1999) assessing potential substitutes for MTBE, some fossil-based and some biofuels. The fossil-based alternatives (e.g., tertiary-butyl-alcohol (TBA), ethyl-tertiary-butyl-ether (ETBE), and tertiary-amyl-methyl-ether (TAME)), were reported to be either not available at the quantities
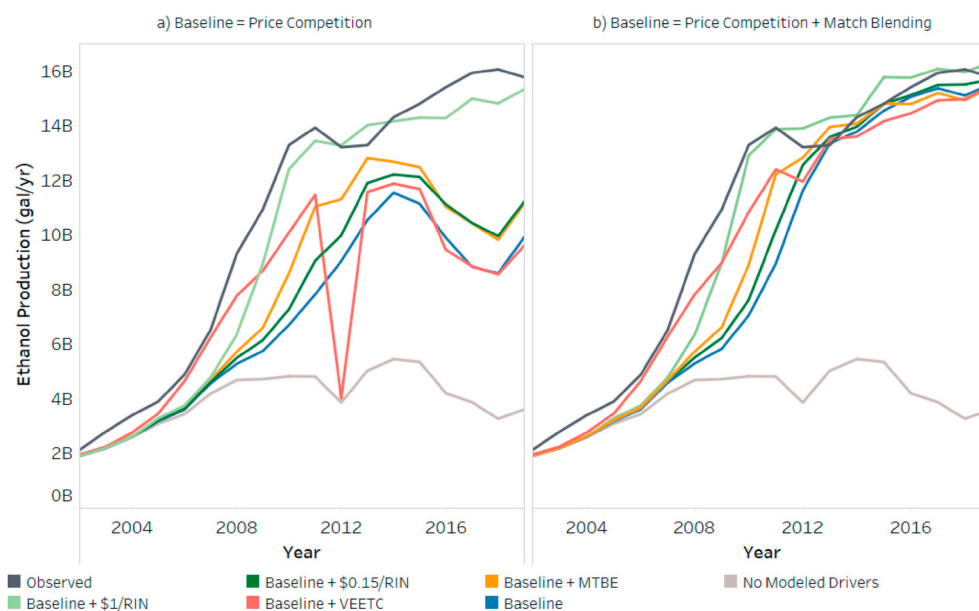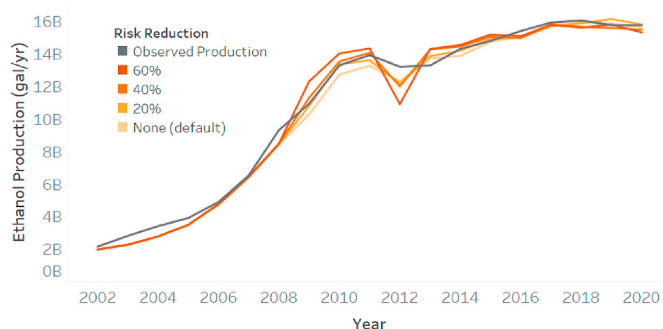

Fig. 3. Simulated ethanol production from 2002 to 2019 using the BSM-EtOH with only price competition (a) and price competition plus match blending (b) as baseline, and with addition of single policies (oxygenation requirement and MTBE restrictions, VEETC, and RFS via constant D6 RINs [2005–2019]). Observed production from the Alternative Fuels Data Center added for reference (U.S. Department of Energy, 2020).
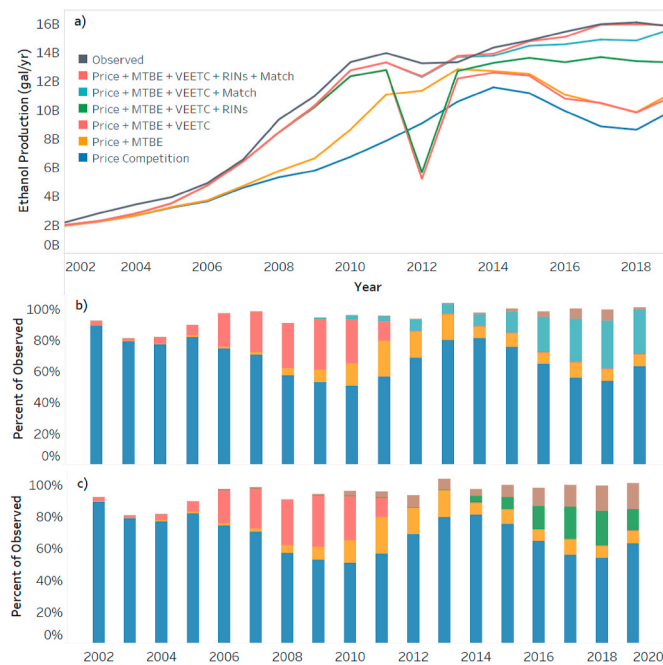
Fig. 4. Simulated ethanol production from 2002 to 2019 using the BSM-EtOH assuming chronological addition of the five potential drivers (a), along with the percentage of total observed production that each driver contributed as it was added both if match blending was assumed to be implemented before RINs (b) and if RINs were assumed to be implemented before match blending (c). Percent of observed was calculated as the incremental *scenario production/observed production* for each successive scenario. Observed production from the Alternative Fuels Data Center added for reference (U.S. Department of Energy, 2020).

needed (TAME) or had the same water quality concerns as MTBE (TBA and ETBE) (California Energy Commission, 1999). Ethanol was the only substitute available in the quantities needed that did not have the water quality concerns. Thus, it seems unlikely that refineries would not have used ethanol in place of MTBE even if they weren't encouraged to do so with the RFS1. That said, as a mandate the RFS Program certainly *could* have been responsible for the full volume of ethanol produced and consumed in the United States. But *as events played out*, we estimate it was not the major driver for the increase in ethanol production and consumption in the United States over the period from roughly 2002–2012.

Fig. 5. An RFS-induced reduction in risk perception accelerates production to earlier years and increases production levels. Simulated ethanol production from 2002 to 2019 using the BSM-EtOH with sensitivity analysis on the estimated effects of the RFS program, showing the potential risk reduction (20%, 40%, and 60%) from the RFS program starting in 2005, using the "Price + MTBE + VEETC + RINs + Match" scenario from Fig. 4 as the default. Observed production from the Alternative Fuels Data Center added for reference (U.S. Department of Energy, 2020).

3.3. RFS program with alternate D6 RINs and risk values

The preceding results examined phaseout of MTBE, VEETC, and the RFS as policy factors that influenced the growth in ethanol production. The simulations used the historical financial value of D6 RINs as the metric to represent the effects of the RFS program. Historical D6 RINs are obviously a limited representation of the potential effect of the RFS Program, as other values would likely have been realized if other factors had been different (e.g., see $0.15 and $1.00 simulations in Fig. 3). To expand on this limited representation, additional simulations were conducted to offer detailed insight about the potential effects of the RFS program.

It is possible that the RFS1 was able to spur investment in ethanol facilities by increasing policy certainty and decreasing investment risk, thus encouraging the development of ethanol infrastructure. This type of effect would not be captured by the RIN values used in our analysis. We analyzed the possibility that the RFS might have also reduced the perceived risk of investment through test cases that directly address the potential risk reduction value of the RFS program in assuring investors ethanol would have a market even if oil prices dropped. We approximate the investment risk-reduction value of the RFS program by setting the expected required rate of return for investors to 40%, 60%, and 80% of the base value (a 60%, 40%, or 20% reduction).[11] A lower expected required rate of return would mean investors were confident in their investments (e.g., from the RFS program), which might represent a system in which infrastructure was not limiting. This base value can vary, depending on the maturity of the technology, which directly influences the investment risk.

Fig. 5 shows the results of this sensitivity analysis of RFS program effects, displaying ethanol production effects of changes in perceived investment risk. The default case shows "Price + MTBE + VEETC + RINs + Match" scenario from Fig. 4 (dark yellow line). Considering simulated investment risk perception effects for the most aggressive case, if the RFS had decreased the investment risk for ethanol facilities by 60% (dark orange line), simulated ethanol production would have accelerated by one year relative to the default scenario (dark yellow line) in the 2008–2011[12] timeframe. The observed ethanol production line falls between the 20% and 40% risk reduction lines after 2008 (medium and light orange lines), which suggests RFS1 might have accounted for the gap between the observed and default lines (close to one billion gallons). These results suggest the overall effects of the RFS1 could have accelerated ethanol production growth by one year and increased annual production level by up to two billion gallons with these sensitivity assumptions. (As an additional sensitivity, oil price variation was included with a D6 RIN variation, which can be found in the S.I.)

3.4. Results summary by driver

Using the trajectories displayed in Figs. 3–5, Table 3 was developed to show the potential ranges of impacts on ethanol production for each policy and economic driver.

4. Conclusions and policy implications

This retrospective analysis illuminates the roles of policy and economic factors in the ten-fold expansion of ethanol markets during the past two decades, thus providing context for future policy action. By

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[11] The base value is based on the current state of technology versus nth plant, where the required rate of return decreases as industry learning occurs and technology moves toward the nth plant state (See S.I. and Vimmerstedt et al. (2015) for more information.).

[12] Although we implement the RFS investment risk decrease in 2005 with the passage of the Energy Policy Act, there is a 3-year construction period; therefore, production changes are not observed until around 2008.

comparing historical ethanol production to simulated ethanol production in a set of cases, we explored the potential individual and combined effects of these factors. We used the BSM-EtOH system dynamics model to test cases in which factors are included or excluded, and found that price competitiveness could explain much of the production increase, and that policies, including the RFS and others, primarily shift production increases to earlier years and may increase ultimate annual production levels by up to 42%, with VEETC contributing the most in earlier years and D6 RINS in the later years (especially if it is assumed to be implemented before match blending). This finding is consistent with Taheripour et al. (2020).

There are many other factors prior to 2002 that are not included in this study that were also critically important to the eventual increase in biofuels in the U.S. These include the RVP waiver to E10 (and later to E15) which enabled E10 to be sold year-round, the creation of the Reformulated Gasoline Program (RFG) which created a demand for octane in roughly 1/3 of the gasoline pool, the 1978 oil Embargo which stimulated much of the early research and investments in this area, the lack of fossil-fuel based alternatives to MTBE that didn't have similar environmental risks, and the Clean Air Act itself. We do not assess the incremental effects of all these factors in this paper as our focus is on the factors that came into play during the 2002–2018 timeframe when biofuels were observed to increase in the U.S. That said, all these factors likely played a significant role together and separately in the increase in biofuels in the U.S.

The relative roles of policy and economic factors from 2002 to 2018 were flexibly and quantitatively explored through the BSM-EtOH system dynamics simulation framework, and this framework can be used to estimate a range of potential quantitative effects of the RFS based on sensitivity analysis.

4.1. Ethanol's competitiveness regarding volumetric fuel and octane prices may explain much of the production increase during periods of rapid growth

The analysis indicates that ethanol's competitiveness as a source of combustible volume, energy, and octane in the gasoline market is estimated to explain much—but not all—of ethanol production increase during the study period. Petroleum, agricultural, and refining prices during much of the period made ethanol competitive with gasoline on a volumetric basis. The same is likely not true at higher blends as documented for a case in Brazil (Babcock, 2013). Logistical constraints that needed to be overcome were largely surmounted in coastal areas far from the biofuel production regions due to the need for a substitute for MTBE in RFG areas. Ethanol also became competitive as an octane enhancer in the present simulations, particularly after match blending enabled production of a lower-cost BOB that was blended with ethanol to meet octane targets. This octane value raised simulated demand for ethanol, and hence production, above estimated levels with volume extending value alone.

4.2. The VEETC and the MTBE phaseout contributed to earlier growth relative to a scenario absent these drivers

Although this analysis estimated that price competitiveness of ethanol was the strongest driver of ethanol production growth, policies contributed significantly to accelerating the timing and raising the ultimate level of ethanol production growth in the simulations in the earlier years (i.e., 2002–2011). Simulated VEETC and MTBE phaseout policies accelerated the timing of ethanol production growth to earlier years, contributing an annual maximum production increase of 42%, relative to cases without these factors.

Table 3
Metric of modeled effects by driver.

Driver	Rationale	Range of Estimated *Potential* Effect (2002–2019) Annual EtOH Production above Baseline from Fig. 3 (billion gallons)	Range of Estimated *Actual* Effect (2002–2019) Annual EtOH Production above Baseline from Figs. 4 and 5,[a] (billion gallons)
Price competition	With higher oil prices, blending ethanol into gasoline, up to applicable constraints, becomes economically advantageous. There is no range, as we used this as a baseline assumption; however, simulations estimated price competition to account for at least 50% of observed production.	Baseline	Baseline
MTBE replacement as part of the California and federal RFG programs	MTBE was the preferred oxygenate before 2001, but concerns about groundwater contamination and associated liabilities created a need for a substitute. The federal RFG program, which has been in effect since 1995, created a demand for oxygenate in O_3 non-attainment areas. The California RFG program, which has been in effect since 1996, created a demand for oxygenate in O_3 nonattainment areas.	0.0–3.2	0.0–3.2
Federal ethanol tax subsidy	This tax subsidy, which went into effect in 2004 and expired at the end of 2011, lowered the cost for blenders to mix ethanol into gasoline.	0.0–3.8	0.0–3.7
RFS1 standards[a]	The RFS1 standards, which were in effect from 2005 to 2008, created or contributed to demand for biofuels.	0.0	*0.0–2.0*[a]
RFS2 standards	The RFS2 standards, which have been in effect since 2009, created or contributed to demand for biofuels. D6 RINs are used as the market mechanism for the RFS2 program They are not an independent driver but are evidence of an effect from RFS2.	0.0–6.2	0.0–1.1 (assuming RINs implemented *after* match blending) 0.0–3.6 (assuming RINs implemented *before* match blending)
Transition to match blending	The octane value of ethanol allowed refineries to transition from producing 87 octane BOBs to cheaper 84 octane BOBs.	0.0–6.5	0.0–6.6 (assuming RINs implemented *after* match blending) 0.0–6.7 (assuming RINs implemented *before* match blending)

[a] Fig. 5 was used to estimate potential the RFS1 effect, which also would have translated to RFS2; this upper value is **not** included in the RFS2 range to avoid double counting.

4.3. The RFS contributed to increased ethanol production in later years and may have increased production in the earlier years if perceived risk of investment was decreased

The simulated effects of the D6 RINs indicated a maximum increase in ethanol production of 1.1–3.6 billion gallons (depending on if RINs are assumed to be implemented after or before match blending, respectively). Sensitivity analysis suggested a production increase of up to two billion gallons per year and one year of acceleration based on risk mitigation effects of the RFS. As historical events unfolded, RINs appear to have influenced ethanol production levels by an annual maximum of 7%–22% (depending on if RINs are assumed to be implemented after or before match blending, respectively). However, if conditions had not aligned (e.g., low oil prices and the presence of MTBE as the octane enhancer), the policy would likely have played a much greater role in the growth of the industry (Fig. 3 versus Fig. 4).

The BSM-EtOH system dynamics simulation framework used in the present analysis readily represents complex relationships between physically and financially constrained processes. The model's ability to closely match observed ethanol production volumes as demonstrated through this hindcasting analysis builds confidence that the BSM-EtOH simulations of various factors provide insight in the role of policy in the development of ethanol production. This effort may provide a useful foundation for future prospective analyses using the full BSM, delivering additional confidence in the associated trajectories. Limitations to the BSM-EtOH model that could be addressed in future analyses include lack of distribution infrastructure buildout, the representation of the RFS program through D6 RINs, and data unavailability. In addition, it would also be useful to look at the cost of these policies and how to design and implement policies to be more cost effective.

The insights gained through this analysis could be leveraged by decision makers in future policy discussions. For example, the combination of ethanol policies may have helped to hedge market uncertainty when oil prices dropped in later years of the simulation. In addition, the "lock in" of ethanol after the switch to match blending may have helped dampen the impact of VEETC expiration. These effects point to a diverse set of moderate policies and incentives for establishment of economic structures that will support industry longevity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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